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DOES PHS (PREDICTED HEAT STRAIN) MODEL PREDICT ACCEPTABLE SKIN AND CORE TEMPERATURES WHILE WEARING PROTECTIVE CLOTHING?

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INTRODUCTION

Predicted Heat strain (PHS) model was developed as a part of the EU BIOMED II program and later adopted by ISO 7933[1]. It was aimed at predicting human physiological responses to the environments for occupational groups [2]. This model was validated from data coming from 672 experiments in 8 European thermal physiology laboratories and 237 experiments in the field. The thermal insulation values of clothing ensembles used in the laboratory studies were 0.38±0.34 clo, and 0.77±0.18 clo for field studies. The validation range for clothing ensembles was 0.1 to 1.0 clo [3,4]. Therefore, one of the most obvious drawbacks of the current PHS model is it covers a very limited range of clothing thermal insulation values. The PHS model didn't consider high insulating protective clothing and the moisture condensation effect inside of clothing ensembles either. Therefore, the current PHS model may fail predicting human physiological heat strain at some specific scenarios, such as firefighters wearing high insulating protective clothing ensembles.

The main aim of this study was to examine the prediction accuracy of current PHS model specified in ISO 7933. The observed and predicted skin temperature and core body temperature (i.e., rectal temperature) while wearing three different protective clothing ensembles were plotted and statistically compared. Finally, reasons behind the weak prediction accuracy of the PHS model were discussed.

METHODS

Subjects

Six healthy male subjects voluntarily participated in the study. The subjects had the following characteristics: age=29±3 yr; weight=80±8 kg; height=178±5 cm; body surface area=1.98±0.12 m^2; body mass index=25.2±2.2 kg/m^2. Subjects were informed on the nature of experiments and signed an informed consent before the participation.

Experimental garments

Three occupational clothing ensembles were selected for the study. The characteristics of 3 clothing ensembles are described in Table 1.

Table 1 Details of clothing ensembles.

Code	Clothing ensemble components	Thermal insulation clo	Evaporative Resistance Pa m^2/W
HV	Short sleeve t-shirt, briefs, long trousers with 3M reflective materials, socks, sports shoes	1.20	25.7
MIL	Polyamide/cotton jacket, long trousers, short sleeve net t-shirt, briefs, socks, sports shoes	1.65	42.1
FIRE	RB90 firefighting clothes, underwear, t-shirt, briefs, socks, sports shoes	2.58	122.4

Note: HV: high vision clothing; MIL: military clothing; FIRE: firefighting clothing.

Test procedure

The subjects came into a controlled climatic chamber, and were asked to walk on a treadmill at a speed of 4.5 km/h. The heart rate, rectal (T_{re}) and skin (T_{sk}) temperatures were recorded continuously. The metabolic rate was measured from the 10^{th} min of the exposure for 5 minutes. The exposure termination was based on one of the following three criteria: (i) subjects felt the conditions were intolerable and were unable to continue, (ii) the rectal temperature T_{re} reached 38.5 ^{o}C or (iii) subjects walked 70 minutes on the treadmill.

Physiological measurements

The rectal temperature sensor (YSI-401, Measurement Specialties Inc., USA) was inserted by subjects at a depth of 10 cm inside the anal sphincter. Skin temperature sensors (ACC-001, Rhopoint Components Ltd, UK) were taped on the left side of the body at 4 sites, i.e., chest, upper arm, thigh and calf. The rectal and skin temperatures were recorded via a LabVIEW program (National Instruments, USA) with an interval of 15 s when the subject started walking on the treadmill. The mean skin temperature was calculated according to the Ramanathan formula [5]

$$T_{sk}=0.3\ T_{sk\_chest}+0.3\ T_{sk\_upperarm}+0.2\ T_{sk\_thigh}+0.2\ T_{sk\_calf}$$

Test Conditions

All trials were performed at 40 ^{o}C. Two levels of water vapor pressure in the climatic chamber were selected: 2 and 3 kPa, when combined with the ambient temperature, resulted in relative humidities of 47 % and 86 %, respectively. For clothing ensembles HV and FIRE, the trials were conducted at 2 kPa. The clothing ensemble MIL was performed at 3 kPa. The air velocity was maintained at 0.33±0.05 m/s for all exposures.

Statistical analysis

Data are presented as mean ± standard deviation (SD). The root mean square deviation (RMSD) was used to check the prediction accuracy on the mean skin temperature and rectal temperature. The RMSD is a frequently used measure of differences between values predicted by a model and the values actually observed from the thing being modelled or estimated [6,7]. The best prediction value is that which gives the minimal RMSD value.

RESULTS

The subjects successfully completed all 3 trials. One subject stopped the exposure at the 63rd min during FIRE due to the rectal temperature reached 38.5 °C. The predicted and mean observed skin temperature and rectal temperature curves while wearing three functional clothing ensembles HV, MIL and FIRE over the exposure time are plotted in Figure 1. In the graphs, the predictions on body core temperature (T_{re_p}) for clothing ensembles HV and MIL are pretty good. The initial rate of rise is slightly greater than observed curves due to the different initial starting points. However, the predictions on body core temperature for clothing FIRE show a rise much greater than that shown by the experimental data. The predicted end point rectal temperature at the 63rd min is 1.8 °C greater than the observed value. For the predictions on skin temperature, a much shallower rise in the first 30 minutes shown on the curves and predicted values are continuously lower than the still rising observed temperatures.

