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Assessment of the risk of heat disorders encountered during work in hot conditions

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Abstract ***Objective***: To co-ordinate the work of the main European research teams in the field of thermal factors in order to develop and improve significantly the methods presently available for assessing the risks of heat disorders encountered during work in hot conditions. ***Method***: Each item from the required sweat rate model was reviewed on the basis of the most recent literature. A database with 1,113 laboratory and field experiments, covering the whole range of hot working conditions, was assembled and used for the validation. ***Results***: Influence of clothing ensemble on heat exchange: methods and formulas were developed that take into account the dynamic effects associated with forced convection and the pumping effect associated with body movements and exercise. *Prediction of the average skin temperature:* the model used in the required sweat rate standard ISO 7933 was extended to cover more severe conditions with high radiation and high humidity and different clothing and take into account the rectal temperature for the prediction of the skin temperature. *Criteria for estimating acceptable exposure times in hot work environments:* criteria were reviewed and updated concerning the maximum increase in core temperature and the acceptable water loss, for acclimatised and non-acclimatised subjects. These limits are intended to protect 95% of the population. *Measuring strategy:* a strategy was developed to assess the risks in any working situation with varying conditions of climate, metabolic rate or clothing. A detailed methodology was developed in three stages: an "observation" method for the recognition of the conditions that might lead to thermal stress; an "analysis" method for evaluating the problem and optimising the solutions; and an "expert" method for in-depth analysis of the working situation when needed. *Validation:* the different results were used to prepare a revision of the interpretation procedure proposed in the ISO standard 7933. We validated the modified approaches using the database. This involved the whole range of conditions for which the model was extended, namely conditions with high and low radiation, humidity and air velocity as well as fluctuating conditions. Based on these results, the *predicted heat strain* model was developed: it is presently proposed as an ISO and CEN standard.

Keywords Heat stress · Prevention · Strategy · Indices · ISO 7933

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Introduction

ISO 7933 "*Analytical determination and interpretation of thermal stress using calculation of 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 with sets of data.

Although such comparisons were always limited to the particular set of data, systematic criticisms concerned many components of the standard:

1. Predicted skin temperature (t_{sk}): the ISO 7933 algorithm was proposed in a study by Mairiaux et al. (1987) based on a limited set of data for mainly nude subjects. This t_{sk} prediction was later criticised for decreasing with increasing clothing.
2. Respiratory heat losses: although these losses are quite limited in hot climates, they are often of the same order of magnitude as convective losses. Furthermore, as the heat storage is determined by the difference between the required and predicted evaporation rates, the respiratory losses may become significant. The algorithms used in ISO 7933 had to be confirmed.
3. Prediction of the rectal temperature: as rectal temperature remains, with heart rate, the easiest physiological parameter to record at the work place, a need was identified for it to be predicted directly by the model.
4. Heat storage distribution: for the derivation of a valid estimate of the core temperature (t_{co}), the distribution of the heat storage between the core and the skin layer had to be investigated.
5. Increase in t_{co} due to activity: one main objection to the ISO 7933 method of interpretation was that it did not take into account the normal increase in t_{co} due to activity even in moderate and neutral climate.
6. Evolution of the mean t_{sk} and the sweat rate (SW) with time: by far the main criticism of the ISO 7933 standard was that it assumes that a steady state was reached instantaneously. This made it impossible to predict the situation in cases of intermittent exposure. Furthermore, heat accumulation was assumed to remain the same during the whole exposure, while it obviously tends to 0, towards an equilibrium state in t_{co}. A need was identified for the model to be able to predict the SW, the t_{sk} and the rectal temperature (t_{re}) at any time, taking into consideration all of the past exposure.
7. Evaporation efficiency: ISO 7933 adopted an expression for the computation of the evaporative efficiency as a function of skin wetness. The algorithm used was criticised in recent publications and needed confirmation.

   In addition, the algorithm presented in ISO 7933 assumed that the efficiency remained at 50% when the required evaporation rate E_{req} was greater than the maximum evaporation rate E_{max}. In this case, the predicted evaporation rate was limited quite logically to E_{max}, but the SW was predicted as being equal to $2 \times E_{max}$. For more humid environments, E_{max} was decreasing and, therefore, also the predicted SW: it was predicted that, in extremely humid climates, a subject would sweat less with increasing humidity. This was contradicted by the literature and had to be revised.
8. Maximum wetness: ISO 7933 assumed that the maximum wetness for unacclimatised subjects is limited to 0.85. This had to be confirmed.
9. Limit criteria: ISO 7933 proposed limits for acclimatised and unacclimatised subjects at two levels of protection:
   - "Alarm" level, supposed to protect the entire population.
   - "Danger" level, supposed to protect most of the workers.

