Comparison and validation of heat stress indices in experimental studies

Philippe MAIRIAUX and Jacques MALCHAIRE
Université Catholique de Louvain
Unité Hygiène et Physiologie du Travail
Clos Chapelle-aux-Champs 3038
B - 1200 Bruxelles

Abstract

The present study aimed at 1) deriving the best methodology for using heat stress indices in fluctuating ambient conditions, 2) assessing various ways for improving the prediction ability of the Required Sweat Rate index (SW_{req}).

The data base included the results from five experimental series involving 32 volunteers; these series involved environmental variations at constant metabolic rate, work-rest cycles in constant ambient conditions and alternate periods of work in heat and rest in neutral conditions.

Observed and predicted variations in sweat rate were compared.

During exposures to rapid changes in climatic conditions, the best prediction of the body sweat loss was provided by a model involving the simulation of the response of skin temperature and sweat rate to a step change in ambient conditions. The model used exponential weighting algorithms with time constants of 3 and 10 minutes respectively for these two variables.

The study showed also that the prediction accuracy of SW_{req} index can be significantly improved by adopting a new expression for the calculation of the evaporative efficiency of sweating, by predicting the mean T_{sk} value as a function of the parameters of the work situation and by applying to the predicted values of sweat rate the exponential weighting. Among the various heat stress indices tested in the study, the Required Sweat Rate Index was the one giving the best approximation of the body sweat loss.

Key words: heat stress, sweat loss, skin temperature, thermal indices

Résumé

Les objectifs de la présente étude étaient (1) de déterminer la méthodologie idéale pour l'application des indices thermiques aux conditions ambiantes fluctuantes et (2) d'évaluer plusieurs voies d'amélioration de la valeur prédictive de l'indice de sudation requise (SW_{req}).

La base de données a inclu les résultats de 5 séries expérimentales concernant 32 volontaires. Ces séries comprenaient des variations climatiques à métabolisme constant, des cycles travail-repos dans des ambiances stables et des périodes alternées de travail à la chaleur et de repos dans des conditions neutres.

Les variations de débit sudoral observées et prédites ont été comparées. Durant les expositions aux variations rapides de conditions climatiques, la meilleure prédiction de la perte sudorale a été procurée par un modèle comprenant la simulation de la réponse de la température cutanée et du débit sudoral à une variation échelon des conditions ambiantes. Le modèle utilise des algorithmes de pondération exponentielle avec des constantes de temps de 3 et 10 minutes respectivement pour ces deux variables.

L'étude a montré également que la précision de la prédiction par l'indice SW_{req} peut être améliorée de manière significative en adoptant une nouvelle expression pour le calcul de l'efficacité évaporatoire de la sudation, en prédisant la température moyenne de la peau en fonction des paramètres de la situation de travail et en appliquant aux valeurs prédites de débit sudoral cette pondération exponentielle.

Parmi les différents indices thermiques comparés par l'étude, l'indice SW_{req} a été celui donnant la meilleure approximation de la perte de poids corporelle par sudation.

Mots-clés: travail à la chaleur, perte sudorale, température cutanée, indices thermiques

1. Introduction

Most heat stress indices have been developed from experimental data obtained in constant environmental conditions, allowing the various physiological responses of human subjects to reach a near steady-state level. Actual working conditions in the coal and steel industries involve however intermittent variations in working activity and in climatic parameters. Procedures have been proposed in order to apply the indices to these fluctuating conditions, namely the use of a time-weighted average of the metabolic and climatic parameters - this is the recommended procedure for the WBGT index - or the averaging of derived parameters like the required (E_{req}) and the maximum (E_{max}) evaporative rates for the Required Sweat Rate Index (ISO DIS 7933). The validity of such procedures is far from being established, especially when considering the evaluation of short-term exposures in severe ambient conditions. As suggested by Malchaire (1986), an optimal heat stress index should provide an accurate prediction of the worker's physiological state at any time of the exposure, thus allowing the occupational physician or the industrial hygienist to assess the permissible duration of exposure and the duration of rest breaks. This objective implies that the index value at a given time takes proper account of the characteristics of past exposure and the response-time constant of the physiological variable considered. This feature of the index variation can only be studied in well-controlled conditions where both the input parameters (metabolic rate, climatic parameters) and the output variables (sweat rate, body temperatures, heart rate) are measured with accuracy.

