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VERIFICATION OF ELECTRONIC DEVICE TECHNOLOGY FOR MEASUREMENT AND EVALUATION OF THERMAL EXPOSURE OF FIRE FIGHTERS AND MEMBERS OF RESCUE TEAMS

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ABSTRACT

Background: The work of members of rescue teams could be associated with very high physical and thermal loads. If not timely interrupted, any extreme labour-thermal load may lead to a failure of the body and fatal collapse. This risk may be significantly reduced by devices that monitor the response of the body during the intervention and inform rescuers about the need to interrupt the exposure when the critical value of the reference indicator is achieved. The aim of the study was to test the correlation between the data of the newly developed device for signaling the strain of rescuers and the indicators of physiological response of the body. **Material and Methods:** The tests were performed on 2 physically fit fire fighters dressed in a protective rescue suit and using insulating breathing apparatus, over a wide range of heat load under a model load on a bicycle ergometer in a climatic chamber. **Results:** The study provided a significant correlation between the body temperature measured in the ear canal and the temperature under the suit sensed by the tested device – the Safety Ambient Monitor (SAM) ($R = 0.9007$). The temperature under the suit also correlated with the temperature of the chest skin ($R = 0.8928$) and heart rate ($R = 0.8613$). **Conclusions:** A statistically significant correlation was proven between the temperature sensed by the SAM and the body temperature. The technical solution of sensing the temperature under the suit using the verified SAM technology does not affect or limit fire fighters in their work and minimizes the possibility of damage to the sensor and signaling failures. *Med Pr* 2018;69(1):1–11

Key words: heart rate, correlation, body temperature, fire fighter, physical strain, thermal load

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INTRODUCTION

In dealing with emergency situations, the work of fire fighters as well as the work of mine rescuers and members

of rescue teams is spasmodically associated with high and often even extreme physical and thermal loads. If not timely interrupted, any extreme labour-thermal load may lead to a failure of the body and fatal collapse [1,2].

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During 12 real interventions (4 interventions when fighting house or apartment fires, 3 interventions regarding traffic accidents, trailer fire, 2 car fires, cistern fire and freeing from an elevator), the measured average heart rate (HR) was 100–120 min⁻¹ but fitfully it reached even 180 min⁻¹. The corresponding average values of energy expenditure (EV) ranged between 15–25 kJ×min⁻¹; on a short-term basis, however, they reached net values of 50–60 kJ×min⁻¹ [3].

In the model situations, when carrying a wounded person under difficult circumstances and when ascending quickly up the stairs with baskets containing 1 or 2 hoses to the 6th floor (measured using an integral method), the net EV was 48–130 kJ×min⁻¹ (888–2167 W) whereas the HR values at the ascent end were around 180 min⁻¹ [3]. Similarly are high values found by a number of authors in testing fire fighters as well as mine rescuers [4].

For the model conditions in the mine, the measured values of energy expenditure ranged between 184 W and 966 W, while the average HR values were around 153±17 min⁻¹; however, short-term HR values were 180–200 min⁻¹. The core body temperature reached the average values of 38.1–38.3°C, individually even up to 38.9°C [5–7]. Working conditions are especially challenging if the work must be done with a breathing apparatus [5,8,9]. Health risk may be significantly reduced by devices that monitor the response of the body during the intervention and inform rescuers about the need to interrupt the exposure when the critical value of the reference indicator is achieved.

In work-medical practice, evaluation of the labour-thermal load of workers in hot workplaces takes grounds in changes of physiological parameters, primarily the body core temperature, liquid loss by perspiration and respiration, heart rate, and skin temperature. The evaluation also may use computation programs to predict perspiration production and body core temperature stemming from accurately defined indicators on metabolic production of the organism, heat-humidity conditions of the environment, and thermal resistance of clothing [10,11].

Recently, Yokota et al. [12] have published a model for evaluation of the labour-thermal load, which enables to predict body core temperature, skin temperature, perspiration production and heat stress index (physiological strain index (PSI) [13]) based on input data including microclimatic conditions of the environment, HR, metabolic production, height, weight, and

clothes characteristics. These methods have only limited use in monitoring load of fire fighters and rescuers in terrain conditions due to unpredictable and quickly changing heat-humidity conditions at the place of the intervention. Monitoring of the labour-thermal load of fire fighters and rescuers in terrain conditions requires using methods that put minimal load on the worker and are safe from the point of view of possible faults and failures of the early warning system.