These criteria were criticised as being too vague and too stringent and had to be revised. Indeed, as will be discussed later, the t_{co} limit of 38 °C in itself offers a large degree of safety, as heat-strain effects are likely to occur only at temperatures of 39 °C or higher.

10. Maximum sweat rate (SW_{max}): ISO 7933 assumed constant values of SW_{max} for acclimatised and unacclimatised subjects. These values were reduced by a factor of 2 when the metabolic rate was smaller than 65 W/m^2. This discontinuity led to inconsistent results and had to be revised. In addition the "danger" and "alarm" criteria had to be abandoned and new values of SW_{max} proposed.
11. Maximum water loss: the limit values adopted in ISO 7933 were criticised by some researches in the field, particularly in mines, and needed to be revised. Rehydration during exposure has been taken into account to estimate the maximum water loss.
12. Limit of t_{co}: the limit of 38 °C commonly adopted and implicitly adopted in ISO 7933 was specified for the first time in a WHO document in 1969 (WHO 1969). Since then, this document was often quoted and the 'quotation' altered. A revision of the basis of this limit and of the protection that it offers was necessary.

Objectives

The specific objectives of the research project were therefore:

1. To design and validate a strategy for the assessment of the strain 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 working environment.
2. To extend the validity of the present modelling on the role of the clothing.
3. To improve the validity of the present indices in case of high radiation, high humidity or high air velocity.
4. To better define the criteria for the determination of the maximum allowable exposure duration and in particular the interindividual differences in sweating rate, evaporation efficiency, water loss and increase in t_{co}.

These different objectives will be addressed below.

Strategy in three levels for the management of the thermal working conditions

Introduction

One of the main reasons for the lack of risk prevention in industry, and particularly in small and medium size enterprises, is the cost of the assessment studies. In the majority of the cases, simple prevention/control measures can be taken directly by the employers and the workers themselves, once they are aware of the problem. In a few cases a more detailed study of the work situation is needed with the assistance of persons trained in occupational health and safety. In even fewer situations, the assistance of experts is required. With this in mind, a strategy in three stages was developed for the management of the thermal working conditions. All stages are strictly orientated towards prevention, as the main objective of the assessment of the risks linked to the thermal working environment is not to quantify the risks, but to prevent or to eliminate, or at least to reduce these risks.

Stage 1: "observation"

The first stage is designed to be used by people from the company and, possibly, by the workers themselves. Therefore, it has to be easily understood even by untrained people. It must take advantage of what the users know best, that is, their working conditions, the technical process, the characteristics of the heat or cold sources and the possibilities for control measures. This method, therefore, acknowledges explicitly the competence and the skill of the workers and deliberately relies on them to improve the working conditions. It simply helps them to structure and systematise their approach, so that it is not solely based on perceptions and opinions. At the end of the "observation", the user should be able to determine whether a more thorough "analysis" is necessary or not. Work was performed in the research project to develop worksheets to describe and evaluate working conditions as well as to assist in finding solutions for existing problems. These worksheets were improved, based on a validation study conducted with the participation of 53 potential users.

Stage 2: "analysis"

The second stage is designed to be used by occupational health specialists, that is, by occupational physicians, occupational hygienists, ergonomists, safety engineers... with general training in the management of heat problems. It still uses concepts and techniques commonly accepted in the field, avoiding, therefore, more "scientific" considerations. When necessary for prevention, it requires measurements with instruments inexpensive, easy to use and readily available in the field. It remains orientated towards prevention and, therefore, uses measurements and indices that make possible to best identify the causes of the problems and the means to solve them. At the end of the "analysis" the user should be able to determine whether more thorough "expertise" is necessary or not.

Stage 3: "expertise"

This stage might be needed in very complex cases for which satisfactory solutions could not be found, even after a detailed "analysis". The methodology to be used, the measurements to be made and the evaluation to be performed vary, depending on the problem. In addition, this stage will be carried out with the help of experts who should be able to decide the best procedure to collect the information indispensable to solve the problem. Therefore, there does not exist one unique expert method. The document is limited to what this "expertise" study should obviously include and report.