The present review aims at presenting a critical assessment of (1), the methodology suggested in order to adapt the heat stress indices to fluctuating ambient conditions (Malchaire 1986), (2) the various proposals made by several research terms (Candas and Hoeft 1987; Hettinger et al. 1986; Malchaire 1986) for improving the prediction ability of the procedure specified in the ISO DIS 7933 "Hot environments - analytical determination and interpretation of thermal stress using calculation of required sweat rates".

Most researchers in this programme chose the body weight loss as the reference strain variable to assess the predictive ability of the indices, and this is also the choice made for this review. In order to allow a reliable comparison to be made between the various prediction procedures, a distinct data base was constituted using the recordings of several experimental series.

2. Material and methods

2.1. Experimental data base

The data collected originated from three types of heat exposure:

a. Environmental variations at constant metabolic rate

series 1: five subjects, average metabolic rate (M), 143 W/m², air temperature (T_a) ranging from 21°C to 47°C, mean radiant temperature (T_r) ranging from 18°C to 54°C, ambient water vapour pressure (P_a), 0.9 kPa, air velocity (V_a), 0.6 m/s, duration of exposure, 155 min (Vogt et al. 1983).

b. Work-rest cycles in a constant ambient condition

series 2: seven subjects exercised at 50% of VO_2max (average M: 270 W/m²), at either T_a = T_r = 28°C and P_a = 1.8 kPa, or T_a = T_r = 38°C and P_a = 3.7 kPa. V_a being constant at 0.1 m/s; duration of exposure 170 min. The work-rest cycle involved 15 min work followed by 15 min rest (Mairiaux et al. 1977).

series 3: eight subjects exercised for 30 min at M=166 W/m², 20 min at M=213 W/m² and 15 min at 261 W/m² with rest breaks between the exercise periods and a final rest break of 60 min. Ambient conditions were either T_a =T_r = 35°C and P_a = 1.9 kPa or T_a = T_r = 40°C and P_a = 4.5 to 5.0 kPa. Four climates were studied during the final recovery: T_a being 40°C, 35°C, 27°C or 24°C. Air velocity was constant at either 0.2 m/s or 0.9 m/s. Total duration of exposure was 165 min.

c. Alternate periods of work in heat and rest in neutral conditions

series 4: seven subjects exercised at three levels of metabolic rate (166, 199 and 243 W/m²) for periods lasting 20 to 28 min, or 30 to 42 min, in a hot, humid climate (T_a = T_r = 42°C; P_a = 3 kPa) with V_a = 0.64 m/s. Rest periods lasted 15 min and took place in dry and neutral ambient conditions (T_a = T_r = 28 $\pm$ 1°C; P_a = 0.9 kPa). The total exposure duration was either 200 min or 230 min (Mairiaux et al. 1987).

series 5: five subjects performed light work (M = 99 W/m²) in warm conditions (T_a = 42-43°C) while exposed to a high radiant heat load (T_r = 78-82°C); they rested in near neutral conditions (T_a = T_r = 20-23°C). Air velocity was 0.6 m/s at the workplace and 0.1 m/s in the rest-room; ambient humidity was kept at a low level (P_a = 1.0 kPa). Each session involved 4 work periods of 30 min duration separated by 10 min rest periods (Vogt 1986).

In series 1, 3, 4, 5, the subjects were young male students (under 30 yrs) unacclimatized to heat; the subjects of series 2 were coal miners partially acclimatized to heat and their age ranged from 28 to 49 yrs. The subjects were naked (Clo = 0.1) in series 2 and 3, and naked or clothed in series 1 (Clo = 0.6) and series 4 (Clo = 0.5); they were clothed (Clo = 0.7) in series 5.

2.2. Data processing

The experimental exposures involving continuous (series 1) or discrete (series 4 and 5) measurements of body weight loss have been divided into several subperiods, each subperiod being delimited so as to include one work (or heat stress) period and one rest period. the duration of these subperiods (n = 162) ranged from 30 min to 85 min. In series 2 and 3, the body weight loss was only measured at the end of the experimental session and therefore the whole period of exposure (165 or 170 min) was considered for the analysis.

