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Development and Validation of the Predicted Heat Strain Model

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Eight laboratories participated in a concerted research project on the assessment of hot working conditions. The objectives were, among others, to co-ordinate the work of the main European research teams in the field of thermal factors and to improve the methods available to assess the risks of heat disorders at the workplace, and in particular the "Required Sweat Rate" model as presented in International Standard ISO 7933 Standard (1989). The scientific bases of this standard were thoroughly reviewed and a revised model, called "Predicted Heat Strain" (PHS), was developed. This model was then used to predict the minute by minute sweat rates and rectal temperatures during 909 laboratory and field experiments collected from the partners. The Pearson correlation coefficients between observed and predicted values were equal to 0.76 and 0.66 for laboratory experiments and 0.74 and 0.59 for field experiments, respectively, for the sweat rates and the rectal temperatures. The change in sweat rate with time was predicted more accurately by the PHS model than by the required sweat rate model. This suggests that the PHS model would provide an improved basis upon which to determine allowable exposure times from the predicted heat strain in terms of dehydration and increased core temperature.

Keywords: heat stress index; required sweat rate

INTRODUCTION

The ISO 7933 (1989) Standard, entitled *Analytical Determination and Interpretation of Thermal stress using Calculation of the Required Sweat Rate* was published for the first time in 1989. It was abundantly criticised and many papers were published comparing one version (not always specified) of the Required Sweat Rate index to sets of data (for example, Haslam and Parsons, 1987, 1994; Smolander *et al*., 1991; Kampmann and Piekarski, 2000).

Although such comparisons were always limited to a particular set of data, definite limitations were shown concerning:

- the prediction of the skin temperature;
- the influence of the clothing on convective and evaporative heat exchanges;
- the combined effect of clothing and movements;
- the increase of core temperature linked to the activity;

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- the prediction of the maximum allowable exposure durations.

Considering these major limitations as well as the fact that this standard appeared to be little used in practice, a joint research project between some of the main European research teams in the field of thermal factors was started, with the support of the European Union.

The specific objectives of the research project were:

1. To design and validate a strategy for the assessment of the stress related to hot working conditions, a strategy that can be used by practitioners in the field to determine maximum allowable exposure duration and to optimise the improvement of the working environment. The description, justification and validation of this strategy were published by Malchaire *et al*. (1999)
2. To improve the prediction of the heat exchanges between a clothed person and the environment, taking into consideration the characteristics of normal and special clothing ensembles. The new algorithms were described and validated by Havenith *et al*. (1999) and Holmér *et al*. (1999).
3. To better define the criteria for the determination of the maximum allowable exposure duration and in particular the inter-individual differences in sweat rate, evaporation efficiency, water loss and increase in core temperature. These criteria were reviewed by Malchaire *et al*. (2000).
4. To improve the validity of the expression for the prediction of the mean skin temperature: a new model was developed and validated by Mehnert *et al*. (2000).
5. To review systematically the algorithms used in the ISO 7933 (1989) Standard, taking into consideration the results of the most recent investigations, concerning:
    - 5.1. The respiratory heat losses.
    - 5.2. The influence of protective clothing on radiation exchanges.
    - 5.3. The prediction of the mean skin temperature.
    - 5.4. The exponential averaging for the skin temperature and the sweat rate.
    - 5.5. The prediction of the mean body temperature.
    - 5.6. The distribution of heat storage in the body.
    - 5.7. The prediction of the rectal temperature.
    - 5.8. The evaporation efficiency.

Following the fundamental changes brought to the algorithms and the prediction scheme, and in order to avoid any confusion with the previous versions of the Required Sweat Rate index, it was decided to change the name of the heat stress evaluation procedure to the Predicted Heat Strain (PHS) model.

In the next section, this paper describes and justifies, based on the literature, the development of the PHS model. In the last section, this model will be validated using a database of some 909 laboratory and field experiments gathered by the different participants in the European joint research project.

DEVELOPMENT OF THE PHS MODEL

Respiratory evaporative (E_{res}) and convective (C_{res}) heat losses

Although quite limited in hot climates, these losses are often of the same order of magnitude as convective losses on the body surface. Furthermore, heat storage is determined by the difference between the required and predicted evaporation rates and the respiratory losses become significant. An accurate prediction of these exchanges is therefore required.

Livingstone *et al*. (1994) reported data about the relationships between the metabolic rate (M in watts), the ventilation rate (V in l. min^{-1}), the temperatures of the expired air (t_{ex} in °C) and the inspired air (t_{in} in °C), and the partial water vapour pressure of the inspired air ($p_{a,in}$ in kPa).

From these data, the following expressions can be derived

$$V = 0.076 \cdot M \quad (R = 0.992)$$

$$t_{ex} = 28.6 + 0.115 \cdot t_{in} + 0.641 \cdot p_{a,\,in} \quad (R = 0.979).$$

The convective respiratory heat exchange is given by

$$C_{res} = c_p \cdot V \cdot (t_{ex} - t_{in})$$

where c_p is the specific heat of air (W min l.$^{-1}$ (°C)$^{-1}$).

With the above expressions of V and t_{ex}, the following expression was derived (with both C_{res} and M in watts or in W m^{-2})

$$C_{res} = 1.52 \cdot 10^{-3} \cdot M \cdot (28.6 + 0.641 \cdot p_{a,\,in} - 0.885 \cdot t_{in})$$

For the evaporative heat loss (E_{res}), the expression proposed by Varene (1986) was adopted

$$E_{res} = 1.27 \cdot 10^{-3} M \cdot (59.3 + 0.53 \cdot t_{in} - 11.63 \cdot p_{a,\,in})$$

Influence of radiation on protective clothing

Concerning the influence of the clothing characteristics on convection and radiation (Havenith *et al*., 1999; Holmér *et al*., 1999) the model developed is valid only if the clothing has “normal” reflective characteristics.This has to be corrected when reflective clothing is used (reflection coefficient F_R), covering the fraction A_p of the body surface.