The best indicator of organism overheating is the body core temperature (t_c) which reacts to metabolic and climatic load. Its direct measurement in terrain conditions is not possible. The only mini-invasive system for remote monitoring of t_c is a thermometer pill, although its routine use is limited due to high costs and results may be influenced by water and food intake [14]. This is the reason to search for methods that would be accurate enough (better than ±0.5°C) to determine the body core temperature from physiological indicators well-measured on the body surface under non-rest conditions. In the past methods were published to have been based on prediction of the body core temperature from temperature measured at selected places on the skin, thermal flow on the skin and heart rate [14–16] or only from the heart rate [17].

The methods were verified in the laboratory and terrain conditions in a wide range of thermal-humid conditions, metabolic demands, and various clothes. The reliability of the calculated values compared with the body core temperature measured by some of the invasive methods (rectal temperature, esophageal, intestinal) was better than the required ±0.5°C. Although the mentioned methods are maximally gentle from the monitored person's point of view, they required scanning the monitored parameters directly from the surface of the monitored person, which might be the cause of faults and failures of the early warning system.

The aim of the work was to validate the correlation between data measured using the technology of the Safety Ambient Monitor (SAM) and indicators of physiological responses of the body under experimental conditions of a climatic chamber.

MATERIAL AND METHODS

The Safety Ambient Monitor device (Photo 1) was developed at the VŠB – Technical University of Ostrava for monitoring and evaluation of those working conditions in order to minimize hazard by an early warning.



Photo 1. Safety Ambient Monitor (SAM) – the tested device measuring thermal exposure of fire fighters and members of rescue teams, and signaling the strain of rescuers and the indicators of physiological response of the body

The device records and evaluates the air temperature and humidity under the suit and outdoor temperature. Based on defined limits, it signals any excess of these limits and alerts wearers to impending critical conditions of body overheating. The device also registers and analyzes movements of the monitored person and alerts to loss of consciousness or to fall from a height of that person. The unit weighs about 130 g, has a size of a mobile phone and its battery lasts 48 h. Charging is done via a micro-USB connector and the unit parameters are set from a PC.

For testing purposes, we selected 2 professional fire fighters (FF) aged 32 and 42 years old, well adapted for the profession of a fire fighter (seniority as a fire fighter, respectively: 10 years and 13 years) and physically fit (maximal oxygen consumption per minute (VO_{2max}) = 43.6 ml/min/kg and 42.7 ml/min/kg), who, prior to testing, had successfully passed the stress test in a functional laboratory of the Department of Physiology and Pathophysiology, Faculty of Medicine, University of Ostrava, Ostrava, the Czech Republic.

First of all, those experimental persons (fire fighter 1 – FF1, fire fighter 2 – FF2) completed a continuous

load test on a bicycle ergometer (Ergo 900, Ergo-Line), in the case of which the load, after an initial warm-up, rose from the start value of 75 W by 25 W every minute up to maximum. Fans' parameters were found and the gas analysis was done using the instrument OxyconPro (Jaeger – CareFusion, Germany). The achieved values of the maximum oxygen consumption per minute, heart rate (HR) and VO_2 at the level of anaerobic threshold (AT) are listed in the Table 1.

After a complete 2-hour recovery in optimal microclimate conditions, they underwent a submaximal exercise test according to the design by Hollmann [18], in which the load was increased for the start value of 30 W every 3 min by 40 W. The FFs underwent this test in the laboratory microclimatic conditions in the rescue suit with the same equipment as during the subsequent testing in the climatic chamber.

The FFs were dressed in a standard rescue suit Tiger Plus. Under the suit, they had short underpants, a T-shirt with short sleeves and socks. Both of them had rescue leather shoes afoot and standard helmets for fire fighters on their heads. On their backs, they were carrying a breathing apparatus weighing 14.1 kg (Photo 2). During the test the FFs did not use a breathing apparatus, but Oxycon Pro analyzer. Oxycon Pro has automatic calibration and its accuracy of measurement is 3% or 0.05 l/min.

The results were used for calculating individual equations for the relationship between the magnitude of the load and strain physiological indicators.

The technology for signaling the load of rescuers was verified in a climatic chamber of the Department of Work Physiology at the Health Institute in Ostrava. The climatic chamber has an inner space of 2×3×2 m. Conditioned air is conveyed to the chamber from an engine room through a duct hole sized 1×1 m and located in the wall along the chamber longitudinal

Table 1. Continuous load* test of professional fire fighters on a bicycle ergometer in the climatic chamber in suit under normal heat-humidity conditions

Fire fighter	Age [years]	Body weight [kg]	Parameters				AT	
			VO_{2max} [l/min]	VO_{2max}/kg [ml/min]	HR_{max} [bpm]	W_{max}/kg [W/kg]	HR [bpm]	VO_2 [l/min]
FF1 (N = 1)	32	75.8	3.30	43.6	184	4.0	130	1.6
FF2 (N = 1)	42	86.0	3.67	42.7	160	3.8	134	2.4

* Load (after an initial warm-up) rises from the start value of 75 W by 25 W every minute up to maximum value.

