THE VALIDITY OF ISO 7933:1989 DURATION LIMIT EXPOSURE (DLE) AND PREDICTED SWEAT RATE (SWP) FOR CLOTHED SUBJECTS

D.K. Bethea and K.C. Parsons

Human Thermal Environments Laboratory
Department of Human Sciences, Loughborough University, Leic, UK.

INTRODUCTION

ISO 7933:1989 "*Hot environments--Analytical determination and interpretation of thermal stress using calculation of required sweat rate*"(1) provides an analytical method for the assessment of heat stress in industry based on the human heat balance equation. The aim of this project was to validate ISO 7933, Alarm DLE (Duration Limited Exposure) and SW_p (predicted sweat rate) against the observed physiological responses of subjects wearing clothing in a hot, humid environment. The Alarm criteria are meant to protect all the workers from an "excessive increase in core temperature" (above 38°C).

MATERIALS AND METHODS

Six samples of 8 healthy male subjects (mean ± SD; age 26 ± 3 years, weight 74.56 ± 6.82 kg, height 1.75 ± 0.05 m) participated in 6 validity experiments (1 to 6) where responses to hot environments were compared with responses predicted according to the analysis presented in ISO 7933. Subjects wore 100% cotton boiler suits with front fastening press-studs, open sleeves and leg cuffs, a cotton T-shirt, cotton undershorts and socks, and trainers. The clo value was estimated at 0.8 clo using ISO 9920 (2). Subject weights--semi-nude and clothed, pre- and post-experimentation and at 15-min intervals--were taken during the experiment. Water intake was monitored and sweat loss was corrected accordingly. Subjects exercised continuously by stepping at a predetermined height at a rate of 15 complete (up/together/down/together) steps per minute. Metabolic rate was estimated using the American College of Sports Medicine (3) equation for $\dot{V}O_2$ while stepping (Fig. 1), and units were converted to $W \cdot m^{-2}$. At 25 minutes, Douglas Bag samples were taken.

$$\dot{V}O_2(\mathrm{ml \cdot kg^{-1} \cdot min^{-1}}) = \left[\mathrm{steps \cdot min^{-1} \times 0.35\ ml \cdot kg^{-1} \cdot step^{-1}}\right] + \left[\mathrm{m \cdot step^{-1} \times steps \cdot min^{-1} \times 1.33 \times 1.8\ ml \cdot kg^{-1} \cdot m^{-1}}\right]$$

Figure 1. ACSM equation for estimating O_2 consumption while stepping.

Dry bulb temperature, black globe temperature, wet bulb air temperature, humidity and air velocity measures were recorded at 1-min intervals. Aural temperature (insulated from the environment), 4-point mean skin temperature (chest, upper arm, thigh, calf) and an upper back site were also measured. Heart rate was recorded using a Polar Sports Tester heart rate monitor. A priori predictions of the subject's physiological responses were obtained using ISO 7933 by inputting the desired environmental measures, the clo value and the estimated metabolic rate. They were then corrected using the actual environmental measures for each experiment to obtain SW_p and DLE values.

RESULTS

No measured metabolic rate data were available for the 1st experiment. Across all experiments, there was a good correlation between the estimated metabolic rate and the observed metabolic rate ($r^2 = 0.769$), but there was also a significant difference ($P < 0.006$) between the data sets. The importance of this difference in relation to the predictions made by ISO 7933 was also investigated. Table 1, shows the data input to the SW_{req} model and the resultant interpretations.

Table 1: Input data and the resultant interpretations of ISO 7933.