In this case, it is assumed that, for the fraction of the body surface uncovered by the reflective clothing ($1-A_p$), the reflection coefficient is 0.93 and a correction factor F_{clR} is introduced in the computation of the dynamic radiation coefficient

$$F_{clR} = (1-A_p)\cdot 0.93 + A_p\cdot F_R$$

Prediction of the mean skin temperature (t_{sk})

Following the work reported by Mehnert *et al*. (2000), the models for the prediction of t_{sk} are

- for clothed subjects ($I_{cl}\geq 0.6$ clo):

$$t_{sk,\ clothed} = 12.2 + 0.020\cdot t_a + 0.044\cdot t_r + 0.194\cdot p_a - 0.253\cdot v_a + 0.00297\cdot M + 0.513\cdot t_{re}$$

- for nude subjects ($I_{cl}\leq 0.2$ clo):

$$t_{sk,\ nude} = 7.2 + 0.064\cdot t_a + 0.061\cdot t_r + 0.198\cdot p_a - 0.348\cdot v_a + 0.616\cdot t_{re}$$

For clothing insulation (I_{cl}) between 0.2 and 0.6 clo, a linear interpolation between both models is used

$$t_{sk} = t_{sk,\ nude} + 2.5\cdot(t_{sk,\ clothed} - t_{sk,\ nude})\cdot(I_{cl} - 0.2)$$

Exponential averaging for the skin temperature and the sweat rate

By far the main limitation of the ISO 7933 Standard is to assume that a steady state is reached instantaneously. This makes it inappropriate for the prediction of responses to intermittent exposure. Furthermore, heat accumulation is assumed to remain the same during the whole exposure, while it obviously tends to 0, towards an equilibrium state in core temperature. Modifications had to be brought to the model so that it is possible to predict the sweat rate and the skin and rectal temperatures at any time, taking into consideration all of the past exposure.

According to the results of the previous ECSC research programme (Malchaire, 1986), the skin temperature and the sweat rate tend to their equilibrium value as a first order system, according to the following expression

$$V(t) = V_0 + \Delta V\cdot[1-\exp(-t/\tau)]$$

where $V(t)$ is the value at time t; V_0 is the initial value; ΔV is the increase of parameter V in the new condition, ($V_0+\Delta V$) being therefore the new equilibrium value; t is time and τ is the time constant (in minutes).

As shown by Malchaire (1991), for numerical applications, this expression can be replaced by a recursive expression

$$V_i = V_{i-1}\cdot k + V_{max}\cdot(1-k)$$

where V_i is the value at time i; V_{i-1} is the value at time ($i-1$), Δt min before; V_{max} is the target value ($V_0+\Delta V$) in the previous equation; τ is the time constant (in minutes) and k is equal to $\exp(-\Delta t/\tau)$.

Malchaire (1991) has reported values of the time constants equal to 3 min for the skin temperature and 10 min for the sweat rate.

Mean body temperature

Concerning mean body temperature, ISO 7933 implicitly assumes a skin–core weighting of 0.3–0.7 regardless of the skin and core temperature. This is contradictory to the literature and had to be revised.

Many papers have presented expressions to compute the “mean body temperature” (t_b), as a function of the rectal (t_{re}) and the skin temperature (t_{sk}) (Gagge and Nishi, 1977; Kähkönen, 1993; Stolwijk and Hardy, 1966; Colin *et al*., 1971).

All take the form $t_b=\alpha\cdot t_{sk}+(1-\alpha)\cdot t_{re}$.

Conditions for which these expressions were derived are usually not fully documented. However, a consensus seems to exist concerning the fact that $\alpha=0.30$ for vasoconstricted skin and 0.1 for vasodilated skin.

The paper by Colin *et al*. (1971) suggests that this coefficient is not simply a function of the vasodilatation status and the blood flow to the skin but varies with the heat storage, and therefore, indirectly, with the rectal temperature. Therefore it is assumed that

- $\alpha=0.3$ for $t_{re}\leq 36.8$°C
- $\alpha=0.1$ for $t_{re}\geq 39$°C
- α varies between 0.3 and 0.1 according to: $\alpha=0.3-0.09\cdot(t_{re}-36.8)$.

Distribution of the heat storage in the body

The distribution of the heat storage between the core and the skin layer had to be investigated in order to be able to derive a valid estimate of the core temperature.

The core temperature t_{co} has to be derived from the heat dS stored during the last time interval taking into account the increase in skin temperature (from t_{sk0} to t_{sk}), the previous core temperature t_{co0} and the previous skin–core weighting α_0.

As t_{sk} and t_{co} are different from t_{sk0} and t_{co0}, the skin–core weighting changes. On the other hand, the increase in skin temperature during the last minute concerns directly the outer surface of the skin but progressively the skin layer of thickness α.

The proposed model assumes that, inside this skin layer, the temperature varies linearly from t_{sk0} to t_{co0} initially and from t_{sk} to t_{co} at the end of the minute.

The core temperature t_{co} at time i can be calculated from the following expression

$$t_{co} = \frac{1}{1-\frac{a}{2}}\left[\frac{dS_i}{c_p W_b} + t_{co0} - \frac{t_{co0}-t_{sk0}}{2}\alpha_0 - t_{sk}\frac{\alpha}{2}\right]$$

where c_p is the specific heat of the body (J kg^{-1}(°C)$^{-1}$) and W_b the body mass (kg); α and t_{co} have to be determined knowing that α varies as a function of t_{co} as indicated before. This may be solved iteratively.

Prediction of the rectal temperature (t_{re}) from the mean core temperature

As rectal temperature remains, with heart rate, a physiological parameter easy to record at the work place, the modified model attempts to predict it directly.

The expressions developed above make it possible to predict the mean skin (t_{sk}) and core (t_{co}) temperatures. This core temperature can itself be considered to be the mean of the rectal temperature (characteristic of the muscle mass) and the oesophageal temperature (characteristic of the blood and influencing the hypothalamus).

The heat storage due to thermal imbalance during a given unit of time results in an increase in rectal and oesophageal temperatures. According to Edwards *et al*. (1978), the rectal and oesophageal temperatures (t_{oe}) are linked by an expression such as

$$t_{oe} = a \cdot t_{re} + b \cdot \Delta t_{re} + c$$

where Δt_{re} is the increase in t_{re} from one time interval to the next.

The analysis of 10 cases from the database, for which both t_{oe} and t_{re} were available, minute by minute, gave the following expression

$$t_{oe} = 1.31 + 0.962 \cdot t_{re} + 7.03 \cdot \Delta t_{re}$$

Assuming that the mean core temperature t_{co} discussed previously is the average of the rectal and the oesophageal temperatures, this can be written

$$2 \cdot t_{co} = 1.31 + 1.962 \cdot t_{re} + 7.03 \cdot \Delta t_{re}$$

or

$$2 \cdot t_{co} = 1.31 + 1.962 \cdot t_{re0} + 9 \cdot (t_{re} - t_{re0})$$

where t_{re0} is the rectal temperature one minute before and therefore Δt_{re} is given as $(t_{re} - t_{re0})$.