Conclusion

The final version of the strategy was prepared and validated in the field with the contribution of 53 potential users.

This strategy (Malchaire et al. 1999) with three stages is proposed for the management and control of working conditions with thermal problems. It rests on two basic principles:

- It is *participative*: the workers play the essential role in the dynamics of the improvement of the working conditions. Occupational health specialists and experts are there to help these workers to find the solutions.
- It is *structured* in three stages, which require complementary knowledge and competencies.

Influence of the clothing on convective heat transfer

Convective heat loss is an important part of the heat loss from the human body, especially in moderate climates. An important aspect of convective heat transfer is the effect of wind speed and movements on the convective heat transfer coefficients of the surface air layer and the clothing.

Tables in ISO 9920 (1995) give static insulation values of different clothing ensembles. One aspect of clothing in convective heat transfer is that the area of heat exchange at the clothing surface is larger than at the body surface. This increase in surface area is called the clothing area factor (f_{cl}) and is determined by:

$f_{cl} = 1 + 1.97 \times I_{cl} (I_{cl} \text{ in } m^2K/W)$

The present research project mainly focussed on the combined effect of movement and wind on the surface air layer and the clothing insulation. In the literature the clothing efficiency factor, F_{cl}, has been introduced, which is the ratio of the nude insulation to the clothed insulation:

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

In this way it was aimed to incorporate the effect of wind and movements on clothing insulation. However, F_{cl} only incorporates the effects of wind on the surface air layer ($h_c + h_r$) and not on the clothing itself.

It was aimed to add the effects of effective air velocity on the clothing insulation (I_{cl}). Holmér et al. (1999) have suggested different correction equations, based on human experiments and manikin measurements. During the project, the experimental data from two laboratories were merged and analysed together. As a result (Parsons et al. 1999), the following equations were derived for the effects of effective wind velocity on the surface air layer and on the clothing insulation:

$$CORR_{Ia} = EXP^{(0.047 \cdot Vair^2 - 0.472 \cdot Vair + 0.117 \cdot Vwalk^2 - 0.378 \cdot Vwalk)}$$

$$CORR_{IT} = 1.044 EXP^{(0.066 \cdot Vair^2 - 0.398 \cdot Vair + 0.094 \cdot Vwalk^2 - 0.378 \cdot Vwalk)}$$

with V_{air} being the relative air speed (< 3 ms^{-1}) and V_{walk} walking speed (< 1.2 ms^{-1}).

If movement did not consist of walking, an alternative calculation of air speed, incorporating the movement effects is used:

$V_{eff} = V_{air} + 0.0052(M - 58)$

This V_{eff} replaces V_{air} in the equations, and v_{walk} is set to 0.

The new "predicted heat strain" model requires the static clothing insulation as an input variable. Within the model, the clothing insulation is handled as follows:

- Based on the values for the relative wind speed and the work intensity provided by the user, the reduction factors of insulation of the surface air layer and the clothing are calculated ($CORR_{Ia}$ and $CORR_{IT}$).
- For nude subjects, $CORR_{tot} = CORR_{Ia}$
- When $I_{cl} > 0.6$ clo $CORR_{tot} = CORR_{IT}$
- For $0.2 < I_{cl} < 0.6$ clo $CORR_{tot} = (0.6 - I_{cl}) \times CORR_{Ia} + I_{cl} \times CORR_{IT}$
- This correction factor is used by the model to calculate the dynamic clothing insulation: $I_{T\ dynamic} = CORR_{tot} \times I_{T\ static}$
- These corrected values for the total insulation are then used to calculate the convective heat loss from the subject.

Influence of the clothing on evaporation

During heat exposure, heat loss from the human body is strongly dependent on evaporative heat loss for the maintenance of thermal balance, which itself is a function of the clothing characteristics.

In ISO 9920 (1995) the derivation of evaporative resistance R_T using the permeability index i_m is described by

$$R_T = \frac{I_T}{i_m \cdot L} = \frac{0.06}{i_m} \left(\frac{I_a}{f_{cl}} + I_{cl} \right)$$

thus, when i_m and the clothing insulation I_T are known, the vapour resistance can be calculated. ISO 9920 provides i_m values for typical clothing configurations, with a rule-of-thumb i_m of 0.38 for normal one or two-layer permeable garments.

