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Effect of previous lowering of skin temperature on the time of safe exposure to a hot environment: a case study

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Objective. The purpose of the study was to determine the influence of initial conditions of a microclimate on volunteers' permissible exposure limits to a hot and humid environment. *Materials and methods.* Eighteen experimental studies with the participation of three volunteers were performed under controlled microclimate conditions (two climate chambers). The skin temperature and body core temperature were measured after they had stabilized in the following microclimate conditions: temperature of 17, 21 and 23 °C, relative humidity of 50% and hot microclimate conditions, i.e., temperature of 35 and 42 °C, humidity of 80% and physical work load at 30 W. The time needed to reach a body core temperature of 38 °C was determined under hot conditions. Heat accumulation was calculated. *Results.* Lowering volunteers' skin temperature under conditions of stabilized physiological parameters prolongs the time necessary for the body core temperature to reach 38 °C during physical work in a hot and humid environment. *Conclusions.* Appropriate acclimatization before exposure may prolong the time of safe work in a hot environment, e.g., during activities of rescue services.

Keywords: heat load; skin and body temperature; heat accumulation; time of safe exposure to heat; pre-cooling

1. Introduction

Exceptional working conditions in an extreme hot environment are linked in a majority of cases with intervention measures, especially during rescue operations, or with emergency repair of defective equipment, e.g., in mines.

Exposure to such heat load concerns, first of all, rescue workers, firemen and machine operators. Building awareness of the kind of heat load that workers may be exposed to during work or a rescue operation performed in a hot and humid environment is critical to their safety [1–5].

For this reason, it is necessary to perform rational assessment of the real safety level of rescue workers and people working under extreme conditions of a hot environment. This assessment should rely on a scientific knowledge base about potential physiological reactions of the human body to the occurrence of heat load. Determining the safety duration of exposure to work in a hot environment is one of the most important areas of research to reduce problems related to employees' thermal stress [6–8].

Tools that are usually applied in such cases allow for estimation of the safe exposure time based on the thermal balance.

It is assumed that the evaporation of perspiration from the skin is the leading factor for heat transfer from a human body under hot conditions. This approach is reflected in Standard No. EN ISO 7933: 2004 'Ergonomics of the thermal environment – analytical determination and interpretation of heat stress using calculation of the predicted heat strain' [9]. Conditions may occur, however, in which evaporation of sweat is not possible [10]. Then, the working time is limited to about a quarter of an hour or even several minutes. This is caused by the accumulation of heat generated in the human body combined with the heat transfer between the body and the surrounding environment [10,11].

Perception of the surrounding environment as warm or hot is conditioned by accumulation of heat, which is growing over time in the human body. This results in increasing body temperature. Physiological mechanisms against excessive accumulation of heat ensure that the optimum level of the core body temperature (t_{cr}) stays within the range of 36.7 °C ≤ t_{cr} ≤ 37.3 °C.

The regulatory processes put a strain on the human body. The bigger the heat load, the bigger the core body temperature deviations from the optimum value that the body maintains under neutral conditions. A core body temperature increase of 1 °C, i.e., up to t_{cr} = 38 °C in relation to the initial t_{cr} = 37 °C, is considered admissible and safe for human health.

In the event of fast accumulation of heat, in order to avoid risks to the health and safety of workers, the work time should be limited and work discontinued after a core

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body temperature level of $t_{cr} = 38$ °C has been slightly exceeded [7,8,11].

Excessive accumulation occurs most often (excluding disease states) during extreme human activities: in sport, during military activities and at work on technological heat sources. Two factors are decisive here: environmental conditions (high temperature and humidity) and high physical exertion [12]. Current research focuses on ways to reduce active heat accumulation in extreme conditions, which would create opportunities to extend the safe activity time. These studies are conducted in many directions [11–22]. Various cooling methods aimed at reducing the human heat load have been studied.

The aim of Watkins et al.'s [13] study was to identify a pre-cooling method that would reduce physiological and perceptual strain, and inflammatory response, while wearing personal protective equipment (PPE) under heat exposure. Pre-cooling involved ice slurry consumption before exposure to a hot environment while wearing a firefighter protective ensemble. According to these authors, ice slurry consumption was the best solution (compared with other solutions like vest or cooling forearms) and reduced the rectal temperature compared to the control before the heat exposure. The authors suggest consuming 500 ml of ice slurry 15 min prior to work in the heat.

In conditions in which it is possible to equip a person with heavier protective clothing (military or rescue operations), one of the frequently studied solutions is a cooling vest [3,14,15]. A cooling vest could be filled with ice (ice vest) [16,17] or phase-change materials (PCM) [18,19] and receive heat from the human body, reducing the heat accumulation in the body.

Another tested solution is the water immersion method, i.e., immersing different parts of the body in cold water [16,20]. After applying this method, at the end of the recovery period, the core body temperature was significantly lower in conditions of hand/forearm immersion. The heart rate responses during the recovery period and a second work bout were significantly lower for hand/forearm immersion. The lowering of the temperature of the bodies and limbs was also used in sport to achieve higher fitness during competitions [21,22].