FF1 – a person with 10-year-exposure as a fire fighter, FF2 – a person with 13-year-exposure as a fire fighter.

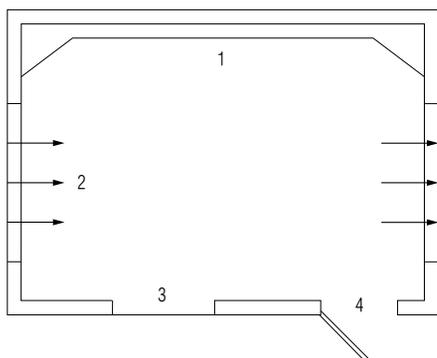
VO_{2max} – maximum oxygen consumption per minute, VO_{2max}/kg – oxygen consumption per kg of weight, HR_{max} – maximum heart rate, W_{max}/kg – maximum work rate achieved during an incremental cycle ergometer test per kg, AT – the values of the heart rate with the corresponding oxygen consumption at anaerobic threshold.



Photo 2. Fire fighter in a standard rescue suit with breathing apparatus on a bicycle ergometer in the model work (load value: 100 W) inside the climatic chamber

axis and removed in the wall on the opposite side (Figure 1).

The back wall of the chamber is created by a radiating panel. The source of radiation is 12 heating units (each of 250 W) connected serially and placed in 3 superposed rows. There are 3 metal rods and a metal net to protect the heating units from a direct contact. The



1 – vertical radiant panel, 2 – air flow direction, 3 – control room window, 4 – entrance to the chamber.

Inner space: 2×3×2 m.

Arrows – direction of conditioned air, which is conveyed to the chamber from an engine room through a duct hole located in the wall and sized 1×1 m, along the chamber longitudinal axis, and removed in the wall on the opposite side.

Fig. 1. Climatic chamber used for the professional fire fighter load test

chamber allows for experimenters to adjust the air temperature in the range 20–60°C, airflow speed in the range of 0.2–2.0 m×s⁻¹, relative humidity in the range of 30–90%. Intensity of heat radiation from the back wall of the chamber (I_A) can be gradually increased up to 700 W×m⁻².

The load on the bicycle ergometer in the climatic chamber was set uniformly at 100 W for all phases. The calculated values of the oxygen consumption per minute, heart rate, and energy expenditure (kJ, W), which the FFs reach after the 100 W load in a fire fighter's suit under normal heat-humidity conditions, are stated in the Table 2.

Ambient conditions were continuously measured at a height of 110 cm above the floor, at the level of the chest of experimental persons. The measured physical parameters, dry air temperature (t_a) (°C), air relative humidity (RH) (%), air velocity (v_a) (m×s⁻¹), radiation temperature in the direction from the chamber front wall (t_{rA}) (°C) and from the opposite wall (t_{rB}) (°C), and the intensity of radiation from the chamber front wall (I_{rA}) (W×m⁻²) and from the opposite wall (I_{rB}) (W×m⁻²), were measured using the instrument – the Indoor Climate Analyzer, type 1213, made by the company Brüel and Kjaer.

The resulting temperature (t_g) (°C) was measured with a spherical thermometer made by Ahlborn company, having a ball diameter of 150 mm. Monitored values were recorded at 3-minute intervals. For each phase, the measured values were used for calculating mean values and standard deviations (SD). Detailed heat-humidity conditions measured during each phase are given in the Table 3.

In all stages, the FFs were forehead-oriented to the radiating panel. To be able to communicate, the FFs were not connected to a breathing apparatus and they breathed atmospheric air from the chamber. Within 2 testing days, the FFs passed 5 phases

Table 2. Professional fire fighter parameters after the load of 100 W on the bicycle ergometer in the climatic chamber in suit under normal heat-humidity conditions

Fire fighter	VO ₂ [l/min]	HR [bpm]	Energy expenditure		
			kJ/min (gross)	kJ/min (net)	W (net)
FF1 (N = 1)	1.48	140	30.28	25.0	416.8
FF2 (N = 1)	1.67	132	33.51	28.2	470.6

FF1 – a person with 10-year-exposure as a fire fighter,

FF2 – a person with 13-year-exposure as a fire fighter.

VO₂ – oxygen consumption per minute, HR – heart rate.