The rectal temperature is then given by

$$t_{re} = t_{re0} + \frac{2t_{co} - 1.962t_{re0} - 1.31}{9}$$

Evaporative efficiency of sweating

ISO 7933 adopted an expression for the computation of the evaporative efficiency as a function of skin wetness (w). The validity of this expression had to be confirmed based on more recent publications.

Several expressions are reported in the literature for the prediction of the evaporative efficiency of sweating (η) as a function of skin wetness (w) (Vogt *et al*., 1982; Givoni, 1976; Hettinger *et al*., 1985; Alber and Holmér, 1994).

The comparison of these expressions shows that:

- The expression proposed by Vogt *et al*. (1982) leads to higher evaporative efficiencies for the same skin wetness, that is, to a lower strain, in terms of SW_{req}, than the other expressions.
- The expressions proposed by Hettinger *et al*. (1985) and Givoni (1976) provide about the same results. Both were derived from experiments with clothed subjects instead of nude subjects in the case of the expression by Vogt *et al*. (1982).
- The predictions using the Hettinger *et al*. (1985) expression are also very close to the recent data from Alber and Holmér (1994), who analysed differences in evaporative efficiencies between women and men.

The expression adopted in the current ISO 7933 Standard can therefore be confirmed for the majority of workplaces, for required skin wetness smaller or equal to 1.This expression is

$$\eta = 1 - w^2/2$$

Problems, however, occur under very humid conditions where the maximum evaporation rate (E_{max}) decreases with increasing humidity. As the evaporation efficiency is assumed to remain equal to 0.5 when the wetness reaches 1, it results from the model that the predicted sweat rate decreases also with increasing humidity. Therefore, a subject would sweat less in an extremely humid environment. This is clearly contradicted by the results of Zintl (1979) and Kohler (1976).

Therefore, the sweating efficiency may not be taken equal to 0.5 regardless of the sweating, as soon as the skin surface is predicted to be completely wet. The skin being completely wet (w=1), it is reasonable to assume that the layer of water on the skin can increase if the air humidity increases.

As shown by Candas (1980), the efficiency tends to 0 on a cylinder if the layer of water increases. Therefore, the evaporation efficiency should be below 0.5 and tend to 0 as a function of the skin wetness, which would take more the meaning of thickness of the water layer on the skin than of the equivalent fraction of the skin completely wetted.

Such a relationship can be described by

$$\eta = 1 - w^2/2 \quad \text{for } w \leq 1$$

$$\eta = (2-w)^2/2 \quad \text{for } 1<w\leq 1.7$$

$$\eta = 0.05 \quad \text{for } w>1.7$$

The predicted evaporation rate remains estimated using w (limited to $w_{\max}$):

$$E_p = wE_{\max},$$

while the predicted sweat rate is a function of η calculated above:

$$SW_p = E_p/\eta.$$

Development of the Predicted Heat Strain (PHS) model

Based on these results, the Required Sweat Rate index was revised concerning 14 aspects and renamed to the Predicted Heat Strain (PHS) model:

1. New formula to compute the respiratory evaporative and convective heat losses;
2. Consideration of the reflective characteristics of the clothing;
3. New algorithms for the prediction of the heat exchanges between a clothed person and the environment, taking into consideration the characteristics of normal and special clothing ensembles;
4. Prediction of the mean skin temperature using two expressions developed for nude and clothed subjects, with interpolation for I_{cl} between 0.2 and 0.6 clo;
5. Exponential averaging to compute minute by minute the skin temperature and the sweat rate;
6. Skin–core weighting for the computation of the mean body temperature;
7. Computation of the core temperature considering the distribution of heat storage in the body;
8. Prediction of the rectal temperature from the mean core temperature;
9. Computation of the evaporation efficiency of sweating as a function of the wetness, especially for very humid conditions;

taking in account also the aspects discussed by Malchaire et al (2000):

10. Increase in core temperature associated with the metabolic rate;
11. Maximum wetness for non acclimatised subjects;
12. Estimation of the maximum sweat rate from the metabolic rate, for acclimatised and non acclimatised subjects;
13. Rectal temperature limited to 38.0°C;
14. Maximum water loss of 7.5% of body mass for an average subject.

VALIDATION OF THE PHS-MODEL

The database

The eight partners had the data from many laboratory and field experiments run in the past available and most were used in the literature for different purposes. The data from 909 experiments (672 laboratory and 237 field experiments) were gathered to a common database. For each experiment, the minute by minute data were available for the primary parameters (t_a, p_a, t_r, v_a, M, I_{cl}) and for the physiological response (t_{re} and SW). Subjects were acclimatised in 60% of the experiments.

Table 1 gives the mean and standard deviation for the six parameters recorded minute by minute in the 672 laboratory experiments and in the 237 field experiments. The ranges of values of air temperature (t_a), humidity (p_a), radiation (t_r-t_a), and metabolic rate (M) were similar for both sets of experiments. The range of air velocity (v_a) was smaller for the laboratory experiments (maximum value of 1 ms^{-1} instead of 4 ms^{-1} for the field experiments). Thirty-seven percent of the laboratory experiments (N=248), and 95% of the field experiments (N=225) concerned clothed workers (I_{cl} value greater than 0.5 clo).

With the exception of the air velocities greater than 1 ms^{-1}, it can be concluded that the set of laboratory experiments covered the range of conditions encountered in the field.

The effect of air velocity on clothing insulation was investigated with special experiments up to 3 ms^{-1}, and the validity of the algorithms for the computation of the convective and evaporative heat exchanges was shown to extend up to 3 ms^{-1} (Havenith *et al*., 1999; Holmér *et al*., 1999). The range of validity of the PHS model can therefore be considered as extending to air velocity of 3 ms^{-1}. This corresponds to the 95% confidence upper limit for the field experiments. From these 95% confidence intervals, it is concluded that the model can only be validated for the values of parameters in the ranges indicated in Table 1. These limits do not appear to restrict severely the application of the PHS model in industrial situations. Particular attention will, however, be exercised for field conditions with velocities greater than 1 ms^{-1}.