In order to check the impact of the initial preparation (before exposing the worker to a hot environment) on the safe exposure time, the studies were carried out with the participation of volunteers in a climate chamber. This article discusses the results of studies on the variability of skin temperature (t_{sk}) and core temperature (t_{cr}) as well as heat accumulation (ΔS) of a human body in a hot and humid environment, depending on the way in which the body has been prepared for exposure to an unfavourable environment.

The study aimed to explore whether the safe exposure time could be prolonged under conditions of big heat load provided that prior adequate preparation to the exposure has been made.

Table 1. Description of physical and physiological parameters of volunteers.

Parameter	Volunteer sub_1	Volunteer sub_2	Volunteer sub_3
Age (years)	23	21	21
Height (m)	1.81	1.83	1.85
Body weight (kg)	82	83	100
V_{O2max} (L/min)	3.1	3.7	3.2

Note: V_{O2max} = maximal oxygen consumption.

1.1. Assumptions made in the studies

It was assumed that, since accumulation of heat in the human body is dependent on the relative increase of body temperature, the factor that significantly accounts for the value of the core temperature and the length of time after which the core temperature reaches $t_{cr} = 38$ °C can be attributed to the initial body temperature, t_c. This temperature is dependent on a thermal environment, in which a human was present before taking up work tasks in a hot environment [8].

2. Methodology

Tests were performed in two climatic chambers during 18 tests, with the participation of three volunteers.

2.1. Volunteers' characteristics

Tests involving human participants received approval from the Bioethics Committee at the Medical University of Warsaw, Poland. The study involved a group of three students, aged 21–23 years, admitted to take part in the experiments following a medical examination. The check included their overall physical state and physical exercise capacity based on V_{O2max} (maximal oxygen consumption) (Table 1).

For testing purposes, the volunteers wore cotton clothing, which readily absorbed sweat and was water vapour permeable. The thermal insulation of clothing was tested with the Newton-type sweating thermal manikin under controlled microclimate parameters in the climatic chamber. The effective thermal insulation (I_{eff}) of the tested clothing had the following parameters: $I_{eff} = 0.122$ °C m^2/W (0.79 clo) based on the parallel method of calculation; $I_{eff} = 0.191$ °C m^2/W (1.23 clo) based on the series method.

2.2. Test apparatus and measured parameters

2.2.1. Climatic chambers

Chamber 1 was the place to study the variability of air temperature (t_a) 10 °C $\leq t_a \leq$ 35 °C, relative humidity (RH) 20% $\leq RH \leq$ 80% and air velocity (V_a) 0.1 m/s $\leq V_a \leq$ 1.5 m/s. Chamber 2 was used to perform

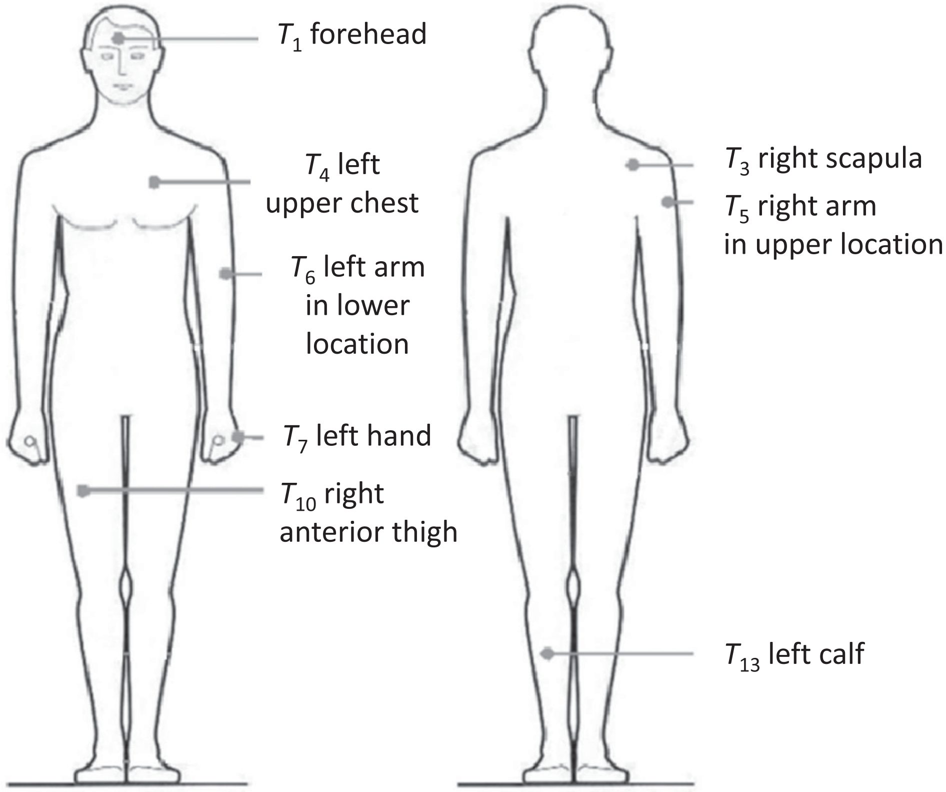

Figure 1. Distribution of sensors to measure temperature at eight points on the skin surface.
Note: T_1, T_3–T_7, T_{10}, T_{13} = skin temperature (°C) measured at the points on the skin surface.

tests for a significantly wider scope of microclimate parameter variability, i.e., air temperature 40 °C $\leq t_a \leq$ 70 °C, relative humidity 20% $\leq RH \leq$ 90% and air velocity 0.3 m/s $\leq V_a \leq$ 3.0 m/s.