Table 3. Heat-humidity conditions and the time in the climatic chamber during professional fire fighter load test on the bicycle ergometer in suit

Phase No.	Exposure time [min]	Temperature [°C] (M±SD)			Intensity of radiation [W×m ⁻²] (M±SD)			RH [%] (M±SD)	v [m×s ⁻¹] (M±SD)
		t _a	t _e	t _{rA}	t _{rB}	t _{rA}	t _{rB}		
1									
FF1	30	22.6±0.4	23.9±0.5	24.3±1.2	24.0±0.4	without the radiant	without the radiant	41.2±0.7	0.29±0.11
FF2	30	22.9±0.2	23.7±0.3	24.3±0.3	24.4±0.4	panel	panel	38.5±0.0	0.32±0.04
2									
FF1	30	31.7±1.2	35.9±2.4	56.1±2.0	33.5±1.9	660.0±8.3	509.0±6.4	29.9±1.4	0.33±0.01
FF2	30	31.7±1.2	35.9±2.4	56.1±2.0	33.5±1.9	639.0±8.7	511.5±5.1	29.9±1.4	0.33±0.01
3									
FF1	30	40.8±2.1	43.7±2.3	59.3±0.4	40.5±2.5	695.0±7.1	537.1±8.5	41.5±2.8	0.32±0.02
FF2	30	42.4±0.1	45.5±0.0	58.3±0.4	41.6±0.3	680.0±2.6	550.0±3.5	27.5±9.9	0.27±0.04
4									
FF1	25	50.4±0.2	50.0±0.6	56.8±0.5	45.6±1.6	672.3±4.9	585.7±11.3	27.6±2.8	0.21±0.02
FF2	27	50.8±0.3	50.8±0.1	57.0±1.1	47.7±1.1	674.6±3.5	592.3±7.8	28.9±0.7	0.22±0.02
5									
FF1	30	33.5±0.4	34.2±0.3	34.1±1.1	33.5±0.3	505.5±6.4	501.4±2.1	71.6±1.4	0.24±0.03
FF2	25	32.9±0.1	33.6±0.0	33.8±0.4	33.0±0.1	502.9±2.8	498.3±1.4	72.4±2.8	0.22±0.01

FF1 – a person with 10-year-exposure as a fire fighter (N = 1), FF2 – a person with 13-year-exposure as a fire fighter (N = 1).

M – mean, SD – standard deviation.

t_a – dry air temperature, t_e – resulting temperature, t_{rA} – radiation temperature in the direction from the chamber front wall, t_{rB} – radiation temperature from the opposite wall, I_{rA} – intensity of radiation from the chamber front wall,

I_{rB} – intensity of radiation from the opposite wall, RH – air relative humidity, v – air velocity.

(P1–P5) with different air temperature, radiation intensity and relative humidity (RH). During phases P1–P4, the thermal load was increased from a very modest load in P1 ($t_a = 22^\circ\text{C}$, $t_{rA} = 24^\circ\text{C}$, RH = 30–40%) up to P4 ($t_a = 50^\circ\text{C}$, $t_{rA} = 57^\circ\text{C}$, RH = 30%). In P5, the relative humidity was very high (RH = 70%) at relatively low air temperature ($t_a = 33^\circ\text{C}$) and temperature from the chamber front wall $t_{rA} = 34^\circ\text{C}$. Intensity of radiation was adjusted to achieve the desired air temperature (t_a) in individual phases P1–P5.

The period of exposure in various phases was set to 30 min or until reaching critical HR or body temperature values. The exceeded limit value was the reason to interrupt the test and to set it to HR 200-age and the body core temperature – 38.5°C . On the first testing day, the FFs underwent phase E1 and E2, on the second day – stage E3 to E5, and between individual phases, there was a 2-hour break which the FFs spent in light clothes in optimal climatic conditions in a rest room.

Monitored physiological parameters, heart rate (HR) (bpm) and the skin temperature at the inferior sternum ($t_{sk,chest}$) ($^\circ\text{C}$) were measured using the multi-variable monitoring device – MLE 120X BioHarness. The HR was captured through electrode sensors housed within the chest strap with the TEAM System station for BioHarness device. Skin temperature data was collected through an infrared sensitive sensor behind a clear window on the apex of the monitoring device; values were displayed on a monitor and continuously recorded at 30-second intervals in the memory of the computer. Precision of measurement for HR data is $< \pm 1$ beat/min; for methods involving temperature measurement, a threshold of accuracy stands at 0.1°C [19].

The body core temperature was measured continuously in the left ear canal (t_{ac}) ($^\circ\text{C}$) using the thermocouple type T sensor with accuracy of ± 0.2 K. Having otoscopically checked the cleanliness of the ear canal, the temperature sensor was introduced deep into the ear canal and thermally shielded by a 5-centimeter foam insulation and helmet plastic skeleton.