Within this research project, the calculation of clothing insulation was improved, the table for i_m was extended, and the effects of wind and movement on i_m were studied, which resulted in an empirical model for this relationship (Havenith et al. 1999). Using this approach for the determination of dynamic heat and vapour resistance, the total procedure would then be to:

- Provide as input to the model, the static heat resistance, and the relative air and walking speeds, from which the model will calculate a correction factor and dynamic heat resistance as described above.
- Estimate the static vapour permeability i_m(from example tables).

The model will then determine $i_{m\ dynamic}$ based on the correction factor for dry heat loss (Havenith et al. 1999, 2000),

$$i_{m\ dynamic} = (4.9 - 6.5 \cdot CORR_{IT} + 2.6\ CORR_{IT}^2) \cdot i_{m\ static}$$

with $CORR_{IT} > 0.4$ and $i_{m\ dynamic}$ limited to 0.9

- From this, calculate $R_{T\ dynamic}$

$$R_{T\ dynamic} = \frac{i_{T\ dynamic}}{i_{m\ dynamic}\ 16.7}$$

Prediction of the skin temperature

Introduction

The model used in the required sweat rate index (ISO 7933 1989) for predicting the mean t_{sk} was criticised for not being valid in conditions with high radiation and high humidity. The aim of the present study was to improve the prediction model using a very large database.

Material and methods

A common structure was defined to pool into one database, 1,113 different data files from experiments run previously by the partners, with minute-by-minute values of ten parameters of stress and strain. Data points in steady-state conditions were selected from the experiments. Each observed t_{sk} was a weighted average of at least four local measurements. As few data (fewer than 10%) were available for women, it was decided to derive the t_{sk} prediction model using only the data from studies on men. Accordingly, the final TSK database included 1,999 data points from 1,399 conditions with 377 male subjects.

The analysis was performed separately for nude ($I_{cl} \leq 0.2$ clo) and clothed ($0.6 \leq I_{cl} \leq 1.0$ clo) subjects. The final TSK database was then split into 1,212 data points for nude subjects and 787 data points for clothed subjects.

The relationship between the mean t_{sk}, the primary parameters, the metabolic rate and the t_{re} was assumed to be an additive model. A bootstrap method was used for the multiple correlation analysis (1,000 samples) (Mehnert et al. 2000).

Results

The nonparametric bootstrap for the subset of nude subjects yielded a prediction model without the metabolic rate being statistically significant:

$$t_{sk} = 7.19 + 0.064t_a + 0.061t_r + 0.198p_a - 0.348v_a + 0.616t_{re}$$

The multiple correlation coefficient between observed and predicted values is equal to 0.86, and 83.3% of the predicted t_{sk}s are within the range of ± 1 °C of the observed values.

The following prediction model was obtained for the clothed subjects:

$$t_{sk} = 12.17 + 0.020t_a + 0.044t_r + 0.194p_a - 0.253v_a + 0.00297M + 0.513t_{re}$$

Although the correlation coefficient (0.77) is lower than for the nude subjects, 81.8% of the predicted values are within the range of ± 1 °C of the observed values.

Conclusion

This part of the project was aimed at deriving an improved model for the prediction of the mean t_{sk} in warm and hot environments. The resulting models are based on the largest database ever assembled for that purpose, from nine research laboratories all over Europe and in a wide range of ambient conditions. It can, therefore, be anticipated that the model will be valid for most situations in industry and for the general working population. In particular, the present models extend the validity to conditions with high radiant heat load or high humidity. As few data were available in the database for clothing insulation values in the range 0.2 to 0.6 clo, a linear interpolation between the prediction for nude and for clothed subjects will be used.

Modifications brought to the required sweat rate index

Respiratory evaporative and convective heat losses

Based on the work done by Livingstone et al. (1994) and Varene (1986), the following expressions were derived (with respiratory convective (C_{res}), respiratory evaporative E_{res} heat losses and M in watts or in Wm^{-2}).

$$C_{res} = 1.5210^{-3}M(28.6 + 0.641p_{a,in} - 0.885t_{in})$$

and

$$E_{res} = 1.2710^{-3}M(59.3 + 0.53t_{in} - 11.63p_{a,in})$$

Mean body temperature

From papers by Kähkönen (1993) and Colin et al. (1971), it is assumed that the relationship between the "mean body temperature" (t_b), the rectal (t_{re}) and the t_{sk} takes the form: $t_b = \alpha\ t_{sk} + (1\text{–}\alpha)t_{re}$, with:

- $\alpha = 0.30$ for $t_{re} < 36.8$ °C
- $\alpha = 0.10$ for $t_{re} \geq 39$ °C
- α varies between 0.3 and 0.1 according to: $\alpha = 0.3\text{–}0.09(t_{re}\text{–}36.8)$.