2.2.2. *Measurement method of skin temperature*

The mean weighted skin temperature (t_{sk}) of human subjects (according to Standard No. EN ISO 9886:2004 [23]) was determined on the basis of the measurements taken at eight points (Figure 1), calculated according to Equation (1):

$$t_{sk} = 0.07 \times T_1 + 0.175 \times T_3 + 0.175 \times T_4 + 0.07 \times T_5 + 0.07 \times T_6 + 0.05 \times T_7 + 0.19 \times T_{10} + 0.2 \times T_{13}, \quad (1)$$

where t_{sk} = mean weighted skin temperature (°C); T_1, T_3–T_7, T_{10}, T_{13} = skin temperature (°C) measured at the points shown in Figure 1.

The skin surface temperature at the selected points was measured with the DS 1923 data logger (ibutton Hygrochron™; Maxim Integrated, USA). Sensors for measuring skin temperature were calibrated together with a Pt 100 calibration probe with an accuracy of 0.1 °C in a climatic chamber. The sensors were calibrated depending on the function in the skin temperature range 25–37 °C. The sensors were affixed to the skin surface with self-stick adhesive patching.

2.2.3. *Measurement method of the intra-abdominal temperature*

The studies used a non-invasive ambulatory temperature monitoring system placed in the digestive tract to measure the intra-abdominal temperature (t_{ab}). Sensors (telemetric capsules) of the VitalSense system (Philips Respironics, USA) were applied. After the capsule had been activated and swallowed by the volunteers, measurements of t_{ab} (treated equally to t_{cr}) were performed every 1 min. The accuracy of measurement was 0.1 °C. The results were transmitted to the receiver and the data recorder.

2.2.4. *Calculation of body temperature*

The body temperature (t_c) is a parameter defined from the core body temperature (t_{cr}) and the mean weighted skin surface temperature (t_{sk}). The body temperature is determined on the basis of Equation (2) [10,23]:

$$t_c = (1 - \alpha) \times t_{cr} + \alpha \times t_{sk}, \quad (2)$$

where t_c = body temperature (°C); α = coefficient taking account of the intensity of skin blood flow; t_{cr} = core temperature (°C); t_{sk} = mean weighted skin surface temperature (°C).

Values of the coefficient α adopted for Equation (2) depend on the characteristics of a thermal environment occupied by a human. For the hot environment, the value has been determined as $\alpha = 0.1$ [10].

2.2.5. *Calculation of the accumulation of heat*

Accumulation of heat in the volunteers' bodies under the hot environment was determined on the basis of temperature gains of their core body (Δt_c) that were changing over time during the experiment. Heat accumulation was calculated from Equation (3) [9,24]:

$$\Delta S = \Delta t_c \times m \times C_c, \tag{3}$$

where ΔS = heat accumulation (heat storage, kJ); Δt_c = gain of body temperature during the experiment in climatic chamber 2 (°C); m = body weight of the volunteer (kg); C_c = average specific heat of a human tissue, 3.49 kJ/(kg·°C).

2.3. *Test procedure*

Chamber 1 was used to stabilize subjects' physiological parameters. This notion should be understood as attaining physiological values that remain stable over time and correspond to the state of rest.

The conditions of the microclimate in the chambers and the test procedure are presented in Figure 2.

In climatic chamber 1, three air temperatures were arbitrarily adopted, i.e., $t_a = 17$, 21 and 23 °C. A volunteer was asked to remain seated in chamber 1 for 45 min before he could start tests in the other climatic chamber where the hot environment was maintained. In climatic chamber 2, two variants of the hot environment were simulated, i.e., $t_a = 35$ °C, $RH = 80 \pm 1\%$, $V_a = 0.4 \pm 0.1$ m/s and $t_a = 42$ °C, $RH = 80 \pm 1\%$, $V_a = 0.4 \pm 0.1$ m/s (Figure 2). During the stabilization stage in climatic chamber 1, the relative humidity and air velocity were maintained at the constant level of $RH = 50 \pm 1\%$ and $V_a = 0.4 \pm 0.1$ m/s, respectively. After 45 min, a volunteer was asked to move to climatic chamber 2, where the heat load was in the hot environment and the average power load was 30 W. The power load was caused by marching on a treadmill set to the appropriate incline. The speed was 3 km/h. The human body load in the hot environment (in climatic chamber 2) was realized under the following thermal conditions: air temperature 35 °C, $RH = 80 \pm 1\%$, $V_a = 0.4 \pm 0.1$ m/s; and air temperature 42 °C, $RH = 80 \pm 1\%$, $V_a = 0.4 \pm 0.1$ m/s.

The length of the experiment conducted in climatic chamber 2 was conditioned by the assumed criteria for test completion and the response of the human body to heat load. Above all, the increase of core body temperature over time was monitored, and close attention was paid to the moment it exceeded 38 °C. This stage of the experiment was carefully controlled by a medical doctor, who for that part of the experiment occupied climatic chamber 2 together with the volunteers.

The values in question concerned: (a) the mean weighted skin surface temperature (t_{sk}); (b) the mean intra-abdominal temperature (t_{ab}) equivalent to the core temperature (t_{cr}).