The measured values were continuously displayed on the monitor and saved in the computer memory. The device for signaling the load, the SAM, was placed in the inner pocket of the rescue suit on the right chest side. Through the hole in the pocket, the sensors of the SAM for the continuous measurement of the microclimate temperature (t_{suit}) and relative humidity (RH_{suit}) measured microclimate in the space between

the outer and inner layers of the suit. The suit surface temperature ($t_{surface}$) was measured contactlessly shortly after entering the chamber and just before leaving the chamber.

Loss of water due to sweating and breathing (SR) (ml) was measured by weighing FFs before entering and immediately after leaving the climate chamber. During their stay in the climatic chamber, EPs did not eat and drink. At the end of each phase, EPs evaluated their subjective feeling of physical strain and fatigue using a 5-point scales created by authors (Table 4 and 5).

Table 4. Scale of subjective evaluation of the amount of labour-thermal load

Load intensity	Labour-thermal load
1	very light load with no uncomfortable subjective feelings
2	light load with minor uncomfortable subjective feelings, which can be tolerated for a very long time
3	medium load with mid-intensive uncomfortable feelings, which can be tolerated for quite a long time
4	intensive load with uncomfortable feelings, which can be hardly tolerated even for a very short time
5	very intensive load with very uncomfortable subjective feelings leading to the feeling of exhaustion after a very short time with the need to interrupt the work

Table 5. Scale of subjective evaluation of the tiredness level after experiments in the climatic chamber

Tiredness level	Feelings after the labour-thermal load
1	pleasantly tired
2	slightly tired
3	quite tired
4	very tired
5	exhausted

For purposes of statistical evaluation, authors used correlation and regression analyses with the chosen significance level of 5%. Processing was performed using Stata software, version 13.

RESULTS

In various phases, the average production of sweat per hour did not vary too much and ranged around 1.38 ± 0.13 l/h, 3 were no statistically significant differences among the phases. The temperature on the suit

surface at the end of the load reached 28.7°C in P1 up to 49.8°C in P4 on the back (in the direction of radiation) and 26.4°C in P1 up to 44.7°C in P4 on the chest. At the end of P3 and P4, the heart rate exceeded the limit values of SF_{max} , approaching to the maximum values; the body core temperature measured in the ear canal also exceeded the limit value of 38.5°C during the stated phases. During P5, all the indicators of FFs reached lower values than in P4.

Experimental persons (FFs) assessed the load magnitude with grade 1–3 (very slight to medium load causing moderately intensive unpleasant subjective feelings which can be tolerated for quite a long time) within P1 to P3, and with grade 4 (intensive load associated with unpleasant sensations which can be tolerated only with

great effort for a short time) within P4 and P5. They assessed the feeling of fatigue with grade 1 (pleasantly tired) within P1 and P2, and with grade 3 (rather tired) within P3 to P5.

Minimum and maximum values of basic physiological indicators, i.e., the body temperature measured in the ear canal (t_{ac}), heart rate (HR) and the skin temperature on the chest ($t_{sk,chest}$), and the values measured by the SAM device, i.e., the air temperature measured under the suit (t_{suit}) and air relative humidity measured under the suit (RH_{suit}), found during individual experiments and their differences are shown in the Table 6.

The relationship between basic physiological indicators (HR, t_{ac} , $t_{sk,chest}$) on the one hand and the values measured by the verified SAM technology (t_{suit} , RH_{suit})

Table 6. Physiological indicators for professional fire fighters (FF1, FF2) during individual experiments within 5 phases in the climatic chamber

Experiment No.	t_{ac} [°C]		HR [bpm]		$t_{sk,chest}$ [°C]		t_{suit} [°C]		RH_{suit} [%]	
	FF1	FF2	FF1	FF2	FF1	FF2	FF1	FF2	FF1	FF2
1										
min.	35.8	35.5	94	61	33.4	34.6	28.0	27.4	62.9	53.4
max	37.1	37.0	163	137	35.4	36.3	33.6	34.0	81.8	89.8
increase	1.3	1.5	69	76	2.0	1.7	5.6	6.6	18.9	36.4
2										
min.	failure	34.7	65	61	32.9	35.0	28.4	28.6	70.9	59.0
max		37.6	157	158	37.0	37.1	35.4	36.1	91.7	88.4
increase		2.9	92	97	4.2	2.1	7.0	7.5	20.8	29.4
3										
min.	35.6	33.1	110	61	34.4	35.1	29.5	29.0	66.9	58.2
max	38.5	37.7	196	170	38.0	37.7	38.1	38.2	89.7	88.6
increase	2.9	2.3	85	109	3.5	2.5	8.6	9.2	22.8	30.4
4										
min.	34.6	35.4	78	61	34.5	35.2	28.5	31.0	58.2	53.6
max	38.6	38.8	173	178	38.2	38.6	39.3	39.7	85.1	83.2
increase	4.1	3.5	94	117	3.6	2.9	10.8	8.7	26.9	29.6
5										
min.	34.4	35.4	84	61	34.9	35.6	29.7	31.7	58.8	55.2
max	37.8	37.9	173	175	37.2	37.2	37.9	37.3	83.1	82.2
increase	3.3	2.6	89	114	2.3	1.6	8.2	5.6	24.3	27.0