The PHS model makes it possible to predict minute by minute sweat rate and rectal temperature. However, these parameters were observed at discrete moments. In order to give to each experiment a statistical weight proportional to its duration, it was decided to select points using the following criteria:

1. for the sweat rate: only use the mean sweat rate over the whole experiment;
2. for the rectal temperature, selection of data points in each experiment according to:
    - 2.1. 1 point per hour;
    - 2.2. 30–45 min between two points;
    - 2.3. elimination of experiments where t_{re} was greater than 38°C at the first minute;

Table 1. Descriptive statistics of the minute by minute values recorded in the 672 laboratory experiments

		672 lab experiments	237 field experiments	Range of validity	
		Mean (standard deviation) m (s)	Mean (standard deviation) m (s)	Min	Max
Air temperature	t_a (°C)	30.8 (9.1)	28.5 (5.3)	15	50
Humidity	p_a (kPa)	1.95 (1.26)	1.88 (0.82)	0	4.5
Radiation	$t_r - t_a$ (°C)	15.4 (21.8)	8.6 (16.7)	0	60
Air velocity	v_a (ms^{-1})	0.40 (0.25)	1.14 (0.92)	0	3
Metabolic rate	M (W)	243 (114)	245 (106)	100	450
Clothing insulation	I_{cl} (clo)	0.38 (0.34)	0.77 (0.18)	0.1	1.00

2.4. points not necessarily chosen during a steady state condition;
2.5. first point selected after the initial resting period if in neutral conditions;
2.6. value at the last minute always taken.

The numbers of points selected were:

1. for sweat rates: 672 and 237 for laboratory and field experiments;
2. for rectal temperatures: 1937 and 1028, respectively.

The validation of the final PHS programme was performed successively on the laboratory and field experiments of the database.

Validation in well controlled laboratory experiments

The accuracy of the model was tested only on laboratory data where it can be assumed that the errors in the evaluations of the primary parameters are minimal.

Table 2 gives the results of the linear regressions between the observed and predicted values of rectal temperatures and sweat rates for laboratory experiments. The predicted values are on average 27 g/h greater and the standard deviation is smaller than for the observed sweat rates. This was expected, as the PHS model predicts the situation for an average subject while the observed values are greatly dependent upon interindividual differences.

The linear regression for SW in g/h is: $SW_{obs}=0.848 \cdot SW_{pred}+41$ with a correlation coefficient equal to 0.76 and a slope not significantly different from 1.

The 95% confidence interval (CI) of the values was computed in the polar co-ordinates in order for the uncertainty to be proportional to the sweat rate. The equation becomes

$$SW_{obs} = 0.918 \cdot SW_{pred} \quad \text{(with the 95\% CI: 0.540} - \text{1.523)}$$

Figure 1 compares the predicted and observed sweat rates and the 95% confidence interval. A few points are outside this 95% confidence interval. They come from experiments from different partners and demonstrate the influence of interindividual differences. Indeed, identical experiments with other subjects provided data well within the confidence interval.

Figure 2 compares the 1937 pairs of values of rectal temperatures. The means and standard deviations of the observed and predicted values are almost the same. The correlation coefficient is equal to 0.66 and lower than for the sweat rates. The regression equation is: $t_{re,obs}=0.664 \cdot t_{re,pred}+12.57$. The equation in polar coordinates is: $t_{re,obs}=1.000 \cdot t_{re,pred}$ with the 95% CI ranging from 0.979 to 1.020. Again, all data points

Table 2. Regressions between observed and predicted sweat rates and rectal temperatures

	Sweat rate (g/h)		Rectal temperature	
	Lab	Field	Lab	Field
n	672	237	1937	1028
Observed (m±s)	424±172	317±187	37.45±0.47	37.40±0.44
Predicted (m±s)	451±154	344±132	37.46±0.47	37.40±0.34
Slope	0.848	1.056	0.664	0.770
Intercept	41	−46	12.57	8.60
r	0.7601	0.7448	0.6585	0.5940
Alpha	0.918	0.851	1.000	1.000
Alpha IC95%	0.540–1.523	0.328–1.936	0.980–1.020	0.981–1.019
Obs−Pred (m±s)	−27.5±114.1	−26.7±125.1	−0.01±0.39	−0.01±0.36

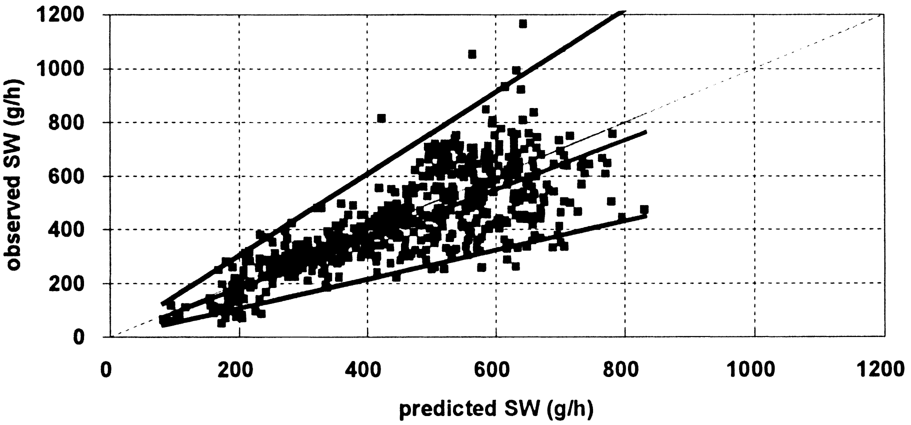

Fig. 1. Observed and predicted sweat rates (with the 95% confidence interval) in the 672 laboratory experiments.

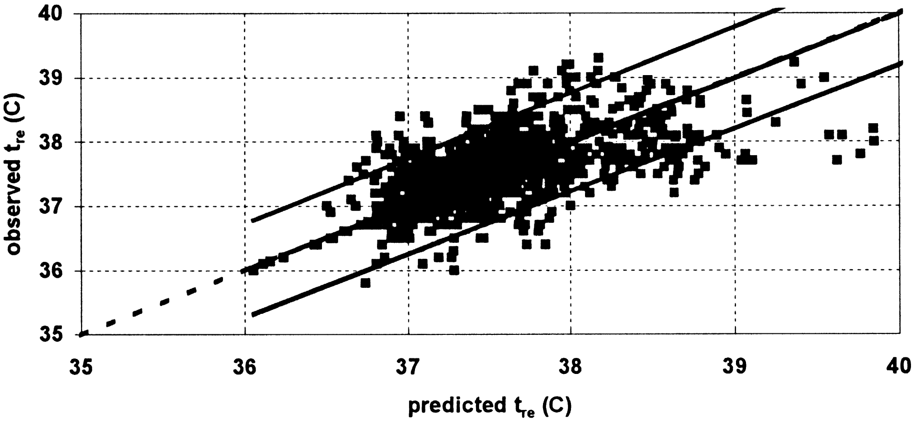

Fig. 2. Observed and predicted rectal temperatures (with the 95% confidence interval) in the 672 laboratory experiments.

outside the 95% confidence interval are due to interindividual differences.