The predicted body sweat loss (SW_p) was calculated for each subperiod of exposure, using the equations given in ISO DIS 7933. As compared to this DIS document, the following modifications were introduced:

- as suggested by Candas and Hoeft (1987), the equation for body heat balance included the respiratory heat exchanges by convection (C_{res}) and evaporation (E_{res}) as follows:

  C_{res} (W/m²) = 0.0014 * M * (35 - T_a)

  E_{res} (W/m²) = 0.0173 * L * (5.619 - P_a)

- the coefficients of reduction of the sensible (F_{cl}) and insensible (F_{pc1}) heat exchanges due to clothing were calculated in accordance with the equations used by the ASHRAE (1985). This should reduce the discrepancy observed for clothed subjects between the predictions derived from the ISO DIS and from other models of human thermoregulation (Haslam and Parsons 1987). The revised equations are as follows:

  $F_{cl} = 1/[1 + (h_c + h_r) I_{cle}]$

  $F_{pc1} = 1/[1 + 2.22 h_c I_{cle}]$

  where F_{cl} is the intrinsic thermal efficiency of clothing (nd)

  h_c is the convective heat transfer coefficient (W/m² °C)

  h_r is the radiant heat transfer coefficient (W/m² °C)

  F_{pcl} is the permeation efficiency of clothing (nd)

  I_{cle} is the effective thermal insulation of clothing (m² C°/W) given by:

  $I_{cle} = I_{cl} - [(1 - 1/f_{cl})/h_c + h_r)]$

  where I_{cl} is the intrinsic thermal insulation (m²/W)

  f_{cl} is the surface ratio between the naked subject area and the clothed subject are calculated as follows:

  $f_{cl} = 1 + 1.97 I_{cl}$.

For each session or subperiod of the experimental exposures, both the sweat rates predicted for each minute of exposure and the cumulated body sweat loss measured at the end of the period were averaged over the period duration and expressed as the average predicted (SW_p, g/min) and observed (SW_{obs}, g/min) sweat rates for this period.

3. Results

3.1. Adaptation of heat stress indices to fluctuating ambient conditions

Malchaire (1986) studied the relationship between the various indices, computed for each minute of exposure, and the simultaneous variations in body sweat rate observed during alternate changes in ambient temperature. This analysis was conducted on the averaged data of a set of experiments carried out at the CNRS "Centre d'Etudes Bioclimatiques" (now LPPE) in Strasbourg (Mairiaux et al. 1984, 1986; Vogt et al. 1983). Results (Table 1) showed that the predictive ability of the indices was low, the coefficients of correlation being less than 0.8 for all indices. The best results were observed with the indices designed to predict body sweat loss: Required Sweat Rate (SW_{req}), P4SR and ITS, and the PMV which is based on the heat balance equation. As stated by Malchaire (1986), the poor correlations observed could be ascribed to two main factors and these are illustrated in Figure 1. First, sweat rate is known to be initiated with a time delay and to respond with a time constant to a step change in the environmental or metabolic heat load (Timbal et al. 1970; Chappuis et al. 1976). Second, the use of a set level of mean skin temperature (T_{sk}) in some of the indices (HSI, ITS, SW_{req}) is bound to induce large errors in the heat exchange calculations; this source of prediction errors was also emphasized by Hettinger et al. (1986).

In order to obtain an accurate prediction of body sweat loss variations in response to changes in environmental heat load, three requirements had thus to be met: estimation of the actual T_{sk} level in a given condition, determination of the T_{sk} response-time constant in order to simulate its variations, and determination of the time constant of the sweating response.

3.1.1. Estimation of mean skin temperature

An equation for predicting T_{sk} was derived by stepwise multiple linear regression from the climatic parameters, clothing insulation value and metabolic rate using experimental data collected by the authors and other data from the literature (Mairiaux et al. 1987). This equation takes into account as input parameters T_a (°C), P_a (kPa), V_a (m/s), M (W/m²) and the thermal insulation of clothing (I_{cl}, Clo). It may be applied to predict T_{sk} in naked to lightly clad (Clo ≤ 0.6) subjects, unacclimatized to heat and exposed to ambient temperatures ranging from 27°C to 50°C with minimal radiant heat load.

In an attempt to consider the effect of radiant heat, a separate regression analysis was conducted on a subsample of data for which the temperature differences between T_r and T_a was larger than 2°C. This analysis showed that the regression coefficient determined for T_a (0.138) on the whole set of data could be divided in two coefficients, 0.093 for T_a, and 0.045 for T_r (Malchaire 1986). The limits of validity of this estimation of T_{sk} will be discussed hereunder.