FF1 – a person with 10-year-exposure as a fire fighter (N = 1), FF2 – a person with 13-year-exposure as a fire fighter (N = 1).

min. – minimal value, max – maximal value.

t_{ac} – body temperature measured in the ear canal, HR – heart rate, $t_{sk,chest}$ – skin temperature measured on the left side of the chest using glued thermistor sensors,

t_{suit} – air temperature measured between the outer and inner layer of the suit by the verified technology for signaling the load (safety ambient monitor – SAM),

RH_{suit} – air relative humidity measured between the outer and inner layer of the suit by the verified technology for signaling the load (SAM).

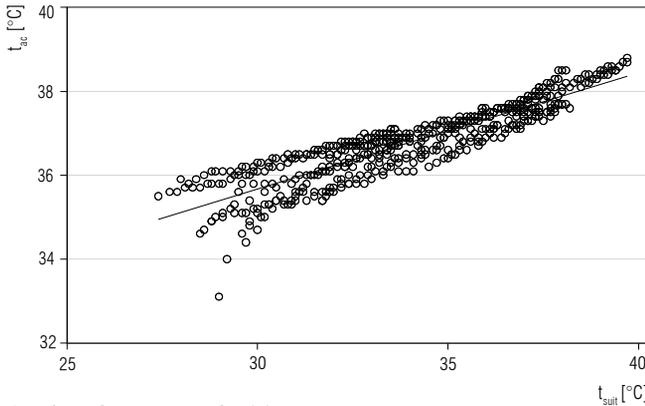
Other abbreviations as in Table 3.

Table 7. Relationships between the air temperature (t_{suit}) and the air relative humidity (RH_{suit}) measured under the suit of professional fire fighters by the verified technology for signaling the load (safety ambient monitor – SAM) and the load physiological indicators: body temperature (t_{ac}), heart rate (HR) and the temperature of the chest skin ($t_{\text{sk,chest}}$)

Relationship	Equation	Correlation coefficient*
$t_{\text{ac}}:t_{\text{suit}}$	$t_{\text{ac}} = 27.32+0.28 \times t_{\text{suit}} \text{ [}^\circ\text{C]}$	0.9007
$t_{\text{ac}}:RH_{\text{suit}}$	$t_{\text{ac}} = 0.06 \times RH_{\text{suit}} + 31.98 \text{ [}^\circ\text{C]}$	0.6651
$HR:t_{\text{suit}}$	$HR = -77.65+6.6 \times t_{\text{suit}} \text{ [bpm]}$	0.8613
$HR:RH_{\text{suit}}$	$HR = 28.22+1.47 \times RH_{\text{suit}} \text{ [bpm]}$	0.6292
$t_{\text{sk,chest}}:t_{\text{suit}}$	$t_{\text{sk,chest}} = 18.31+0.5 \times t_{\text{suit}} \text{ [}^\circ\text{C]}$	0.8928
$t_{\text{sk,chest}}:RH_{\text{suit}}$	$t_{\text{sk,chest}} = 25.00+0.13 \times RH_{\text{suit}} \text{ [}^\circ\text{C]}$	0.7512

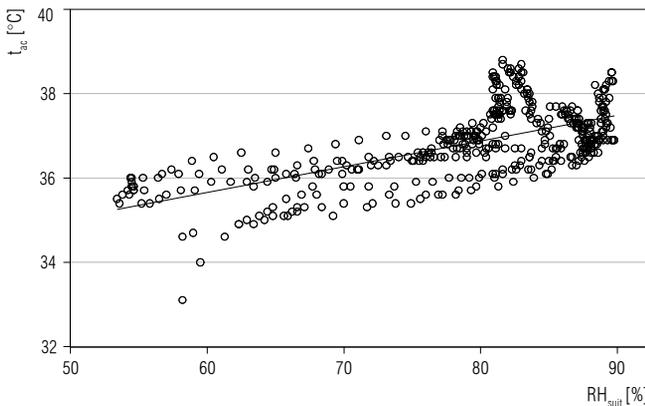
* $p < 0.05$.

Abbreviations as in Table 6.