Prediction of the rectal temperature from the mean core temperature

According to Edwards et al. (1978), the t_{re} and oesophageal temperature (t_{oe}) are linked by an expression such as:

$$t_{oe} = a\ t_{re} + b\frac{dt_{re}}{dt} + c$$

where dt_{re} is the increase in t_{re} from one minute to the next.

From the database it was found that $t_{oe} = 1.31 + 0.962t_{re} + 7.03dt_{re}$.

Assuming that $t_{co} = (t_{oe} + t_{re})/2$, the following expression was derived:

$$t_{re} = t_{re0} + (2t_{co} - 0.962tr_{e0} - 1.31)/9$$

Exponential averaging for t_{sk}, SW

As shown by Malchaire (1991), the t_{sk} and SW at time i can be computed according to the following expression:

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

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, k =

exp $(-\Delta t/\tau)$, and τ is the time constant (in minutes): 3 min for t_{sk} and 10 min for SW.

Evaporative efficiency of sweating

Hettinger et al. (1985) proposed an expression for the prediction of the evaporative efficiency of sweating (η) from the skin wetness (w). This expression is very close to the recent data from Alber-Wallerström and Holmér (1994) and confirms the expression adopted in the current ISO Standard 7933 (1989) for a required skin wetness smaller than, or equal to, 1.

Problems, however, occur under very humid conditions where, according to this expression, a subject would sweat less. This is contradicted by the results of Zintl (1979) and Kohler (1976). Therefore, the fact must be questioned that the sweating efficiency becomes and stays equal to 0.5 regardless of the sweating, as soon as the surface is completely wet. The skin being 100% wet puts a limitation on the magnitude of the effective skin to ambiance water vapour pressure gradient. However, the ratio between the required evaporation and the maximum evaporation can still be greater than 1, and this is a strong stimulus for additional sweating. Therefore, the layer of water on the skin can increase if the air humidity increases and the efficiency will continue to decrease. The relationship can then be described by

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

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

$$\text{and} \quad \eta = 0.005 \quad \text{for} \quad w \geq 1.7\,.$$

The predicted evaporation rate remains estimated using w limited to w_{max}:

$$E_p = w \times E_{max}$$

while the predicted SW is a function of η calculated above:

$$SW_p = E_p/\eta.$$

Maximum wetness limit for non-acclimatised subjects

Based on works by Candas et al. (1979) and Alber-Wallerström and Holmér (1985), the value of 0.85 presently used in ISO 7933 for the maximum wetness is confirmed.

Maximum sweat rate

Based on the publications by Gosselin (1947) and Araki et al. (1979), it is suggested that the maximum sweat rate be estimated using the expression $SW_{max} = 2.6(M-58)$ g/h (with M expressed in watts) in the range from 650 to 1,000 g/h.

For acclimatised subjects the sweating in a given environment is known to be greater, and many researches report an increase of the SW by a factor of 2 compared with unacclimatised subjects. This, however, does not refer to the maximum capacity for sweating. Excluding the studies for which the maximum capacity was not reached, it appears that the SW_{max} would increase only, on average, by a factor of 25% for acclimatised subjects (Havenith 1997).

Increase in core temperature associated with M

According to Saltin and Hermansen (1966), in a neutral condition, the equilibrium t_{co} at a given metabolic rate is: $t_{cor} = 0.002M + 36.6$ (M expressed in watts), and t_{co} reaches t_{cor} with a time constant of about 10 min.

It can be assumed that the body does not attempt to loose this heat store and therefore does not sweat. Therefore SW_{req} is not determined from E_{req} but from $E_{req}-dS_R$, where dS_R is the heat accumulated at a given time to reach this equilibrium temperature.

Limit of internal temperature

The WHO technical report No 412 published in 1969 stated: “it is inadvisable for deep body temperature to exceed 38 °C in prolonged daily exposure to heavy work”. This 38-°C value was proposed for the average subject, so that the probability of a particular subject suffering from any heat disorder is negligible.

