Methodology of investigation of hot working conditions in the field

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

Abstract

The paper describes the methods used by the different teams contributing to the interlaboratory validation study for assessing the primary parameters (temperature, humidity, radiation, air velocity, metabolic rate and clothing) of the hot environments and the physiological constraints resulting from them (core temperature, sweat rate, heart rate). It draws the attention to the practical problems and issues that need to be addressed when selecting a monitoring method (zonal or ambulatory method), when choosing appropriate instruments or again when opting for a specific heat strain index.

Key words: heat stress, measurements

Résumé

Cet article décrit les méthodes utilisées par les différentes équipes de recherche ayant participé à la recherche interlaboratoire des indices climatiques, pour évaluer les paramètres primaires (température, humidité, rayonnement et vitesse de l'air, métabolisme et isolement thermique vestimentaire) des environnements chauds et les astreintes physiologiques qui en ont résulté (température centrale, débit sudoral et fréquence cardiaque). Il attire l'attention sur les problèmes et difficultés pratiques qui doivent être pris en considération lorsqu'une méthode de surveillance est sélectionnée (méthode par zones ou ambulatoire), lorsque les appareils de mesurage les plus appropriés doivent être choisis ou encore lorsque l'on opte pour un indice climatique spécifique.

Mots Cléfs: contrainte thermique, mesurage, indices

1. Introduction

The prediction of heat stress at a given workplace requires

1. the measurement of the climatic parameters: air temperature (t_a, °C), mean radiant temperature (t_r, °C), partial vapour pressure (P_a, kPa) and air velocity (V_a, m/s);
2. the determination of the mean characteristics of the exposed workers: metabolic rate (M, W.m^{-2}), clothing thermal insulation (I_{cl}, Clo), as well as, according to the index that is going to be used, the degree of heat acclimatization, the fraction of the body area exposed to radiation, etc.

All of these data can be determined relatively easily for some types of workplaces where ambient characteristics are constant in time and space and where work is performed continuously. This is especially the case in underground mines.

However, for most situations involving exposure to heat and, in particular, in the steel industry, both climatic and metabolic parameters fluctuate with the degree of exposure and therefore require monitoring. In such cases, it is necessary to determine at any time or for successive time intervals the parameters mentioned above.

Various approaches have been used for this purpose by the different research teams involved in the study on the validation of heat stress indices. The aim of the present report is to present these different methodological approaches, to underline their conditions of use and to propose guidelines for the development of a procedure for data collection in the field.

The heat stress indices can be validated only by comparing their values based on physical quantities with the measurements of strain suffered by workers.

This can be done by measuring either the weight loss (which should reflect the sweat loss of the worker), or the increase in core temperature, or the increase in heart rate at rest. The methods used by the different research teams will be compared and general recommendations formulated.

This paper is based on the following research reports:

1. Hettinger, Th. et al., 1986, Quantification of the heat stress indices for the evaluation of the climatic load in the steel and metal industry. This report will be referred to as the BUW report.

2. Vogt, J.J., 1986, Campaign for the comparison of the validity of the main heat stress indices (INRS report);
3. Malchaire, J., 1986, Validation of the heat stress indices for the prediction of heat strain and of the allowable exposure durations (UCL report).

2. Taking account of temporal and spatial climatic variations

Two methods were used in order to take into account temporal and spatial variations of climatic parameters:

1. characterization of working zones;
2. ambulatory measurements of the parameters.

2.1. *Characterization of working zones (INRS, BUW)*

The method used by the INRS team consisted of dividing the working area into zones where climatic conditions were constant. The thermal mapping, made at the beginning of the shift, was modified if necessary during the observation period in order to adapt it to temporal variations of the climatic parameters. From the chronology of the periods spent by workers in the different zones, it became possible to determine the climatic parameters of exposure minute by minute.

The method used by the BUW team followed the same principle. The zones were, however, fixed spatially once and for all and characterized, where appropriate, by physical quantities varying with time. Once again, knowing where the worker was at a certain time made it possible to determine the conditions of exposure at that time.

This method requires that climatic parameters be determined beforehand in the whole working area, that this area be divided into elementary zones and that climatic conditions be monitored in each of them.

2.2. *Ambulatory measurements*

The method used by the UCL team consisted of following the worker and measuring all the parameters where he was working, at any time. This method does not require any temporal or spatial division of the working area but might, in some cases, interfere with the normal progress of work.

2.3. *Comparison and selection criteria*

The method of division into working zones can be very practical for workplaces involving little moving around and slight climatic variations in time and space. It is assumed that the climatic parameters take the same values at any point inside a zone but vary at the dividing line. For this assumption to be valid and the discontinuity between two zones to be slight, the number of zones might in some instances be very high. Furthermore, the monitoring of the parameters over time should be done constantly in each zone; as this is not feasible, it is done periodically. Interpolations between consecutive values must then be made assuming a linear variation with time. This method might thus prove to be very difficult, or event impracticable, in situations such as those frequently met in the steel industry, with intense, directional and fluctuating radiation. In such cases, the ambulatory method of measurement is simpler to use in principle. It will also be simpler in practice and will result in more accurate estimates of exposure conditions, providing suitable measuring equipment is used.