2.4. *Statistical analysis*

The results of calculations discussed in this article are presented as mean values, standard deviations and variability coefficients. The statistical analysis was based on a one-way analysis of variance (using Statistica version 9.0).

3. Results

3.1. *Influence of the assumed stabilization conditions on skin temperature of the volunteers*

Table 2 presents the mean weighted skin temperatures (t_{sk}) of the volunteers. These were calculated on the basis of values measured during a 45-min stability stage at different air temperatures (t_a) in climatic chamber 1.

Under the thermal conditions generated in climatic chamber 1, the volunteers reached the state of thermal balance with the surrounding environment. This fact was proven by the constant temperature t_{sk} that remained stable over time. On the whole, volunteers tended to perceive the conditions of their stay in the temperatures of $t_a = 17$, 21 and 23 °C as thermally neutral. As is known from the

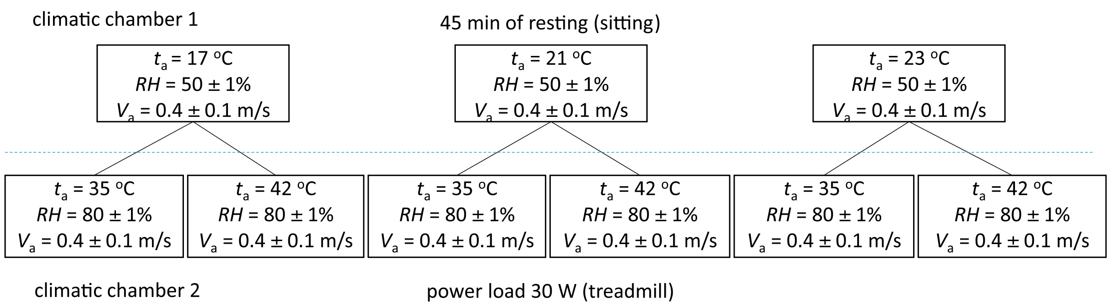

Figure 2. Scheme of tests performed in two climatic chambers.
Note: t_a = air temperature; RH = relative humidity; V_a = air velocity.

Table 2. Mean weighted skin surface temperature (t_{sk}) of the volunteers after stabilization during a 45-min stay in climatic chamber 1 (under conditions of thermal comfort).

Statistical parameter	t_{sk}		
	At t_a = 17 °C	At t_a = 21 °C	At t_a = 23 °C
M	31.83	32.71	33.45
SD	0.47	0.63	0.218
Cv	0.015	0.019	0.006

Note: Cv = variability coefficient; t_a = air temperature.

subject-matter literature, so-called thermal comfort is felt when 32 °C ≤ t_{sk} ≤ 34 °C [7].

The data in Table 2 show that the mean weighted skin temperature of the subjects, having reached stability under conditions generated in climatic chamber 1, tended to increase together with an increase of air temperature. The results of the analysis of variance ($F(2, 15) = 17.7$; $p = 0.00011$) confirm the hypothesis that the value of the stabilization temperature (t_a = 17, 21 and 23 °C) has a significant influence on the average of the participants' skin temperature.

3.2. *Increase of skin temperature of the volunteers as a consequence of the influence of the hot environment*

After the stabilization process had been completed in climatic chamber 1, the volunteers were transferred to climatic chamber 2. This part of the test consisted of performing physical exercises on a treadmill of average 30 W in the hot environment of air temperature 35 and 42 °C and relative humidity of 80%.

The skin temperature of the volunteers, stabilized under the influence of the microclimate maintained in climatic chamber 1, would become their initial temperature ($t_{sk\_initial}$) on entering climatic chamber 2 (Table 2).

It was noted that under the new ambient conditions the character of heat exchange between the human and the environment changed radically. A rapid increase in skin surface temperature was observed. Its initial value in comparison to the ambient temperature t_a = 35 and 42 °C was lower by 2.3 and 9.3 °C, respectively. The substantial growth in skin temperature occurred during the first 7–14 min under the influence of the hot environment.

The analysis of the data concerning the final temperatures (t_{sk_final}), which were recorded by the end of the experiments in the air temperature of t_a = 35 °C, reveals that the final mean weighted skin temperature of the subjects (i.e., reached just before the end of the experiment and leaving climatic chamber 2) was relatively non-diversified. It remained within the range of 36.3–36.9 °C, and the mean value was 36.5 °C. The final temperature is not thus dependent on the initial mean weighted skin surface temperature $t_{sk\_initial}$ (Table 3).

Table 3. Comparison of the mean weighted skin temperature recorded before the volunteers left chamber 2 (t_{sk_final}) at air temperature of 35 and 42 °C and relative humidity 80%.

Statistical parameter	t_{sk_final}	
	At t_a = 35 °C	At t_a = 42 °C
M	36.48	39.01
SD	0.29	0.18
Cv	0.01	0.005

Note: Cv = variability coefficient; t_a = air temperature.

A similar observation concerns the results of studies performed at air temperature equal to 42 °C. In this case, the final mean weighted skin temperature fluctuated between 38.9 and 39.3 °C (irrespective of stabilization conditions in chamber 1), and the mean value was 39.01 °C (Table 3).