Experiment	1	2	3	4	5	6
Inputs (means of each experiment):						
Air temperature (°C)	35	35	40	40	45	45
Relative humidity (%)	60	59	63	62	40	41
Radiant temperature (°C)	35	35	39	39	45	44
Air velocity ($m \cdot s^{-1}$)	0.22	0.28	0.07	0.08	0.08	0.09
Metabolic Rate (Estimated Mean) ($W \cdot m^{2}$)	193	177	173	153	152	87
Metabolic Rate (Measured Mean) ($W \cdot m^{2}$)		158	161	142	135	97
Mean Radiant Temperature (°C)	35	34	39	39	45	44
Partial Vapor Pressure (kPa)	3.382	3.325	4.535	4.510	3.822	3.865
Body area fraction exposed	0.77	0.77	0.77	0.77	0.77	0.77
Clothing insulation (clo)	0.8	0.8	0.8	0.8	0.8	0.8
Interpretations - Estimated Met Rate as Input						
SW_p ($g \cdot h^{-1}$)	374.1	377.2	228	225.7	355.2	302.6
DLE-Alarm-Unacclimatized (min)	33	40	23	27	29	63
Interpretations - Measured Met Rate as Input						
SW_p ($g \cdot h^{-1}$)		370.1	224.0	222.1	348.6	308.8
DLE-Alarm-Unacclimatized (min)		50	25	29	32	55
Mean Observed Sweat Rate ($g \cdot h^{-1}$)	832.4	803.6	1108	900.1	781.4	690.2
Mean Observed time to reach 38°C	*	**	40	43	42	51

** Only 2 subjects reached a core temperature of 38 °C: 67 min and 47 min*
*** Only 1 subject reached a core temperature of 38 °C: 73 min*

Predicted Sweat Rate (SW_p) vs. Observed Sweat Rate (SW_o)

Fig. 2 shows the comparison of the SW_p, when both the estimated and measured metabolic rates are inputs, with the mean SW_o (corrected to 60 min). The error bars show the observed maximum and minimum values from each ex-periment. The dotted horizontal line represents the maximum sweat rate (SW_{max})

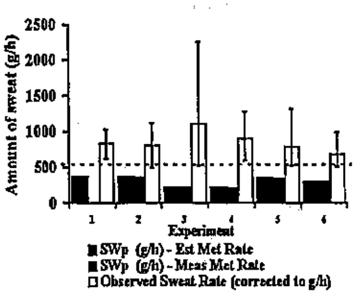

Figure 2. Comparison of SWp and the SWo (corrected to g/h).

of 520 g·h-1 for Alarm criteria as described in the standard. Fig. 3 shows the linear relationship and correlation between the SW_o and SW_p.

Duration Limited Exposure (DLE) vs. Observed Time for Core to Reach 38°C

Fig. 4 shows the comparison of the Alarm DLE when both the estimated and measured metabolic rates are inputs with the observed time to reach a core temperature of 38°C. The experiment lasted a maximum of 75 min, with the >75 min scale on the Y Axis indicating that 38°C was not

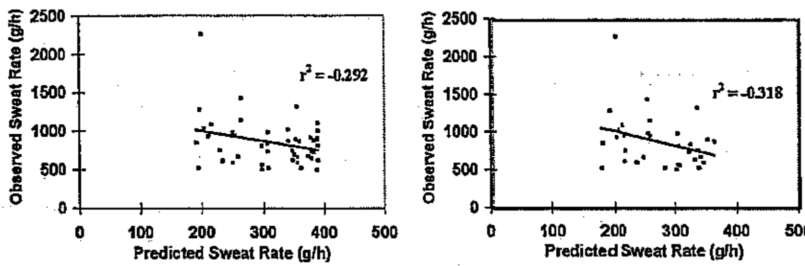

Figure 3. Sc graphs showing the correlation be-tween SWo and SWp for estimated metabolic rate (left) and measured metabolic rate (right)

achieved within the experimental time limit. The error bars again show the minimum and maximum observed times for each experiment. From Table 1, only 2 subjects in Experiment 1 and 1 subject in Experiment 2 reached a core temperature of 38°C. In all but Experiment 6, the DLEs were significantly underestimated. Fig. 5 shows that neither DLE correlated strongly with the observed time.