3.1.2. Time constant of T_{sk} response to climatic changes

Previous observations in the literature showed that the pattern of T_{sk} variations in response to a step change in ambient temperature could be adequately explained by an exponential function. Malchaire (1986) therefore suggested describing the T_{sk} response at a given time (i) using a recurrent equation as follows:

$$T_{sk}(i) = T_{sk}(i-1) + (IT_{sk}(i) - T_{sk}(i-1))\ (1 - \exp(-1/k))$$

where $IT_{sk}(i)$ is the T_{sk} value computed from the basic parameters at time i using the equation of prediction. The value of the time constant (k) in this expression was determined by linear regression analysis between observed and predicted T_{sk} levels, using k values ranging from 1 to 4 min. The best correlation coefficient (r = 0.84) was observed for k = 3 min. Figure 2 gives an illustration of the agreement between predicted and observed values during exposure to T_a changes between 23° and 50°C. Overall, the correlation coefficient was higher than 0.9 in all the conditions involving ambient temperature variations; it was slightly lower (r = 0.88) during P_a variations at constant T_a, and during metabolic rate variations at constant ambient temperature (r = 0.80).

3.1.3. Time constant of sweat rate response

Adopting a similar approach, Malchaire described the transient response of the predicted sweat rate (SW_p) by means of the following equation:

$$SW_p(i) = SW_p(i-1) + (ISW(i) - SW_p(i-1))\ (1 - \exp(-1/k))$$

where ISW(i) is the required sweat rate calculated from E_{req} and E_{max} at time i. While the ISW(i) value did not take into account the maximum wettedness or the maximum sweat rate specified in the ISO DIS, the predicted value ($SW_p(i)$) was limited at a maximum level of 250 W/m² according to the ISO "danger" limit for unacclimatized subjects.

In order to simulate the time-lag observed before the initiation of sweating in subjects previously at, or below, thermoneutrality, the k value at the start of exposure was set at 25 min as long as the predicted sweat rate ($SW_p(i)$) remained lower than 33 W/m² (1.5 g/min); this threshold value constituted the upper confidence limit (at the 5% probability level) of the mean weight loss by respiratory water loss and insensible perspiration, observed before the onset of sweating in 74 weight loss recordings (Mairiaux and Libert 1987). When this threshold was reached, a prediction algorithm based on the combination of a short (k1 = 7 min) and a long (k2 = 20 min) time constant was used. The short k value best approximated the rapid sweating response to a step change in ambient temperature, while the long k value corresponded to the progressive adjustment towards steady-state level (Malchaire 1986). The results obtained using this exponential weighting and the prediction of T_{sk} appear quite satisfactory when comparing the observed sweat rate variations and the predicted ones (Figure 3).

The exponential weighting algorithm was applied to each of the heat stress indices and the sweat rate observed at each minute of exposure was related to the simultaneous value of each index. The Required Sweat Rate index was calculated using either the ISO DIS equations (SW_{norm}) or the prediction model exposed hereunder (SW_{mod}) which, besides the exponential weighting, also included the estimation of mean skin temperature and the simulation of the sweating delay. Table 2 shows that the actual variations in sweat rate could be simulated by five indices with a correlation coefficient larger than 0.90. The prediction model (SW_{mod}) gave a better correlation coefficient and a slope closer to unity than the prediction based on the ISO DIS (SW_{norm}). The prediction fit provided by the Index of Thermal Stress (ITS) was very close to those observed for SW_{norm} and SW_{mod}. When Table 2 is compared with the prediction results obtained with the same indices but without any time-weighting (Table 1), there is little doubt that the exponential weighting of the predicted values greatly improved the accuracy of the prediction. Further analysis of the same data base showed that, for the sake of simplification, a weighting algorithm based on a single time constant (k = 10 min) could be used with not significant loss of prediction accuracy.

The main advantages to be expected from an accurate prediction of the transient variations in sweat rate are twofold: it should provide, firstly, a way of assessing the rise in body core temperature during exposure to heat stress and, secondly, a better prediction of the cumulative body weight loss. This last aspect is considered in section 3.2.2. of this review.

3.1.4. Prediction of core temperature variations

The rate of body heat storage being a function of the difference (E_{req} - E_p) between the evaporative rate required for thermal equilibrium and the evaporative rate predicted by the model, Malchaire (1986) suggested deriving the core temperature variation from the heat storage by assuming that a fraction of this storage is used to bring 10% of the body mass to the predicted mean skin temperature level. In addition, some account was taken of the variations in skin conductance by assuming it to be zero when T_{sk} is 30°C, and to be maximal when T_{sk} is 37°C. The rate of heat storage determining the variation in core temperature would be a fraction (f) of the total heat storage, the f value ranging from 0 at $T_{sk} \leq 30°C$ to 1 at $T_{sk} \geq 37°C$ as follows:

$$f = (T_{sk} - 30)/(37 - 30).$$

The predicted oesophageal temperature (T_{es}) based on these assumptions is compared in figure 4 to the values observed in an experimental situation involving cyclical temperature variations between 23°C and 50°C. The excellent fit of the prediction was obtained by assuming a T_{es} of 36.5°C at the start of the experimental session. The first rise in predicted T_{es} in response to the start of exercise and the rise in ambient temperature to 50°C was evidently larger than the observed T_{es} rise. This discrepancy could be ascribed to the increase in muscle temperature above the T_{es} level, this being not taken into account in the prediction model. The accuracy of the core temperature prediction thus looks promising, provided a muscle temperature component is included in the prediction. This would obviously require further study.