Given the fact that the final mean weighted skin temperature of the volunteers reached a quasi-stable level in the hot environment, $t_{sk\_final} \approx 36.5$ °C (at t_a = 35 °C) and $t_{sk\_final} \approx 39.0$ °C (at t_a = 42 °C), whereas the initial values of the skin surface temperature $t_{sk\_initial}$ differed and were conditioned by the air temperature maintained in climatic chamber 1, the temperature gains $\Delta t_{sk} = t_{sk\_final} - t_{sk\_initial}$ had to differ too.

As can be seen in Figure 3, higher air temperature (t_a) maintained during a 45-min stabilization phase causes a decreased gain of the mean skin temperature Δt_{sk}.

3.3. *Influence of the assumed stabilization conditions on the values of intra-abdominal temperature of the volunteers*

Table 4 presents the mean values of the volunteers' intra-abdominal temperature (t_{ab}) noted in the final phase of their stay in climatic chamber 1 when the temperature t_{ab} stabilized. These values are also regarded as initial temperatures when the volunteers entered climatic chamber 2 ($t_{ab\_initial}$). A hypothesis was checked of whether the air temperature maintained in climatic chamber 1 during a 45-min stabilization phase influenced the value of t_{ab}. The results of the analysis of variance ($F(2, 15) = 0.3574$; $p = 0.7053$) reject the hypothesis that the value of the stabilization temperature (t_a = 17, 21 and 23 °C) has a significant influence on the average of the participants' intra-abdominal (core) temperature t_{ab} after their 45-min stay in climatic chamber 1. This influence would have probably been noticeable after a longer period of influence of the air temperature.

3.4. *Influence of the assumed stabilization conditions on the volunteers' safe exposure time under the conditions of the hot and humid environment*

Table 5 presents the initial values of the core body temperature ($t_{ab\_initial}$) of the volunteers (sub_1, sub_2, sub_3),

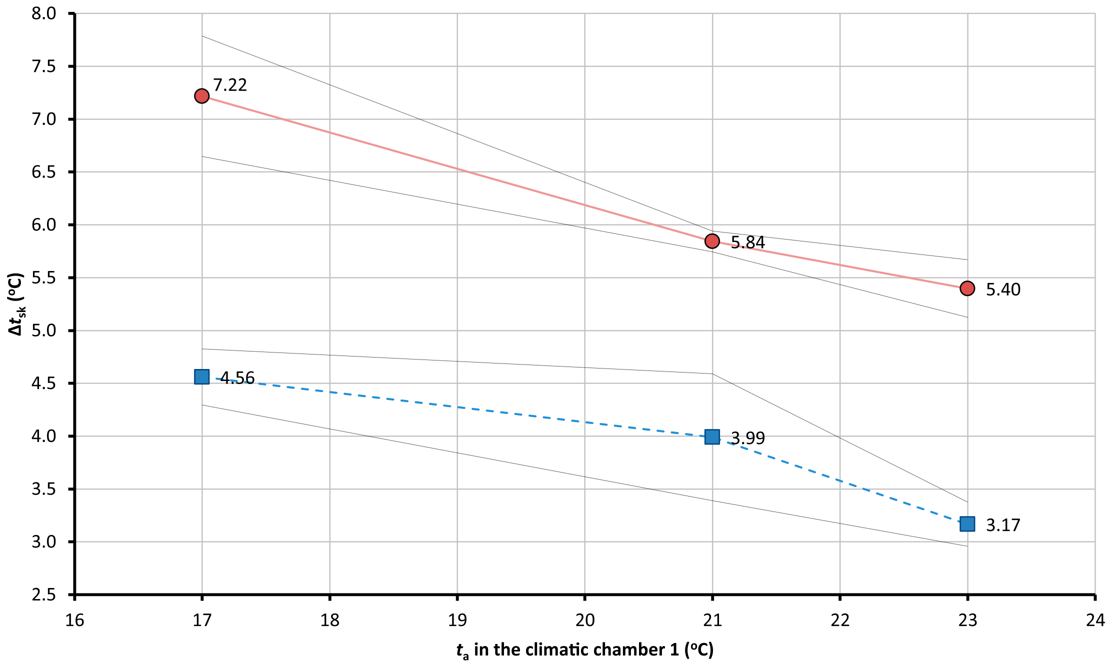

Figure 3. Mean gains of mean weighted skin surface temperature (Δt_{sk}) of volunteers recorded under the conditions of heat load (t_a = 35 and 42 °C) in climatic chamber 2, depending on the air temperature maintained in climatic chamber 1 during stabilization of the participants' physiological parameters before their relocation to climatic chamber 2.
Note: solid line, mean value of Δt_{sk} recorded at air temperature 35 °C (in climatic chamber 2); dotted line, mean value of Δt_{sk} recorded at air temperature 42 °C (in climatic chamber 2); thin lines around the mean values determine the range ± *SD*; t_a = air temperature.

Table 4. Values of the participants' core body temperature (t_{ab}) reaching the level of stability in different air temperatures during a 45-min stay in climatic chamber 1 (under the conditions of thermal comfort, t_{ab_inital}).