Validation in field experiments

Figures 3 and 4 compare the observed and predicted values of sweat rates and rectal temperatures for the 237 field experiments. Table 2 gives the results of the linear regressions. The accuracy of the climatic and physiological measurements being lower for experiments in the field, it appears logical that the correlations between observed and predicted values are lower and that the 95% confidence intervals are larger. The linear regressions are

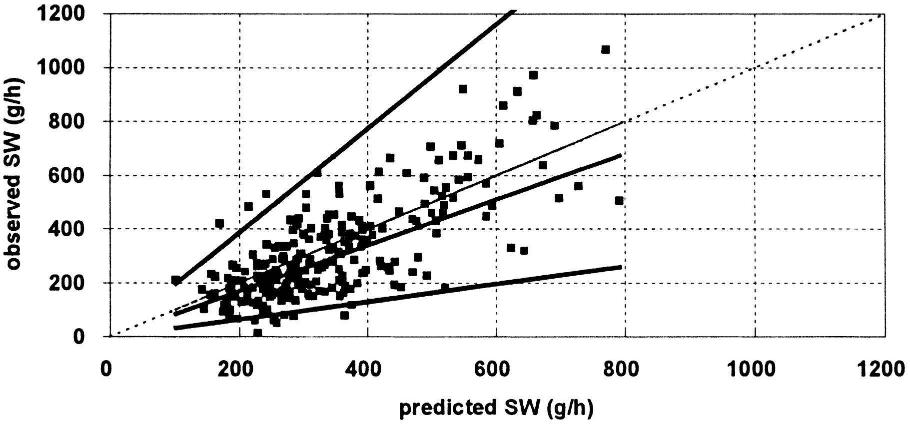

Fig. 3. Observed and predicted sweat rates (with the 95% confidence interval) in the 237 field experiments.

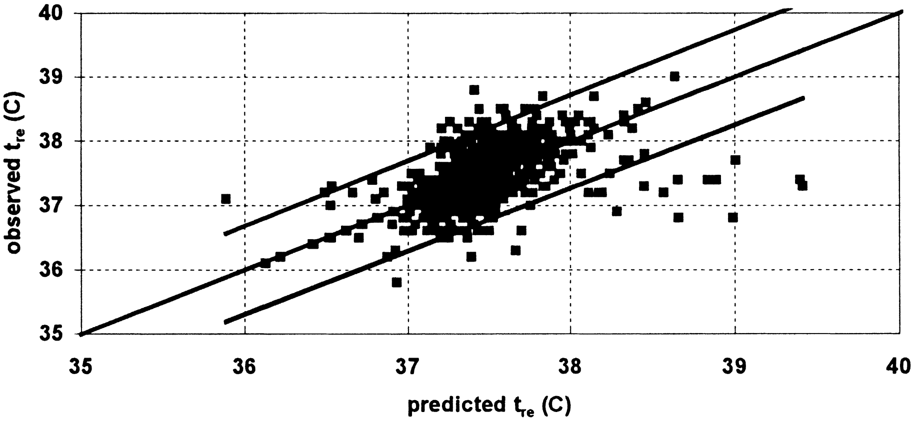

Fig. 4. Observed and predicted rectal temperatures (with the 95% confidence interval) in the 237 field experiments.

$$SW_{obs} = 1.056 \cdot SW_{pred} - 46, \quad R = 0.74$$

$$t_{re,\,obs} = 0.770 \cdot t_{re,\,pred} + 8.60 \quad R = 0.59$$

The equations in polar coordinates are

$$SW_{obs} = 0.851 \cdot SW_{pred} \quad \text{(with the 95\% CI: 0.328 −1.936)}$$

$$t_{re,\,obs} = 1.000 \cdot t_{re,\,pred} \quad \text{(with the 95\% CI: 0.981 −1.019)}$$

COMPARISON BETWEEN THE PHS MODEL AND THE ISO 7933 STANDARD

The purpose of the comparison between the Required Sweat Rate index as it is in the ISO 7933 and the new PHS model is important to determine whether this PHS model results in different and better predictions. Comparisons will be restricted to the predicted sweat rates and the Duration Limit of Exposure (DLE) values, since ISO 7933 does not make it possible to predict the rectal temperature. The DLE predicted by the PHS model (DLE_{PHS}: lowest of the two for dehydration and heat storage) will be compared to those predicted using ISO 7933 (DLE_{ISO}: “danger” level).

The comparison will be limited to unacclimatised subjects (maximum sweat rate: 250 W m^{-2} according to ISO 7933).

ISO 7933 makes it possible to predict the sweat rate for constant climatic and working conditions. In case of different consecutive exposure conditions, the interpretation had to be done, first, for each sequence separately, and, later, globally for the whole set of sequences. Therefore, the maximum (E_{max}) and required (E_{req}) evaporation rates were computed for each minute successively and averaged over the total duration. The final interpretation was done from these mean values to predict the ISO 7933 sweat rate (SW_{ISO}). This is strictly consistent with the standard, although extended to sequences of one-minute duration.

When using this method of interpretation for ISO 7933, the results of the linear regressions between the observed and predicted sweat rates are

$$SW_{obs} = 0.757 \cdot SW_{ISO} + 75, \quad R = 0.74$$
(for laboratory experiments)

$$SW_{obs} = 0.663 \cdot SW_{ISO} + 52, \quad R = 0.52$$
(for field experiments)

When these results are compared to those reported above, it appears clearly that the PHS model gives better predictions, particularly for the field experiments, the correlation explaining 55% (r=0.75) of the total variance instead of 27% (r=0.52).

The improvements brought by the PHS model are not totally reflected by these statistics. Figure 5 compares the evolutions of the SW_{ISO} and SW_{PHS} sweat rates during a laboratory experiment involving different sequences of work and climatic conditions. In this particular case, the averages of the SW_{ISO} and SW_{PHS} min per min values over the entire experiment are about the same. According to the regression analysis performed above, both models would therefore be considered as equally valid. This is not the case obviously when considering the evolution of the sweat rate during the experiment. The SW_{ISO} is assumed to increase or decrease instantaneously as soon as a sequence starts, while the SW_{PHS} follows remarkably the observed values.