3.1.5. Conclusions

The analysis of experimental data carried out by Malchaire (1986) demonstrated that the Required Sweat Rate Index offers at present the best prediction of the actual body sweat loss. A coherent set of proposals has been put forward to allow the prediction of not only steady-state levels but also transient phases of sweating in response to changes in the heat stress parameters.

3.2. Improvement of body weight loss predictions

3.2.1. Proposals

Three main modifications have been suggested by some research teams participating in the ECSC programme in order to improve, in steady-state conditions, the predictive ability of the ISO draft standard.

- **Convective heat transfer coefficient calculations**

In its form at the time of the study, the ISO DIS calculated this coefficient (h_c) from the relative air velocity instead of its absolute value. The relative V_a can be related to the metabolic rate, according to an equation proposed by Fanger (1970) in order to take into account the effect of the body movements. Candas and Hoeft (1987) stated that this equation led to overestimation of the actual convective heat transfer coefficient and in consequence the calculated maximum evaporative rate (E_{max}). These authors suggested using the absolute and not the relative V_a in order to derive h_c. The validity of this proposal seems to depend on the type of "work" considered. In most experimental conditions, the work corresponded to exercise on a cycloergometer. In such conditions, the relationship between body movements and air velocity is restricted to the pedalling legs and the use of Fanger's equation effectively results in h_c values greater than those determined experimentally in similar conditions (Nishi and Gagge 1970). In industry, the work activities are quite different, however, and there seem to be no conclusive data to reject the relationship between metabolic rate and air velocity. In any event, this factor will remain a potential source of error in the heat balance calculations, as two activities requiring the same metabolic rate may be associated with different levels of relative air velocity (Adams 1977).

- **Estimation of mean skin temperature**

Heat balance calculations in the ISO DIS were carried out using a fixed T_{sk} level (= 36°C). this value having been found unsatisfactory by Malchaire (1986) as well as by Hettinger et al. (1986), these authors have each developed a prediction equation. The equation from Mairiaux et al. (1987) is as follows:

$$T_{sk} = 30 + 0.138\ T_a + 0.254\ P_a - 0.57\ V_a + 0.00128\ M - 0.553\ I_{cl}$$

Hettinger et al. have derived the following equation from the experimental data of Ilmarinen (1978)

$$T_{sk} = 30.67 + 0.10\ T_a + 0.46\ P_a - 0.0099\ M + 0.48\ I_{cl}$$

The main difference between these two equations relates to the sign of the regression coefficients found for the metabolic rate and the clothing insulation value. In the Hettinger et al. equation, T_{sk} decreases with any increase in metabolic rate, whereas in Mairiaux et al.'s equation T_{sk} increases with M. This discrepancy may well be related to the influence of air velocity; as this is not considered in Hettinger's equation, the regression coefficient for M may include the negative effect of V_a on T_{sk}. As regards the effect of clothing, the respective coefficients, +0.48 and -0.553, are obviously at variance. This difference could be related to differences in exposure conditions between the two sets of data. In Ilmarinen's set of data, the coefficient was derived from heavily clothed subjects (Clo = 0.7 or 1.0) exposed to a steady ambient condition for 4 hours. In the Mairiaux et al; (1987) set of data, the coefficient was derived from lightly clad subjects (Clo = 0.5 or 0.6) working in hot, humid conditions but resting in neutral, dry conditions. In such conditions, the wetted pieces of clothing had a significant cooling effect on T_{sk} when the clothing was allowed to dry in the rest-room. It is likely that in other conditions the insulation provided by the clothing may result in an increase in T_{sk}. These observations thus emphasize the complexity of the influence of clothing on the body heat exchanges (Candas and Hoeft 1987) and one can hardly expect to find a single coefficient valid for all types of environmental heat stress.