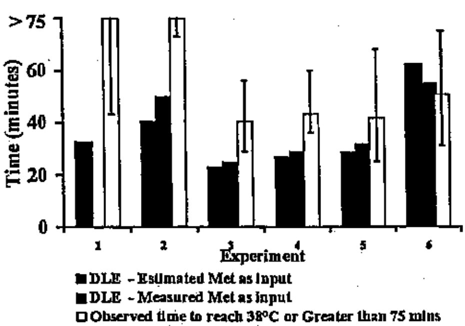

Figure 4. Comparison of Alarm DLE and observed time to reach 38°C

DISCUSSION

Although there was a significant difference between the SWp from estimated and measured metabolic rate inputs, when compared with observed sweat rate values, these differences were small (Fig. 2). However, the differences between the

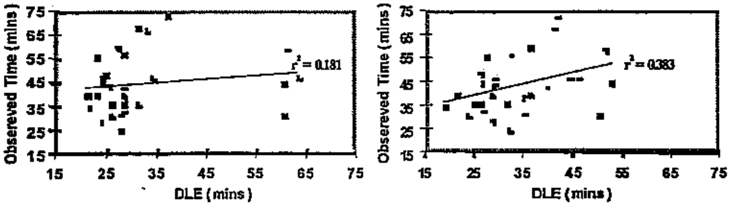

Figure 5. Scatter graphs of Alarm DLE for estimated meta-bolic rate (left) and measured metabolic rate (right) and ob-served time to reach 38°C

metabolic rate inputs had a significant impact on the predicted DLEs (Fig. 4). This is contrary to expectation, since the interdependence of the sweating and heat storage would suggest that the model should show representative changes in both predictions. It would seem therefore that the SW_p values are being constrained, not by the work rate, but by the SW_{max} values (Fig. 2). The SW_{max} value is 520g·h^{-1} and appears to be more representative of the minimum SW_o than the maximum SW_o across all experiments.

The change in direction of the prediction of DLEs, for Experiments 1 to 5 with that of Experiment 6 (Table 1 and Fig. 4), seems to suggest that the model is over sensitive to changes in metabolic rate at the lower end of the scale when predicting DLE for subjects in an environmentally driven zone.

Fig. 3 shows that there is a weak correlation between both SW_p and SW_o and that the relationship is negative, which is incorrect. Fig. 5 showed a poor correlation between the DLEs for both metabolic rate inputs.

The minimum values for observed time to reach a core temperature of 38°C are closest to the DLEs in Experiments 3 and 6, while in Experiments 1 and 2 the minimum values are much greater than the DLE values. In Experiments 5 and 6, however, the minimum values are actually below the DLE times. Therefore, although in the first 4 experiments the subjects are all protected by the Alarm DLE predictions, the removal of subjects in conditions such as those found in Experiments 1 and 2 would be premature and if applied in industry may lead to a reduction in productivity. However if the DLEs were applied for Experiments 5 and 6, the subject's health would be at risk. Not only were the minimum observed times below the DLE limit but so was the mean observed time.

CONCLUSIONS

The SW_{max} values are not valid when applied to clothed subjects since the SW_o significantly exceeds the SW_{max} values. Since SW_p is obtained from SW_{max}, the SW_p is not a valid predictor of the SW_o. ISO 7933 SW_{req} model is not a valid predictor of DLEs and SW_P for people wearing protective clothing in warm humid environments.

REFERENCES

1. ISO 7933, 1989, Hot environments--Analytical determination and interpretation of thermal stress using calculation of required sweat rate, International Standards Organisation ISO/TC 159:1989 (E).
2. ISO 9920, 1995, Ergonomics of the thermal environment--Estimation of the thermal insulation and evaporative resistance of a clothing ensemble, Inter-national Standards Organisation ISO 9920:1995(E).
3. American College of Sports Medicine, 1991, Guidelines for Exercise Testing and Prescription, 4th Edition, Lea & Febiger, 291-297.

ACKNOWLEDGEMENTS

This project is supported by the Health and Safety Executive (HSE), Bootle, Liverpool, UK.