From work by Wyndham et al. (1965), two maximum t_{re}s could be adopted (Malchaire et al. 2000):

- 39.2 °C, which “may rapidly lead to total disability in most men with excessive, often disturbing, physiological changes”.
- 42 °C: the maximum internal temperature to avoid any physiological sequels.

The probability for reaching these temperatures might be limited as follows:

- For 42 °C: Less than 10^{-6} (less than one severe heat stroke every 4 years among 1,000 workers) (250 days/year)
- For 39.2 °C: Less than 10^{-3} (less than one person at risk among 1,000 shifts).

From data by Wyndham and Heyns (1973) and Kampmann (1997a), it was found that the t_{re} should be limited to 38 °C, as suggested by the WHO document, to reach these low probabilities.

Maximum dehydration and water loss

Candas et al. (1985) reported that 3% dehydration induces increased heart rate and depressed sweating sensitivity. The 3% value can then be accepted as the maximum dehydration in industry (not in the army or for sportsmen). Kampmann (1997b) reported, in hot working conditions in coal mines with exposure lasting 4 to 8 h, an average rehydration rate of 60%, regardless of the total amount of sweat produced (ranging from 1,000 to 6,000 g). Considering only the total sweat losses per shift greater than 2,000 g, these data show that 95% of the subjects had a rehydration rate greater than 40%.

Based on these figures, it can be assumed that the maximum water loss is equal to

- 3%/(1–0.6) = 7.5% of the body mass for an average subject.
- 3%/(1–0.4) = 5% of the body mass for 95% of the working population.

Conclusion

As the modifications from the required sweat rate index are so numerous, and to avoid any confusion, it was decided to rename the analysis and interpretation model. The name "predicted heat strain" (PHS) was chosen, as the new model tends to predict the SW and the t_{re} minute-per-minute as a function of the working conditions (Malchaire et al. 2001).

Validation of the predicted heat strain model

Selection of the data points

The data gathered from the eight partners led to a database that included 1,113 laboratory and field experiments with the minute-per-minute data collected for the primary parameters (t_a, p_a...) and for the physiological factors (t_{re}, SW...).

Most of them concerned men (1,020) and 452 non-acclimatised persons exposed, for 661 acclimatised. More than 50% of the laboratory experiments concerned nude subjects (clo ≤ 0.2), while 95% of the field experiments were for clothed workers (clo≥0.5).

From the 95% confidence intervals of the primary parameters, it was concluded that the model will only be valid for the parameters in the ranges given in Table 1.

Data points were selected using the following criteria:

- For the SW: only use the mean SW over the whole experiment.
- For the t_{re}, selection of one datum point/h in each experiment.

Validation in laboratory experiments

Table 2 gives the results of the linear regressions between the observed and predicted values of t_{re}s and SW s for laboratory and field experiments.

Computations were made in polar co-ordinates in order for the uncertainty to be proportional to the SW.

The equation of the mean polar line is: $SW_{obs} = 0.918\ SW_p$ (g/h) with the 95% confidence interval of the slope being (0.540–1.523) and the mean difference between observed and predicted values equal to –27.5 ± 114.1 g/h. Seven points were actually outside the upper limit of the 95% confidence interval. They came from three different partners and demonstrated the influence of interindividual differences. Indeed, for identical experiments but with other subjects, the data were above or below the regression line and in the confidence interval.

The same comparison was conducted between the observed and predicted t_{re}s.

The equation of the mean polar line was: $t_{re\ obs} = 1.000\ t_{re\ p}$ (°C), with the 95% confidence interval of the slope being (0.980–1.020) and the mean difference between observed and predicted values equal to –0.01 ± 0.39 °C.

Again, the points outside the 95% confidence interval were due to interindividual differences.

Validation in field experiments

The accuracy of the climatic and physiological measurements was lower for experiments in the field. Therefore, the correlations between observed and predicted values were lower and the 95% confidence intervals greater.

The equations of the mean polar line were:

$$SW_{obs} = 0.851\ SW_p\ (g/h)$$

with the 95% confidence interval of the slope being (0.328–1.936) and the mean difference between observed and predicted values equal to –26.7 ± 125.1 g/h, and

$$t_{reobs} = 1.000 t_{rep} (^\circ C)$$

with the 95% confidence interval of the slope being (0.981–1.019) and the mean difference between observed and predicted values equal to –0.01 ± 0.36 °C.