The overall validity of the two prediction equations could be assessed by comparing predicted values to values measured in experimental or field studies, in semi-naked subjects, unacclimatized to heat. Figure 2 shows clearly that the actual T_{sk} was significantly underestimated using the Hettinger et al. formula. In clothed subjects exposed to humid conditions, Candas (1987) observed that both the Hettinger and Mairiaux formulæ underestimated the observed T_{sk}, but to a different extent: on average by 2.4°C and 1°C respectively. Figure 5 illustrates the difference in the T_{sk} levels predicted by the two formulæ, for clothed subjects working at 135 W/m² in ambient temperatures ranging from 20°C to 50°C, either in a dry (upper graph) or in a humid (lower graph) climate. The difference in prediction is quite significant in warm conditions (T_a > 30°C), especially at low ambient humidity. This difference is of such a magnitude that the only rational explanation refers to the state of heat acclimatization of the experimental subjects. In the data of Mairiaux et al. (1987), all subjects were unacclimatized to heat, whereas the four subjects of the Ilmarinen's (1978) study were heat-acclimatized. The use of Hettinger's equation should thus be restricted to well-acclimatized subjects. The specific contribution of these estimates of T_{sk} to body sweat loss predictions is examined in Section 3.2.2..

- Evaporative efficiency of sweating and skin wettedness

In the ISO DIS, the relationship relating the evaporative efficiency of sweating (η) to skin wettedness (w) is an exponential function based on experimental data collected in naked and reclining subjects. Using the results of an experimental study from Eissing (1986), Hettinger et al. (1986) proposed a simpler formula ($\eta = 1 - 0.5\ w^2$) valid for clothed working subjects. At maximum skin wettedness (w = 1), the two formulæ result in a similar efficiency level (η = 0.5). At lower skin wettedness, for instance 0.6, the efficiency level derived from the Hettinger formula (0.82) is lower than the ISO level (0.96) and somewhat similar to the figures initially proposed by Givoni (1963) for clothed working subjects. The reduction in evaporative efficiency predicted by this equation seems to be more in line with some experimental results (Alber-Wallerstrom 1985) than that predicted from the ISO relationship. For the reason, Candas and Hoeft (1987) suggested substituting the Hettinger formula for the ISO formula. The effect of this modification on the prediction of sweat rate is examined in the next section.

3.2.2. Validation study

The influence of an exponential weighting of the SW_p values and the contribution of the above proposals to the sweat loss prediction was assessed using the data base previously described. This validation study considered the following prediction procedures:

- . SW_{req} : required sweat rate derived from ISO DIS equations, without taking into account the limits for sweat rate (S_{max}) or skin wettedness (w_{max})
- . SW_p1 : predicted sweat rate derived from ISO DIS equations, S_{max} being set at 250 W/m²; w_{max} = 1.
- . SW_p2 : predicted sweat rate derived from ISO DIS equations; S_{max} = 250 W/m²; w_{max} = 0.85 (danger limits for unacclimatized subjects).
- . SW_p3 : predicted sweat rate derived from ISO DIS equations, the SW_{req} values being exponentially weighted using the Malchaire (1986) algorithm and a single time constant (k = 10 min); SW_p values limited to S_{max} = 250 W/m².
- . SW_p4 : similar procedure as SW_p3, but using the Mairiaux et al. equation for the prediction of T_{sk}.
- . SW_p5 : similar procedure as SW_p4, but using the Hettinger et al. (1986) formula for the calculation of the evaporative efficiency of sweating.
- . SW_p6 : similar procedure as SW_p3, but using Hettinger's equations for the prediction of T_{sk} and the calculation of sweating efficiency.
- . ITS : predicted sweat rate using the Index of Thermal Stress whose predicted SW_{req} values were exponentially weighted with a 10 min time constant.

For each session or subperiod of the experimental exposures, the average sweat rate (SW_{obs} - g/min) observed during the subperiod was related to the predicted value (SW_p - g/min) by linear regression analysis. Table 3 presents the relationships obtained between the average sweat rates observed in 212 periods or subperiods of exposure and the predicted values using the eight prediction procedures. Before discussing these results, it must be pointed out that good agreement between observed and predicted sweat losses does not necessarily mean that the prediction method permits an appropriate simulation of sweat rate during transient phases. As the periods considered for analysis generally included two heat stress variations in opposite directions (see Figure 1), an overestimation of sweating during the heating periods could be cancelled out by an underestimation of sweating during the cooling periods. The accuracy of the prediction of the transient variations of sweating cannot thus be verified using the cumulative body sweat loss figures examined in this validation study.

The accuracy of body sweat loss predictions for short-term exposure periods can, however, be appreciated from the data presented in Table 3. The best correlation coefficient between observed and predicted values was 0.78, whereas Malchaire (1986) reported a higher correlation coefficient (r = 0.87), using a similar analysis of subperiods of exposure. This difference in prediction results can be explained by the differences in exposure conditions between the respective data bases.