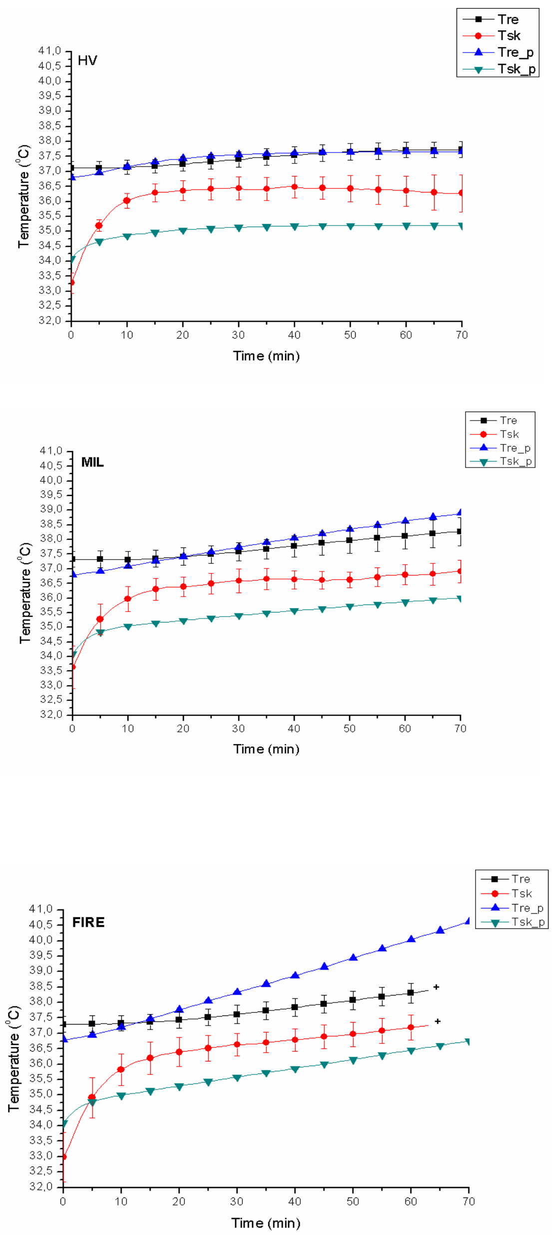

Figure 1 Predicted and observed skin and rectal temperatures plotted as a function of the exposure time for three occupational clothing ensembles: HV, MIL and FIRE. T_{re}, mean rectal

temperature; T_{sk}, mean observed skin temperature; T_{re_p}, predicted rectal temperature; T_{sk_p}, predicted skin temperature.$^{+}$One subjected stopped at the 63rd min of the exposure due to the core temperature reached 38.5 ^{o}C..

Generally, at a given environmental condition and activity intensity, greater clothing thermal insulation resulted in more body heat strain. Hence, the heat strain parameters such as heart rate, skin temperature and rectal temperature were more pronounced. Also, the metabolic rate was usually higher due to heavier clothing equipment. The mean±SD metabolic rate for HV and MIL were 165±6 W/m^2 and 167±7 W/m^2, respectively. For clothing ensemble FIRE, the weight was about 3 times greater than HV and MIL. The mean±SD metabolic rate for FIRE was 190±7 W/m^2. This finding is similar to results described by Dorman and Havenith [8].

The default mean skin temperature and rectal temperature of the PHS model are 34.1 ^{o}C and 36.8 ^{o}C, respectively. However, this is different from our study due to subjects did different activities before came to the laboratory. The weather condition on the exposure day also contributes to this difference. In order to eliminate the effect of the initial difference on the statistical result, points selected for the statistical analysis started from the 10th min of the exposure. Table 1 shows the RMSD values of the current PHS model and the standard deviation of experimental data.

Table 1 The calculated RMSD values for the PHS model and the mean SD for the experimental data.

	HV	MIL	FIRE
t_{sk}	1.21	1.01	0.92
SD	0.38	0.38	0.45
t_{re}	0.10	0.37	1.05
SD	0.26	0.36	0.28

In general, the predictions from any model are more than two times greater than the mean SD of the observed data which indicates that the model predictions fall outside of the 95 % of an average population [9]. For the skin temperature, the RMSD ranged from 2.0 to 3.2 times greater than the subject average mean standard deviation. Therefore, the predicted skin temperature values from current PHS model are not acceptable. One possible reason is that the skin temperature prediction equation in source codes of the PHS program has the poorest and lowest correlation when a clothed subject exercised at a humidity level above 2 kPa [10]. For the rectal temperature, the RMSD values for clothing ensembles HV and MIL were within one SD of the observed data. Hence, the PHS model predicts acceptable rectal temperature values for those two clothing ensembles. However, for such a high insulating clothing ensemble as FIRE, the RMSD was 3.75 times greater than the subject average mean standard deviation. As a result, the prediction on rectal temperature for high insulation clothing ensemble FIRE is not acceptable either. Therefore, further studies are needed to modify the PHS model to include such high insulation protective clothing as firefighting clothing.

CONCLUSIONS

In summary, the PHS model generates unacceptable predictions on body core temperature when human wore thick protective clothing such as firefighting clothing. This is due to the PHS model was developed and validated based on those occupational garments with a thermal insulation value below 1.0 clo. The prediction on the mean skin temperature in those three clothing ensembles was weak. That is in agreement with the empirical equation on the skin temperature in the program source code has the poorest and lowest correlation when a human subject exercised at the test conditions specified in this study. It is therefore recommended that the PHS model should be amended and validated by individual algorithms, physical or physiological parameters, and further subject studies.

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