COMPARISON OF THE EVOLUTION OF SW AND DLE AS A FUNCTION OF PAIRS OF THE PRIMARY PARAMETERS FOR ISO 7933 AND THE PHS MODEL

The sweat rates were predicted by the two methods for 2-h exposures, in conditions with air temperatures

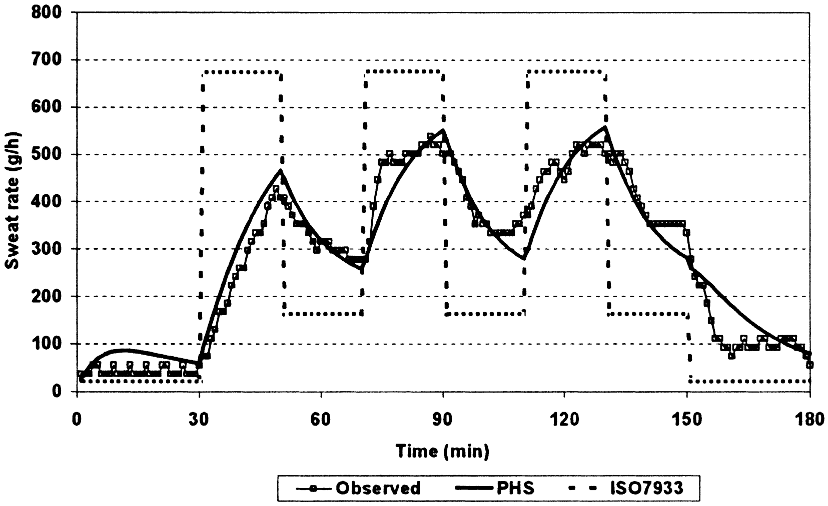

Fig. 5. Comparison between observed and predicted sweat rates using ISO 7933 and PHS in a laboratory experiment with three sequences of work and climate.

varying between 25 and 50°C and one of the other parameters varying in the ranges indicated in Table 3. The other parameters were kept at "normal" values (Table 3). Although the results depend upon these "normal" values, they will describe how the PHS model works and make possible the comparison with the predictions using ISO 7933.

Figures 6–10 give the mean sweat rate, during the second hour of exposure.

The following remarks can be made.

Air temperature and humidity (Fig. 6)

As the metabolic rate is equal to 290 watts in these simulations, SW_{PHS} reaches a maximum of 740 g/h. This will also be the case when the other parameters (t_r-t_a), v_a, I_{cl} vary, except for the metabolic rate since the maximum sweat rate is estimated as a function of M. SW_{ISO} shows some singularities in very humid conditions (35°C, p_a>3 kPa), decreasing with an increase in partial vapour pressure. This is clearly erroneous, as mentioned previously. SW_{PHS} does not show this since the PHS model takes into account the decrease in evaporation efficiency for theoretical wetness greater than 1.

Table 3. Range of variation and normal values of the climatic parameters during the simulations

	Range	Normal values
Humidity p_a (kPa)	0.5–4.5	3
Radiation (t_r-t_a) (°C)	0–60	0
Air velocity v_a (ms^{-1})	0–1	0.3
Metabolic rate M (W)	100–450	290
Clothing insulation I_{cl} (clo)	0–1	0.5

Air temperature and radiant temperature (Fig. 7)

SW_{ISO} and SW_{PHS} are about the same when the radiation load varies: the computation of the radiation exchange is the same in both models for non-reflective clothing.

Air temperature and air velocity (Fig. 8)

The maximum sweat rate is reached between 37 and 43°C when the velocity increases from 0 to 1 $ms^{-1.}$ The influence of the air velocity on SW_{PHS} is greater than on $SW_{ISO,}$ due to the modifications brought to the algorithms for convection and evaporation.

Air temperature and metabolic rate (Fig. 9)

The PHS model assumes that the maximum sweat rate varies as a function of the metabolic rate, with a lower limit of 250 W m^{-2} and an upper limit of 400 W m^{-2}.

SW_{ISO} and SW_{PHS} are about the same when the metabolic rate varies, except for the maximum value, constant in ISO 7933 (250 W m^{-2}) and increasing with M for PHS.

Air temperature and clothing insulation (Fig. 10)

The maximum sweat rate is reached for t_a=35°C for a clo value of 1 and for t_a=43°C for a nude person. Below these air temperatures, the sweat rate increases linearly with the clothing insulation. Clothing insulations equal to 0.8 and 1 clo lead to lower values of $SW_{ISO.}$ This is obviously not correct and disappeared for SW_{PHS} due to the improved influence of the clothing.

As mentioned already, these simulations were made as a function of two parameters, the others

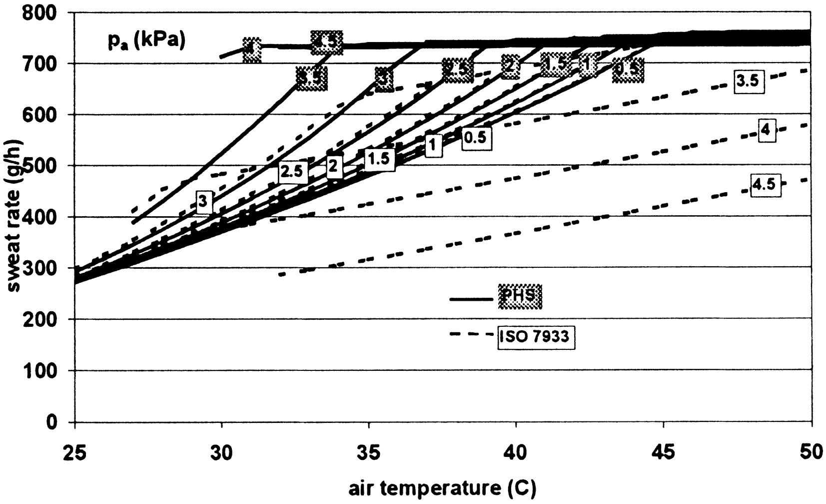

Fig. 6. Evolution of the sweat rate (mean value during the second hour of exposure) as a function of air temperature (t_a) and humidity (p_a).