Comparison between the predicted heat strain model and the ISO 7933 standard

The modifications brought to the required sweat rate model as it is in ISO 7933 are so important that the

Table 1 Ranges of validity of the PHS model

Parameter	t_a (°C)	p_a (kPa)	t_r–t_a (°C)	v_a (m/s)	M (W)	I_{cl} (clo)
Minimum	15	0	0	0	100	0.1
Maximum	50	4.5	60	3	450	1.0

comparison with the new PHS model is not relevant. SWs and t_{re}s are not predicted anymore for an ''alarm'' level and a ''danger'' level, but are for a mean subject. Therefore, 50% of the workers are expected to suffer from higher heat strain than predicted. This ''not relevant'' comparison will still be done, since it is important for the users in industry to know whether the PHS model results in different and more realistic predictions than the required sweat rate model of ISO 7933. As ISO 7933 predicts only the SW and not the t_{re}, comparisons of the two models will be restricted to the predicted SWs.

SW predicted by the PHS model and by ISO 7933 (''danger'' level) are compared. Table 3 gives the results of the linear regressions between the observed and the predicted SWs.

The PHS model gives clearly better predictions, particularly for the field experiments, the correlation explaining 55% of the total variance instead of 27%.

The improvements brought by the PHS model are not totally reflected by these statistics. Indeed, in particular cases, the averages of the SW_{ISO} and SW_{PHS} min-per-min values over the entire experiment can be about the same, and according to the regression analysis performed above, both models would then be considered as equally valid. This is obviously not the case when the evolution during the experiment is considered, as 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 between the predicted heat strain model and the wet bulb globe temperature index

The DLE were computed with the PHS model in 3,680 sets of conditions with the primary parameters varying in the range indicated in Table 4. The clothing insulation was held constant at 0.6, as the wet bulb globe temperature (WBGT) index is valid only for this value.

At the same time, the WBGT and $WBGT_{limit}$ were computed for the same conditions according to ISO 7243 (1982).

This WBGT limit was computed using

$$WBGT_{limit} = 34.3 - M/35.5 \text{(with M in watts)}.$$

Figure 1 compares the DLE_{PHS} with the ($WBGT-WBGT_{limit}$) differences. A negative difference means that the work may be performed continuously. A positive one implies, according to ISO 7243, that rest and recovery periods must be organised. Most of the DLE lower than 4 h are in conditions for which the WBGT difference is positive. In these conditions, according to the WBGT index, work cannot be pursued continuously

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

Parameter	Laboratory experiments	Field experiments
Sweat rate (g/h)		
n	672	237
Observed (mean ± SD)	424 ± 172	317 ± 187
Predicted (mean ± SD)	451 ± 154	344 ± 132
Slope	0.848	1.056
Intersection	41	–46
r	0.76	0.75
Alpha	0.918	0.851
Alpha CI95%	0.540–1.523	0.328–1.936
Obs–pred (mean ± SD)	–27.5 ± 114.1	–26.7 ± 125.1
Rectal temperature (°C)		
n	1,937	1,028
Observed (mean ± SD)	37.45 ± 0.47	37.40 ± 0.44
Predicted (mean ± SD)	37.46 ± 0.47	37.40 ± 0.34
Slope	0.664	0.770
Intersection	12.57	8.60
r	0.66	0.59
Alpha	1.000	1.000
Alpha CI95%	0.980–1.020	0.981–1.019
Obs–pred (mean ± SD)	–0.01 ± 0.39	–0.01 ± 0.36

Table 3 Linear regressions between the observed and the predicted sweat rates

Parameter	Laboratory experiments ($n = 672$)			Field experiments ($n = 237$)		
	Slope	Intersection	r	Slope	Intersection	r
ISO 7933	0.757	75	0.744	0.663	52	0.523
PHS model	0.848	41	0.760	1.056	–46	0.745

and 1-h work-rest regimens must be organised. 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 1 shows that conditions exist when, on the contrary, the WBGT does not exceed $WBGT_{limit}$, while, according to the PHS model, the work duration should be limited.

This is the case, for instance, in the condition:

$$t_a = 20\,°C, t_r = 60\,°C, RH = 20\%, v_a = 1\,m/s,$$
$$M = 450\,W, I_{cl} = 0.6\,clo$$

for which WBGT = 31.7 and $WBGT_{limit}$ = 21.6.