Statistical parameter	$t_{ab\_initial}$ At t_a = 17 °C	At t_a = 21 °C	At t_a = 23 °C
M	36.78	36.86	36.74
SD	0.24	0.20	0.31
Cv	0.006	0.005	0.008

Note: Cv = variability coefficient; t_a = air temperature; t_{ab} = intra-abdominal temperature; $t_{ab\_initial}$ = intra-abdominal temperature when volunteer entered climatic chamber 2 after stabilization.

stabilized under a temperature of t_a = 17, 21 and 23 °C during their stay in climatic chamber 1. The table also presents the times, read from the graphs, after which the participants' core body temperature reached the level of t_{ab} = 38 °C, following their relocation to climatic chamber 2. These are the results obtained from the tests performed in climatic chamber 2 in the conditions of t_a = 35 °C, *RH* = 80%. The variants of the performed tests, depending on the temperature maintained in climatic chambers 1 and 2, were marked with numbers, e.g., 17_35 gives the information that the measurement data collated in this line of the table refer to the experiment where the temperature maintained in climatic chamber 1 was t_a = 17 °C and that in chamber 2 was t_a = 35 °C.

The data presented in Table 5 show that after about 51, 54 and 58 min since the volunteers entered climatic chamber 2, where the thermal conditions were maintained at t_a = 5 °C, *RH* = 80%, their core body temperature reached t_{ab} = 38 °C. Given a significant individual variability in reaching t_{ab} = 38 °C, no marked relationship was found between the ambient temperature t_a = 17, 21 and 23 °C under which the process of reaching stability was taking place, and the average time of reaching t_{ab} = 38 °C.

Table 6 presents the test results obtained in the second variant of heat load, i.e., in the conditions of t_a = 42 °C, *RH* = 80%. As compared with the previous ambient conditions in which the experiments were performed, these proved to be more intensive in terms of strain put on a human body.

The data from Table 6 show that after 30, 27 and 19 min since entering climatic chamber 2 with the thermal conditions maintained at t_a = 42 °C, *RH* = 80%, the volunteers' core body temperature reached t_{ab} = 38 °C. This case clearly showed a relationship between the air temperature t_a = 17, 21 and 23 °C, under which the process of reaching stability was taking place, and the average time needed to reach t_{ab} = 38 °C.

When the volunteers reached the level of t_{ab} = 38 °C, the experiments were continued with the participant's approval, and were strictly monitored by a medical doctor. In consequence, it was possible to collect valuable measurement results exceeding the scope so far relatively well researched. From the data presented in Table 6, it

Table 5. Initial values of core body temperature ($t_{ab\_initial}$) of the volunteers (sub_1, sub_2, sub_3) and times after which their core body temperature reached t_{ab} = 38 °C.

Volunteer	Variant of experiment[a]	$t_{ab\_initial}$ (°C)	Time needed to reach t_{ab} = 38 °C (min)
sub_1	17_35	36.76	51.0
sub_2		36.47	65.0
sub_3		37.12	47.0
	M	36.78	54.3
	SD	0.33	9.5
	Cv	0.009	0.17
sub_1	21_35	36.72	60.0
sub_2		36.75	53.0
sub_3		36.96	60.0
	M	36.81	57.7
	SD	0.13	4.0
	Cv	0.004	0.07
sub_1	23_35	36.51	65.0
sub_2		37.24	45.0
sub_3		36.90	44.0
	M	36.88	51.3
	SD	0.36	11.8
	Cv	0.010	0.23

[a]Temperature in chamber 1_temperature in chamber 2.
Note: Conditions maintained in climatic chamber 2: t_a = 35 °C, relative humidity = 80%. Cv = variability coefficient; t_{ab} = intra-abdominal temperature; $t_{ab\_initial}$ = intra-abdominal temperature when volunteer entered climatic chamber 2 after stabilization.

transpires that after 36, 33 and 27 min since entering climatic chamber 2, the volunteers' core body temperature reached t_{ab} = 38.5 °C. Likewise, this case revealed a relationship between the ambient temperature t_a = 17, 21 and 23 °C and the time needed to reach t_{ab} = 38.5 °C.

The data illustrated in Figure 4. show that actions aimed to stabilize human physiological parameters at an adequate level that are undertaken before the planned exposure to heat load, as was the case with the experiments described, bring concrete benefits in the form of longer safe exposure time in the hot environment. The exposure time which is safe for a worker's health under non-standard conditions of the hot environment can be prolonged by several minutes. This is made possible when work tasks under such conditions are undertaken after adaptation in a temperature higher than 17 °C, e.g., t_a = 21 or 23 °C.

3.5. *Values of heat accumulation in the volunteers' bodies recorded for the hot and humid environment during a physical effort of 30 W*

The accumulation of heat in the volunteers' bodies was calculated according to Equation (3). The obtained results are presented in Table 7.

The data from Table 7 show that the mean heat accumulation in the volunteers' bodies under hot conditions of t_a = 35 °C, *RH* = 80% and average power load 30 W reached 448 kJ. Under hot conditions of t_a = 42 °C, *RH* = 80% and average power load 30 W, this reached 483 kJ. The average and acceptable gain of body temperature was $\Delta t_c \approx 1.47$ °C under the conditions of t_a = 35 °C, *RH* = 80%, and was $\Delta t_c \approx 1.60$ °C under the conditions of t_a = 42 °C, *RH* = 80%. The mean values of heat

Table 6. Values of initial core body temperature ($t_{ab\_initial}$) recorded for the volunteers (sub_1, sub_2, sub_3) and times after which the core body temperature reached t_{ab} = 38 and 38.5 °C.