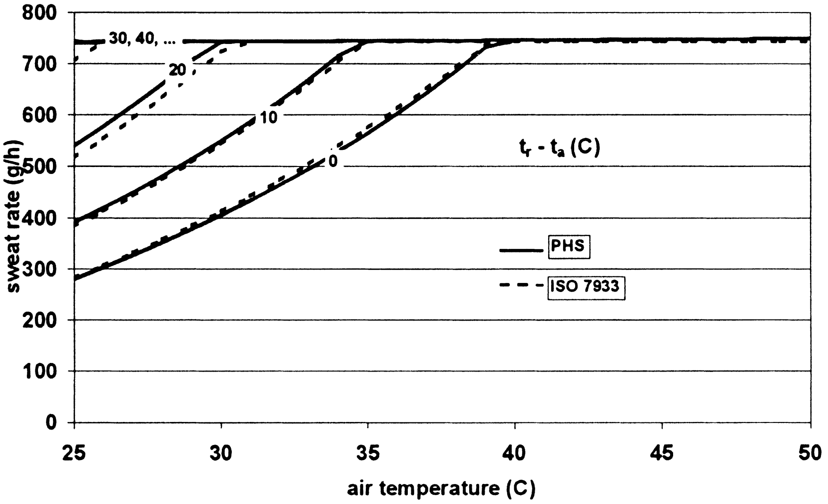

Fig. 7. Evolution of the sweat rate (mean value during the second hour of exposure) as a function of air temperature (t_a) and radiation (t_r-t_a).

being held constant at “normal” values, and the quantitative conclusions may not be generalised. It can, however, be concluded that the PHS model is giving more realistic results than ISO 7933.

COMPARISON BETWEEN THE PHS MODEL AND THE WBGT INDEX

The DLE was computed in 3680 sets of conditions with the primary parameters varying in the range indicated in Table 3. The clothing insulation was held constant to 0.6, as the WBGT index is supposed to apply strictly in this clothing condition. At the same time, the WBGT and $\mathrm{WBGT_{limit}}$ were computed for the same conditions according to ISO 7243 (1982), and using the algorithm developed by Malchaire (1976). This WBGT limit was computed using $\mathrm{WBGT_{limit}}=34.3-M/35.5$ (with M in W). Figure 11 compares the $\mathrm{DLE_{PHS}}$ with the differences $(\mathrm{WBGT}-\mathrm{WBGT_{limit}})$. A positive difference means that the work may not be performed continuously.

Most of the DLE lower than 4 h occur in conditions for which the WBGT difference is positive. In these conditions, according to the WBGT index, work cannot be pursued continuously and 1 h work–rest regimens must be organised. The PHS indicates that, indeed, in many conditions, the $\mathrm{DLE_{PHS}}$ is short. However, as an example, the following three conditions give the same WBGT difference, while, according to the PHS model, the DLE are respectively 30, 236 and 425 min.

$t_a = 40°\mathrm{C}$ RH = 20%

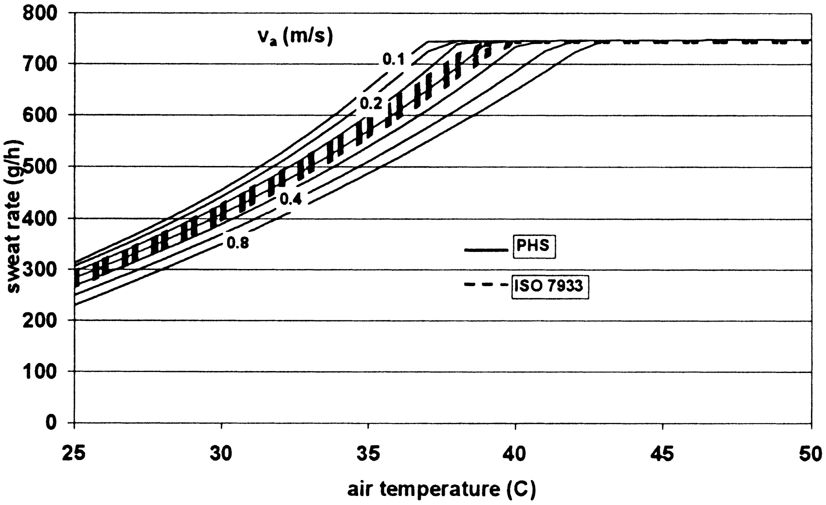

Fig. 8. Evolution of the sweat rate (mean value during the second hour of exposure) as a function of air temperature (t_a) and air velocity (v_a).

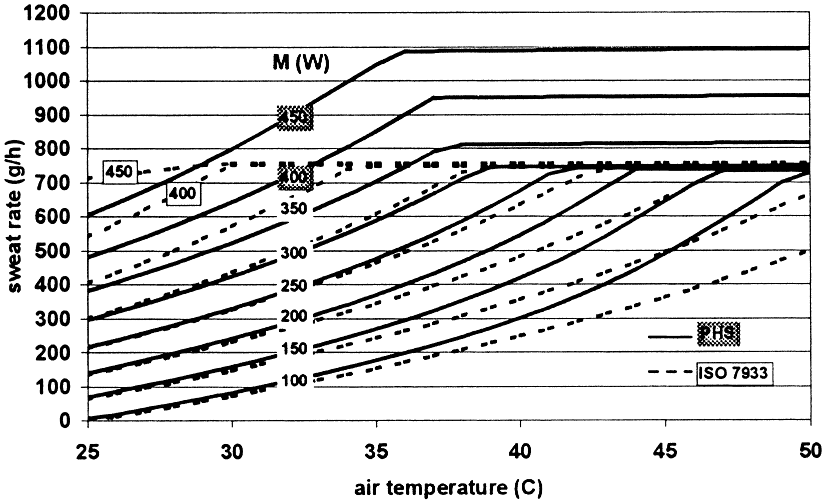

Fig. 9. Evolution of the sweat rate (mean value during the second hour of exposure) as a function of air temperature (t_a) and metabolic rate (M).