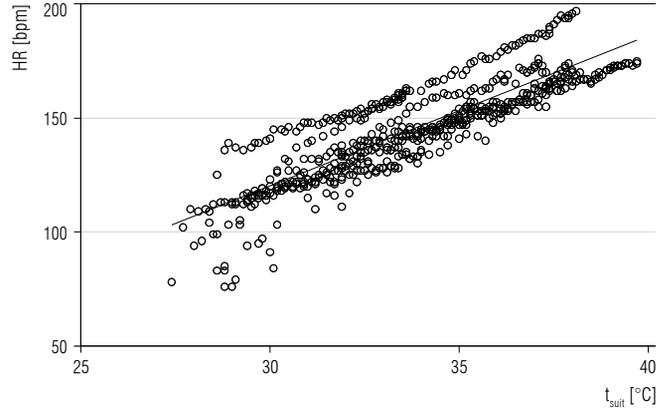
Correlation between t_{suit} and t_{ac} (R) = 0.907.

Fig. 2. Relationship between the professional fire fighters' body temperature measured in the ear canal (t_{ac}) and the air temperature measured between the upper and the inner layer of the suit by the verified technology for signaling the load (t_{suit})



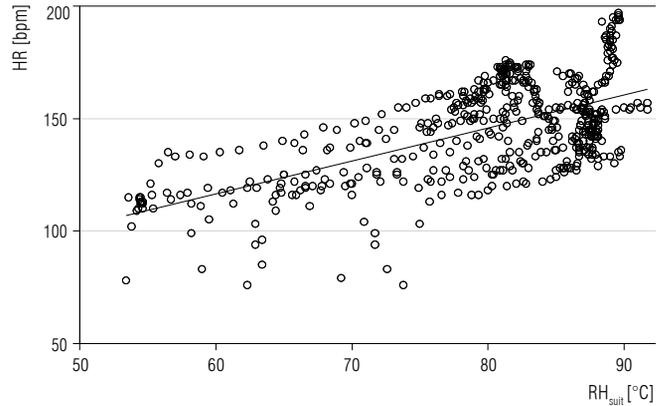
Correlation between RH_{suit} and t_{ac} (R) = 0.6651.

Fig. 3. Relationship between the professional fire fighters' body temperature measured in the ear canal (t_{ac}) and the air relative humidity measured between the upper and the inner layer of the suit by the verified technology for signaling the load (RH_{suit})



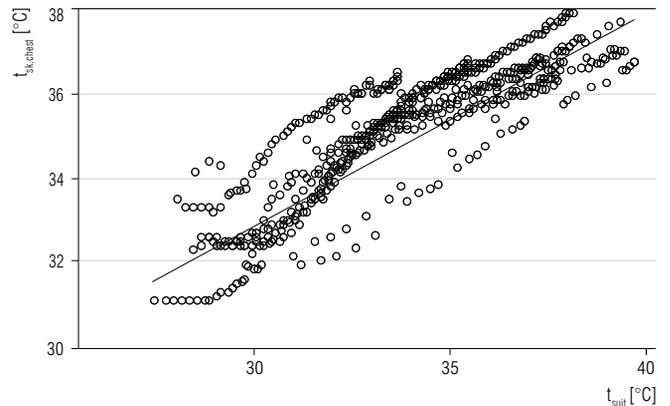
Correlation between t_{suit} and HR (R) = 0.8613.

Fig. 4. Relationship between the professional fire fighters' heart rate (HR) and air temperature measured between the outer and inner layer of the suit by the testing device (t_{suit})



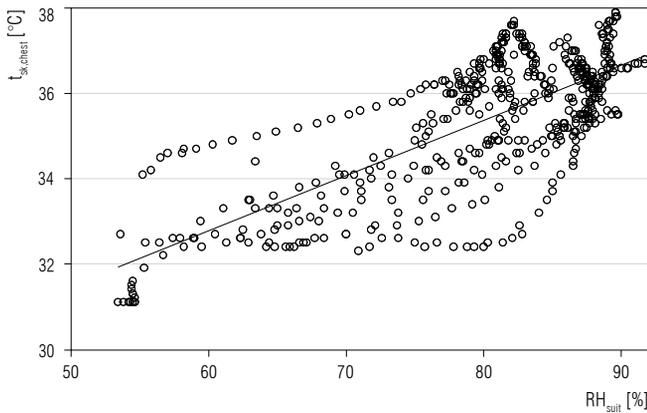
Correlation between RH_{suit} and HR (R) = 0.6292.

Fig. 5. Relationship between the professional fire fighters' heart rate (HR) and relative air humidity measured between the outer and inner layer of the suit by the testing device (RH_{suit})



Correlation between t_{suit} and $t_{\text{sk,chest}}$ (R) = 0.8928.