Volunteer	Variant of experiment[a]	$t_{ab\_initial}$ (°C)	Time needed to reach t_{ab} = 38 °C (min)	Time needed to reach t_{ab} = 38.5 °C (min)
sub_1	17_42	36.57	32.0	39.0
sub_2		36.81	22.0	27.5
sub_3		36.92	36.0	42.5
	M	36.77	30.0	36.3
	SD	0.18	7.2	7.8
	Cv	0.005	0.240	0.216
sub_1	21_42	36.59	35.0	41.5
sub_2		37.00	18.5	23.5
sub_3		37.11	27.5	33.5
	M	36.90	27.0	32.8
	SD	0.27	8.3	9.0
	Cv	0.007	0.306	0.275
sub_1	23_42	36.48	19.0	26.0
sub_2		36.48	19.5	28.0
sub_3		36.80	19.5	27.0
	M	36.59	19.3	27.0
	SD	0.18	0.3	1.0
	Cv	0.005	0.015	0.037

[a]Temperature in chamber 1_temperature in chamber 2.
Note: Conditions maintained in climatic chamber 2: t_a = 42 °C, relative humidity = 80%. Cv = variability coefficient; t_{ab} = intra-abdominal temperature; $t_{ab\_initial}$ = intra-abdominal temperature when volunteer entered climatic chamber 2 after stabilization.

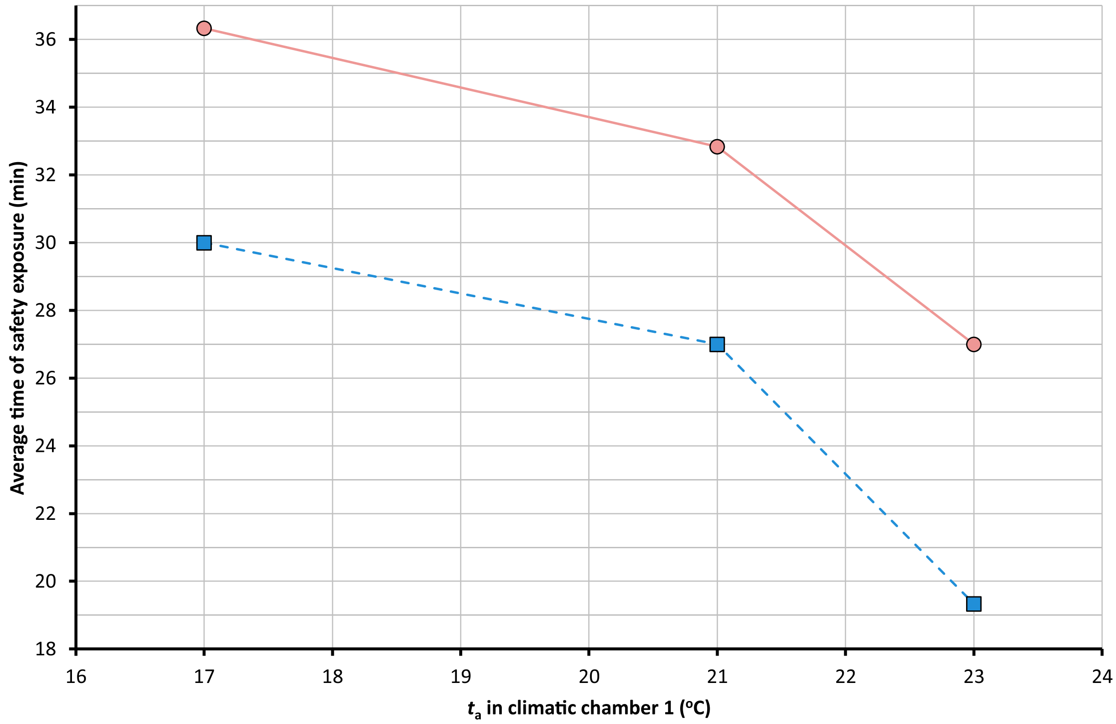

Figure 4. Influence of the stabilization air temperature t_a = 17, 21 and 23 °C maintained in climatic chamber 1 on the exposure time in climatic chamber 2 under conditions of t_a = 42 °C, *RH* = 80%, after which the volunteers' core body temperature reached the level of t_{ab} = 38 and 38.5 °C.
Note: solid line, time needed to reach t_{ab} = 38.5 °C; dotted line, time needed to reach t_{ab} = 38.0 °C. t_a = air temperature; t_{ab} = intra-abdominal temperature; *RH* = relative humidity.

Table 7. Gain of body temperature (Δt_c) recorded at the moment when the volunteers' core body temperature reached the level of t_{ab} = 38 °C, and resulting values of heat accumulation in their bodies.