$t_r = 40°\text{C}$ $v_a = 1.0\ \text{ms}^{-1}$
$M = 450$ W $I_{cl} = 0.6$ clo
WBGT = 27.6 $\text{WBGT}_{\text{limit}} = 21.6$

$t_a = 25°\text{C}$ RH = 60%
$t_r = 45°\text{C}$ $v_a = 0\ \text{ms}^{-1}$
$M = 350$ W $I_{cl} = 0.6$ clo
WBGT = 30.4 $\text{WBGT}_{\text{limit}} = 24.4$

$t_a = 30°\text{C}$ RH = 80%
$t_r = 60°\text{C}$ $v_a = 1.5\ \text{ms}^{-1}$
$M = 300$ W $I_{cl} = 0.6$ clo
WBGT = 31.7 $\text{WBGT}_{\text{limit}} = 25.8$

In these three conditions, the PHS model predicts that after 60 min, equilibrium rectal temperatures of 38.1, 37.6 and 37.6°C, respectively, would be reached and that, after 8 h, the total water losses would be about 7, 6 and 5.2 l. These three conditions are therefore indeed not equivalent, although the differences are lower than the DLE figures given above would suggest.

From this, the WBGT appears to play its role of screening method, suggesting that there might be a thermal stress problem. The PHS model can then be used to determine whether there is indeed a heat stress problem and to organise work accordingly.

Figure 11 shows that conditions exist when, on the contrary, the WBGT does not exceed $\text{WBGT}_{\text{limit}}$, while, according to the PHS model, the work duration should be limited. This is the case for instance in the condition for which WBGT=19.6 and $\text{WBGT}_{\text{li-}}$

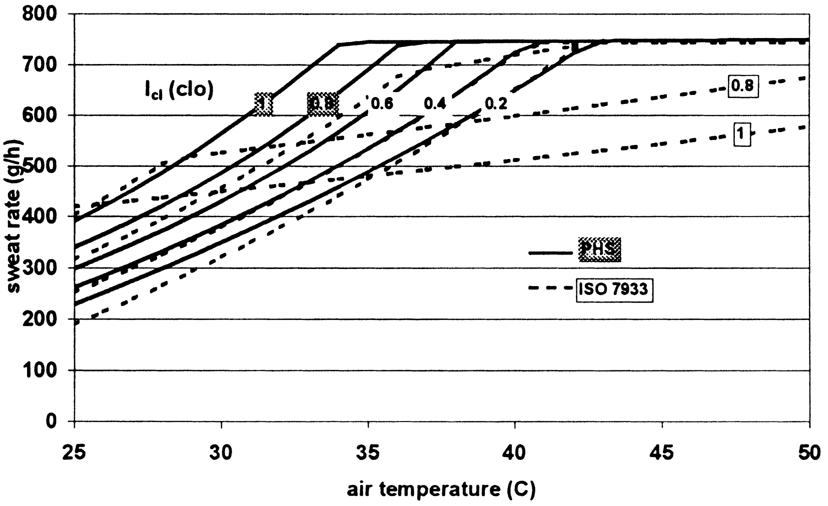

Fig. 10. Evolution of the sweat rate (mean value during the second hour of exposure) as a function of air temperature (t_a) and clothing insulation (I_{cl}).

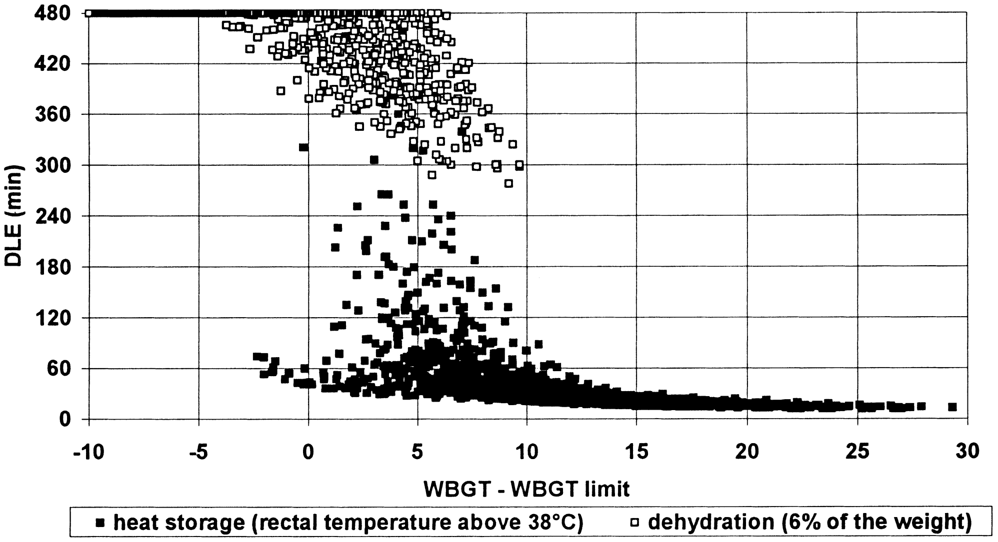

Fig. 11. Comparison between the duration limit of exposure estimated from PHS and the difference between the WBGT index and the WBGT limit in 3680 sets of conditions.

$_{\mathrm{mit}}$=21.6: t_a=20°C, t_r=60°C, RH=20%, v_a=1 ms^{-1}, M=450 W, I_{cl}=0.6. Actually, the PHS model predicts that, in this condition, the rectal temperature reaches 38°C after 53 min but levels at 38.03°C. The DLE for dehydration is equal to 458 min and should be used. All the points in Fig. 11 with negative WBGT difference and $\mathrm{DLE_{PHS}}$ lower than 100 min do indeed correspond to such conditions and therefore should not be interpreted as limitations of the PHS model.

CONCLUSIONS

The Required Sweat Rate prediction model described in ISO 7933 was revised in depth and new algorithms were developed, based on the scientific literature and some new researches, concerning the convective and evaporative exchanges, the skin temperature, the skin–core heat distribution, the rectal temperature and the evaporation efficiency.

The criteria for maximum sweat rate, maximum dehydration and maximum increase in core temperature were revised in a companion paper. This led to the development of a new model, called Predicted Heat Strain (PHS), which makes it possible to predict the actual sweat rate and the rectal temperature for an average subject and to determine Durations Limit of Exposure (DLE) to protect 50% and 95% of the working population.

This PHS model was validated by comparison with data from 672 laboratory experiments conducted previously by the different research partners. The model proved to provide reasonably accurate predictions, taking into account the interindividual differences in thermophysiological response.

The results of the PHS model were also tested in 237 field experiments: the prediction can be considered to be satisfactory considering the fact that the accuracy of the primary data is usually reduced in such conditions.

Both for laboratory and field data, the predictions are clearly more reliable than when using the ISO 7933 Standard. The PHS model was also found to discriminate more than the WBGT index in defining the severity of the potential heat stress.

This PHS model will be proposed for the revision of the ISO 7933 in the coming years.

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