While the experimental conditions analyzed by Malchaire could be termed as moderate (average M = 165 W/m^2 in alternate hot-dry and neutral-dry climate), in the present validation study, several conditions (see Methods) imposed a severe heat stress on the subjects. When comparing the various prediction procedures in Table 3, it can be seen that the ISO DIS in its modified version (SW_p2) gave the worst prediction of the six procedures considered for the Required Sweat Rate Index. A better prediction, in terms of correlation coefficient and slope of the regression line, was obtained with the first procedure (SW_p1), the ISO DIS being used without taking into account the limitation in maximum sweat rate and with the maximum skin wettedness being set at 1.

In contrast to the SW_p1 and SW_p2 procedures, which consisted of unweighted predictions of sweat rate, the four procedures (SW_p3, 4, 5 and 6) involving the exponential weighting of the SW_{req} values produced better predictions. Comparison of SW_p3 (T_{sk} = 36°C) and SW_p4 (T_{sk} predicted) indicates that the prediction of T_{sk} by Mairiaux et al. (1987) equation brought the slope of the relationship closer to unity and reduced its intercept. A separate regression analysis conducted on the various experimental series of the data base showed that this improvement was mainly found when considering the severe exposure conditions (high metabolic rate and high humidity levels) prevailing in series 2 and 3. Comparison of SW_p4 (ISO formula for the efficiency of sweating) and SW_p5 (Hettinger's formula) confirmed the suggestions made by some of the participating research teams (Hettinger et al. 1986; Candas and Hoeft 1987) that the use of a modified equation improves the prediction of body sweat loss: the slope of the relationship was closer to 1 and the intercept was kept to a minimum. It is worth noting that this positive contribution was observed in mild conditions of exposure (experimental series 1 and 4) but not in severe conditions (series 2 and 3), since the efficiency levels predicted by the ISO and Hettinger's formulæ are almost identical when skin wettedness values are close to 1.

The SW_p6 relationship refers to all the proposals made by Hettinger's research team, including its equation for the estimation of T_{sk}. It can be seen that the use of this T_{sk} estimation formula led to a marked overestimation of the actual body sweat loss in comparison to the values predicted by the Mairiaux et al. formula (SW_p5).

The prediction obtained using the Index of Thermal Stress (Givoni 1963) has been included in Table 3 for information purposes. Whereas ITS gave satisfactory results in the experimental data set studied by Malchaire (1986) (see Table 2), the result obtained in this validation study was extremely poor. This observation could be ascribed to the fact that the maximum wettedness allowed by the Index is set at w_{max} = 2 and that no maximum level is specified for sweat rate. In humid conditions, such as those of data base series 2 and 3, the ITS rationale led to very high and unrealistic sweat rates being predicted.

4. Conclusions

The main conclusions arising from this validation study and from the other experimental studies analyzed in the ECSC research programme may be summarized as follows:

1. The Required Sweat Rate Index (ISO DIS 7933) is the heat stress index giving presently the best approximation of the body sweat loss. The validity of the limitation in skin wettedness specified for unacclimatized subjects (w_{max} = 0.85) should, however, be re-examined.
2. When the evaluation of short periods of exposure in varying heat stress conditions is considered, a satisfactory prediction of heat strain, using sweat loss as the reference variable, can only be obtained providing that the predicted sweat rates are exponentially weighted with a 10 minutes time constant.

This conclusion was supported by the results obtained in industry by Hettinger et al. (1986).

3. A further improvement in the prediction accuracy is obtained by means of two modifications to the ISO DIS; first, the calculation of evaporative efficiency of sweating based on the Hettinger et al. (1986) formula and second the estimation of T_{sk} variations using the Mairiaux et al. (1987) equation and an exponential weighting with k = 3 minutes.

Some areas needing further research have been identified: assessment of the effect of radiant temperature and clothing insulation on mean skin temperature, evaluation of the reliability of the T_{sk} prediction in subjects fully acclimatized to heat, and development of a model allowing the derivation of variations in core temperature from the difference between required and predicted evaporative rates.

5. References

Adams, W.C. 1977, Influence of exercise mode and selected ambient conditions on skin temperature. Annals of the New York Academy of Sciences, 301, 110-127.

Alber-Wallerstrom, B. and Holmer, I. 1985, Efficiency of sweat evaporation in unacclimatized man working in a hot humid environment. European Journal of Applied Physiology, 54, 480-487.