Indeed, t_{re} = 38 °C is reached after 53 min, but levels out at 38.03 °C. The DLE for dehydration is equal to 458 min and should be used. All the points in fig. 1 with negative WBGT difference and DLE_{PHS} lower than 100 min correspond to such conditions and should not, therefore, be interpreted as limitations of the PHS model.

Table 4 Ranges and steps of variation of the six primary parameters in Fig. 1

Parameter	Range	Step	Number of values
Air temperature (°C)	20–50	5	7
Relative humidity (%)	20–80	20	4
(t_r–t_a) (°C) (but t_r limited at 60 °C)	0–40	10	< 5
Air velocity (ms^{-1})	0.01–2	0.5	5
Metabolic rate (W)	100–450	50	7
Clothing insulation (clo)	0.6	–	1

Conclusions: social value of the project

As a result of the research, occupational health specialists have available comprehensive methods, not only to assess accurately the risks of heat disorders that workers might encounter while working in hot conditions, but also to protect the workers. The results of the joint research should make it possible to reduce the cost of work accidents in industry as well as the cost of medical care due to morbidity contracted at the workplace.

These methods should make it possible to guarantee the same level of safety and health in all industries in all countries and, in particular, in the southern countries that are directly concerned by these working conditions. The development of more adequate standards will, therefore, pave the road towards a specific directive concerning the assessment of hot working conditions or, at least, clarify the requirements of the European directive EC 89/654 (1989) concerning the minimum safety and health requirements for workplaces.

The social impact was mainly the establishment of better working conditions and the prevention of accidents such as heat cramps and heat strokes at the workplaces, in particular in countries where hot working conditions are omnipresent.

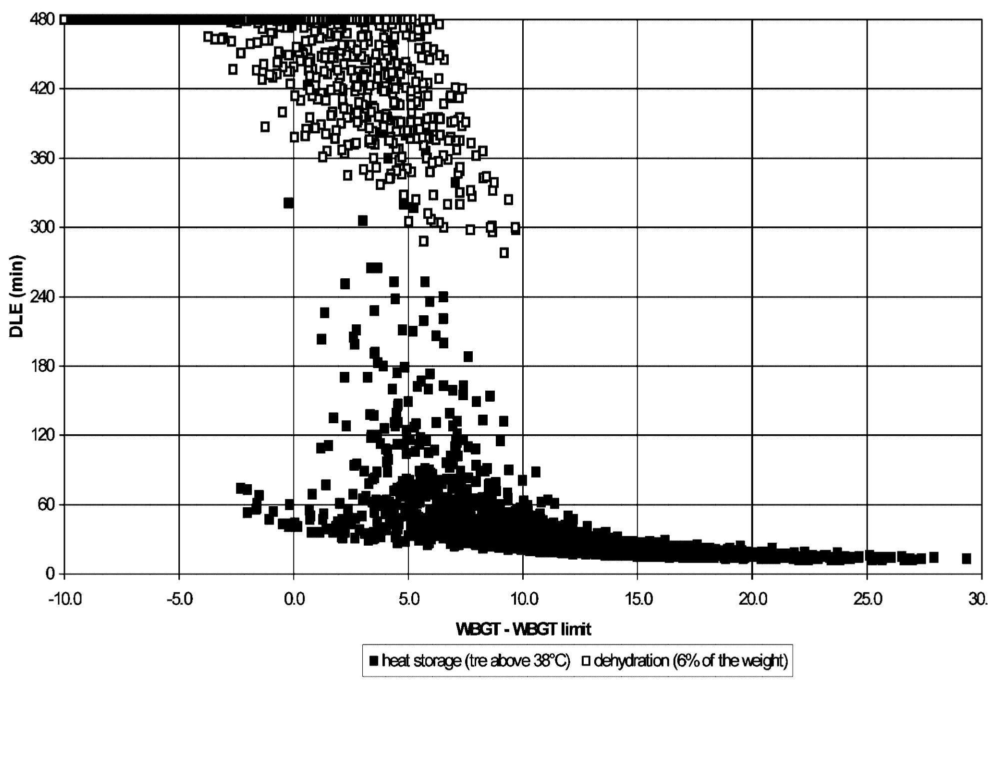

Fig. 1 Evolution of the PHS model duration limit of exposure (lowest value between dehydration and heat storage DLE), according to the difference between the WBGT index and the WBGT limit (ISO 7243)

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