Variant of experiment[a]	Volunteer	Δt_c after reaching t_{ab} = 38 °C	*S* (kJ)	S_M (kJ)	*SD*	Cv	S_M (kJ)	*SD*	Cv
17_35	sub_1	1.52	430.7	465.7	65.0	0.14	447.5	18.8	0.04
	sub_2	1.86	540.7						
	sub_3	1.26	425.7						
21_35	sub_1	1.45	410.9	428.2	19.5	0.05			
	sub_2	1.46	424.4						
	sub_3	1.33	449.3						
23_35	sub_1	1.52	430.7	448.7	144.5	0.32			
	sub_2	1.08	314.0						
	sub_3	1.78	601.3						
17_42	sub_1	1.88	532.8	517.9	58.4	0.11	482.7	37.2	0.08
	sub_2	1.56	453.5						
	sub_3	1.68	567.6						
21_42	sub_1	1.74	493.1	443.8	50.3	0.11			
	sub_2	1.35	392.5						
	sub_3	1.32	445.9						
23_42	sub_1	1.78	504.4	486.3	19.2	0.04			
	sub_2	1.68	488.4						
	sub_3	1.38	466.2						

[a]Temperature in chamber 1_temperature in chamber 2.
Note: Cv = variability coefficient; *S* = heat accumulation, S_M = mean of heat accumulation; t_{ab} = intra-abdominal temperature.

accumulation, i.e., 448 and 483 kJ, differed only slightly, yet they were reached at different times in considerably different hot conditions. The average time needed to reach accumulation of 448 kJ at 35 °C (about 55 min) turned out to be almost two times longer than the time after which heat accumulation reached 483 kJ at 42 °C (about 25 min).

4. Summary and discussion

The purpose of the study was to determine the influence of the initial conditions of a microclimate on volunteers' permissible exposure limits to a hot and humid environment. The study aimed to explore whether the safe exposure time could be prolonged under conditions of big heat load provided that prior adequate preparation for the exposure has been made.

The study investigated to what extent the use of pre-cooling at environmental temperatures of 17 °C and close to the temperature of thermal comfort for humans in resting conditions ($t_a = 21$ and 23 °C) may affect the extension of the safe working time at $t_a = 38$ and 45 °C. Volunteers reached an internal temperature of 38 °C as the safety limit criterion.

It was found that a stable state of the volunteers' skin temperature was reached during their 45-min stay in a seated position under ambient conditions of $t_a = 17$, 21 and 23 °C, relative humidity 50% and air velocity of 0.45 ± 0.05 m/s. It was observed that the mean weighted skin temperature of the volunteers, having stabilized under the conditions maintained in this environment, tended to rise together with air temperature t_a. It was found that air temperature (17, 21 and 23 °C) had no influence on the mean value of the core body temperature t_{ab} after a 45-min stay in the stabilization conditions. Ambient conditions maintained during the stabilization stage were reflected in time, after which the volunteers' core body temperature reached 38 °C in the hot environment.

The volunteers' core body temperature reached $t_{ab} = 38$ °C after about 30, 27 and 19 min from entering climatic chamber 2, where the conditions were maintained at $t_a = 42$ °C, $RH = 80\%$, $V_a = 0.4 \pm 0.1$ m/s. This case demonstrated a relationship between air temperature $t_a = 17$, 21 and 23 °C, under which physiological parameters of the body reached a level of stability, and the average length of time needed to reach the core body temperature $t_{ab} = 38$ °C. An influence on the increased time of exposure is, to a large extent, attributable to the mean weighted skin temperature of a human.

The study has shown that lowering volunteers' skin temperature under conditions of stabilized physiological parameters prolongs the time necessary for the body core temperature to reach 38 °C during physical work in a hot and humid environment.

A separate issue of concern is related to the threat of thermal homeostasis, which is the process of reaching and exceeding the core body temperature $t_{cr} = t_{ab}$ of 38.0 °C. Results of studies on the variability of t_{ab}, carried out with workers under neutral working conditions by means of state-of-the-art measurement methods (the measuring equipment used in the experiments satisfied such requirements), showed that the phenomenon of exceeding the level of $t_{ab} = 38.0$–38.5 °C is not infrequent. Such a case was encountered during field research conducted by the authors. A worker preoccupied with his work tasks was unaware that his body temperature was too high [25].

The literature studies described cases of several machine operators who had their core body temperature higher than 38 °C during 20–90 min of their shift work. In the case of one mine worker, the maximum recorded level was $t_{ab} = 39.7$ °C, and for 50 min his core body temperature even exceeded 39.0 °C [1].

Similar and very frequent cases of excessive t_{ab} that has so far been considered acceptable for human health were found in soldiers during army training activities and in sportsmen. For instance, in the case of footballers, the core temperature recorded for the whole football team was 39 °C by the end of the match played in ambient conditions of 16 °C [1].

The literature, examples of which are discussed in the Introduction, indicates the search for methods for extending the time of safe physical activity in extreme conditions. In cases where it is necessary, vest cooling is preferred in rescue operations, and in sport, cooling of the body or body part before the start. The effectiveness of these methods is generally confirmed in the literature; however, it is noted that extending the time of activity in heat or briefly increasing the thermoregulatory capacity of the body should be considered in terms of specific environmental conditions and human activity [21,22].

The results of the studies provided the grounds to conclude that appropriate preparation of a human to work before planned exposure to a hot environment, i.e., initial lowering of skin temperature, and by this also body temperature, gives the possibility of obtaining a longer time period of safe exposure to this environment.

It therefore transpires that during rescue operations in a hot environment, an adequate acclimatization of rescue workers before the start of the operation, if possible, can have an influence on the time of safe exposure to the ambient conditions they will work in.

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