ASHRAE 1985, Physiological principles for comfort and health. In: ASHRAE handbook of fundamentals (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta), Chapter 8.

Candas, V. et Hoeft, A. 1987, Influence du port du vêtement sur le débit sudoral requis: modification sélective des échanges de chaleur par évaporation. Final report of ECSC research contract No 7247-22-007, Luxembourg.

Candas, V. and Hoeft, A. 1994, Clothing assessment and effects on thermophysiological responses of man working in humid heat. Ergonomics (this issue).

Chappuis, P., Pittet, P. and Jequier E. 1976, Heat storage regulation in exercise during thermal transients. Journal of Applied Physiology, 40, 384-392.

Fanger, P.O. 1970, Thermal comfort. Copenhagen, Danish Technical Press.

Givoni, B. 1963, Estimation of the effect of climate on man - Development of a new thermal index. Haïfa, Technion, Israël Institute of Technology.

Graveling, R.A. 1994, Influence of intermittency and static components of work. Ergonomics (this issues).

Haslam, R.A. and Parson, K.C. 1987, A comparison of models for predicting human response to hot and cold environments. Ergonomics, 30, 1599-1614.

Hettinger, Th., Peters, H., Noack, M. and Müller, B.H. 1986, Die Eignung von Klimaindizes zur Beurteilung der Klimabelastung in der Eisen- und Stahlindustrie. Final report of ECSC research contract No 7247-22-002, Wuppertal.

Ilmarinen, R. 1978, Einflüsse verschiedener Bekleidung auf einige physiologische Grössen des Menschen bei Körperarbeit in unterschiedlich erhöhter Umgebungstemperatur und Luftfeuchtigkeit. Diss., Köln, Deutsche Sporthochschule.

ISO/DIS 7933, 1986, Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rates.

Mairiaux, Ph., Nullens, W., Fesler, R., Brasseur, L. et Detry, J.M. 1977, Evaluation des effets d'un vêtement refroidissant sur l'adaptation aux efforts prolongés réalisés à haute température par des ouvriers mineurs. Revue de l'Institut d'Hygiène des Mines, 32, 99-122.

Mairiaux, Ph., Libert, J.P., Candas, V. and Vogt, J.J. 1984, Physiological and perceptual responses to cyclic heat stress variations. Aviation, Space and Environmental Medicine, 55, 935-940.

Mairiaux, Ph., Libert, J.P., Candas, V. and Vogt, J.J. 1986, Prediction of strain for intermittent heat exposures. Ergonomics, 29, 913-923.

Mairiaux, Ph., Malchaire, J. and Candas, V. 1987, Prediction of mean skin temperature in warm environments. European Journal of Applied Physiology, 56, 686-692.

Mairiaux, Ph. and Libert, J.P. 1987, Physiological factors associated with the onset of sweating. Japanese Journal of Physiology, 37, 699-714.

Malchaire, J. 1986, Validation des indices de contrainte thermique pour la prédiction des astreintes et des durées limites d'exposition. Final report of ECSC research contract No 7247-22-001, Brussels.

Nishi, Y. and Gagge, A.P. 1970, Direct evaluation of convective heat transfer coefficient by naphtalene sublimation. Journal of Applied Physiology, 29, 830-838.

Timbal, J., Colin, J. et Boutelier, C. 1970, Etude de la phase transitoire de la sudation chez l'homme. Pflügers Archives, 318, 305-314.

Vogt, J.J., Meyer, J.P., Candas, V., Libert, J.P. and Sagot, J.C. 1983, Pumping effects on thermal insulation of clothing worn by human subjects. Ergonomics, 26, 963-974.

Vogt, J.J. 1986, Campagne de comparaison de la validité respective des principaux indices de contrainte thermique. Final report of ECSC research contract No 7247-22-006, Nancy.

Acknowledgements

The authors are indebted to V. Candas, J.P. Meyer and J.J. Vogt for having given access to their own experimental data.

SW_{norm}	: Required Sweat rate, as calculated from the ISO/DIS 7933 equations
P_4SR	: Predicted 4 Hours Sweat Rate
ET	: Effective Temperature
HSI	: Heat Stress Index
ITS	: Index of Thermal Stress
PMV	: Predicted Mean Vote
ET*	: modified Effective Temperature
WBGT	: Wet Bulb Globe Temperature Index
dWBGT	: index level relative to the permissible limit as a function of metabolic rate
SW_{mod}	: Required Sweat Rate, as calculated from Malchaire prediction model; for other symbols, see Table 1