Fig. 6. Relationship between the professional fire fighters' skin temperature measured on the chest ($t_{\text{sk,chest}}$) and air temperature measured between the outer and inner layer of the suit by the testing device (t_{suit})



Correlation between RH_{suit} and $t_{sk,chest}$ ($R = 0.7512$).

Fig. 7. Relationship between the professional fire fighters' skin temperature measured on the chest ($t_{sk,chest}$) and relative air humidity measured between the outer and inner layer of the suit by the testing device (RH_{suit})

on the other hand for both experimental persons is provided in the Table 7.

Graphical representation of the correlations of the measured quantities is presented in the Figure 2–7.

The multifactor regression analysis analyzing t_{ac} – t_{suit} and t_{ac} – RH_{suit} relationships did not lead to improvements of observed correlations. Proportion of RH_{suit} in the studied relationship proved to be insignificant.

DISCUSSION

The permissible operating thermal load for the industrial population in the Czech Republic is based on the Government Regulation [20]. Nevertheless, the given limits do not apply to workers of rescue brigades in fire-fighting or liquidation of emergency situations if such persons have been recognized for this work as medically fit. In the Czech Republic the limit values for workers of rescue brigades are not legislatively determined. With regard to the safety of rescuers, however, HR should not exceed the value of 200-age even temporarily and the body core temperature should not be higher than 38.5°C.

Our selected load for testing the signaling device – the SAM was determined in a way that the heat-humidity conditions would cover as wide range as possible and the resulting load in phases 4 and 5 would correspond to or be higher than the average load in regular interventions. This condition was met and the EPs in the last three attempts achieved or exceeded the recommended limit values of HR and the body core temperature so the exposure had to be timely interrupted due to safety reasons.

In order to measure the body core temperature in the laboratory conditions, most authors use some of invasive methods, mostly measured in anus, which is considered to be the “golden” standard [14,21]. Values measured by direct methods are considered little reliable as they can show striking differences against values acquired by invasive methods [21,22]. With respect to our used way of load (bicycle ergometer), the temperature in the ear canal was used for measuring the body core temperature. We have long experience in using this method and when strict conditions are followed, it provides very reliable results.

Direct measurement of the body core temperature by both invasive methods and in the ear canal is not possible in terrain conditions due to technical or safety reasons. Promising results are from works which calculate the body core temperature from physiological indicators easily measurable in non-rest conditions [14–16,23]. However, these methods require scanning the monitored parameters directly from the surface of the monitored person, which might be related with higher or lower level of discomfort and primarily may be the cause of faults and failures of the early warning system.

Our experiments had a very good correlation between t_{suit} and t_{ac} ($R = 0.9007$). The air temperature measured under the suit (t_{suit}) correlated both with $t_{sk,chest}$ ($R = 0.8928$) and HR ($R = 0.8613$) very well. On the contrary, RH_{suit} correlated with the measured physiological indicators t_{ac} and HR very weakly. It may be explained that at the beginning of exercises RH_{suit} achieved the maximum around 90% in 10–15 min and did not increase in the following minutes.

A good correlation between the temperature measured under the suit and the body temperature was a promising solution of this problem. Our results were achieved on a small set of persons, which does not allow deeper statistical processing and evaluation of the tightness of the found relationships. The usability of the air temperature measured under the suit as the indicator of organism load during work in protective suits will require a sufficiently large set of persons in a wide range of labour and thermal load in the laboratory and terrain conditions.

CONCLUSIONS

Based on our experiments, the air temperature measured under the suit proved to be a very good indicator of the overall load of fire fighters or rescuers. The

technical solution of sensing the temperature under the suit using the verified SAM technology does not affect or limit fire fighters in their work and minimizes the possibility of damage to the sensor and signaling failures.

The SAM unit was subsequently also tested in field conditions. First of all, its behavior was tested in the full working temperature range and then a test at Mannequin Men (PyroMan) was performed while some fire fighter suit was attempted to achieve the certification. Another very important testing was made at the Fire Fighters Training Centre equipped with the Flashover Container Trainer. The results from the tests including detailed technical information about the SAM device can be found in Novák et al.'s article [24].

Since the found correlations between the temperature measured under the suit and indicators of work-thermal load were obtained on a small set of 2 experimental persons, the proposed limits cannot be considered as sufficiently proven and it will be necessary to verify them in a larger group of persons under the model conditions or preferably in actual interventions.

Advantages of the proposed solution compared to other similar devices (a list of comparable devices is available in [25]) are the compact design of the whole unit and its ability to evaluate thermal exposure without necessity of an uncomfortable sensor measuring temperature inside the human body (typically in the anus or in the ear).

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