3. Measurement of climatic parameters

Table 1 describes the main characteristics of the instrumentation used by the different teams for measuring the climatic parameters in the field (BUW, INRS and UCL studies).

3.1. *Air temperature*

Few problems were encountered concerning the measurement of air temperature: the equipment consisted of transducers whose precision and time constant complied with the specifications of ISO Standard 7726.

3.2. *Humidity*

The measurement of air humidity appeared to be more difficult. Wet bulb temperature transducers may only be used in stable conditions as the response time constants are very high, of the order of 3 minutes. For ambulatory measurements, faster transducers must be used, such as those of relative humidity based on the principle of thin film capacity.

3.3. *Radiation*

The measurement of thermal radiation and of the mean radiant temperature proved very difficult when radiation conditions were spatially heterogeneous and temporally variable. Conventional transducers (such as the 150 mm - diameter black globe thermometer) are found to be inappropriate as their response-time constant is very long. This time constant actually varies with the thermal capacity of the globe and of its temperature sensor, and therefore might be very different from one instrument to another. consequently, the apparent "averaging" made by the instrument may not be reliably used in order to simulate the averaging performed by the human body exposed to radiation. The EXATEST steradiometer used by the BUW and UCL teams is only a last-resort solution, the instrument being also significantly influenced by convection and the conversion into mean radiant temperature being accurate only after calibration of the instrument and for radiation conditions which are not very heterogeneous spatially. The development of new transducers appears to be essential in this field: this subject is treated separately in this special issue (see paper by Hettinger and Muller).

3.4. *Air velocity*

The problems not solved by the ordinary air velocity transducers (hot-wire and rotating-vane anemometers) concern directivity, spatial and temporal averaging and dynamic range.

- Directivity: the marking of the air-flow direction using a smoke-producing device is only possible when measuring at a fixed point, and the measurement of air velocity in three orthogonal directions may be a solution only when vectorial addition is valid, a fact that must be verified for each configuration of transducers.
- Spatial and temporal averaging: as air velocity might vary greatly in space and time, instantaneous and spot measurements might not be very representative of the exposure conditions. This may be particularly true for ambulatory measurements.
- Dynamic range: hot-wire anemometers are generally limited to the range of 0 to about 2 m/s, while vane anemometers are appropriate in the range of 0.1 to 3 m/s and therefore cover both ranges. Hot-wire anemometers are, however, the most appropriate ones.

Here again, the development of more suitable transducers is needed.

Attention must be drawn to the fact that air velocities measured according to the two survey methods are not strictly comparable. In the zone method, the absolute velocity is always measured, whereas, in the ambulatory method, the relative velocity is measured (provided the transducer is properly oriented) while the worker is moving. This difference can hardly be taken into consideration for the computation of the indices but is unlikely to result in additional inaccuracy as these indices either do not consider the increase of velocity due to the activity (WBGT, ET, etc.) or include a correction factor as a function of the metabolic rate, whatever the activity might be (SW_{req}).

3.5. *Sampling technique*

The sampling technique depends on the method used to take into account temporal and spatial variations, as well as the response time constants of the instruments used. As discussed above, the zone method makes possible for virtually constant conditions, spot checking at differing time intervals. The ambulatory method, on the other hand, requires systematic sampling at short time intervals (of about one minute) of the average value of each parameter during that time interval.

In the absence of specific instruments, only continuous recording of all climatic parameters makes it possible subsequently to achieve this objective (BUW). The solution adopted by the UCL team (two measurements per minute, averaged over 4 seconds) is only a compromise.

3.6. *Measuring points*

ISO Standard 7726 recommends the measurement of all climatic parameters at three heights, in order to determine weighted mean values characterizing the exposure over the whole surface of the body. Such measurements can be taken statically, as is the case when the zone method is used (BUW, INRS), but they are not feasible when the ambulatory method is adopted, and values can only be recorded for the trunk.

3.7. *In practice*

The measuring techniques used by the different research teams are clearly more sophisticated and closer to laboratory techniques than those which will generally be used by practitioners in the field. The criteria for choosing measuring instruments are as follows:

1. transducers with short time constants, of the order of 10 seconds;
2. accuracy according to ISO Standard 7726;
3. suitable dynamic range for the working situation;
4. possibility for continuous graphic or analog recording of the signals;
5. omnidirectional transducer for the measurement of air velocity or, when not available, measurements after identification of the most probable air-flow direction.

4. Thermal insulation of clothing

The different research teams used the tables of thermal insulation of clothing ensembles or of individual garments either from DIN Standard 33403.8 (BUW) or from Olesen and Nielsen (1983 (INRS and UCL), the latter being used for the ISO draft Standard "Estimation of the thermal characteristics of a clothing ensemble". The effective thermal insulation values were adopted. The data given in the ISO Standard, when published, should be used in practice.

5. Metabolic rate

The technique used by the BUW team consisted of measuring the oxygen consumption (VO_2) for each particular activity performed by the worker and calculating the metabolic rate for each minute by time-weighting the metabolic rates of the activities performed during that minute. This technique might prove highly impractical when the number of activities is large and the work is not repetitive.

The main technique used by the INRS team consisted of:

1. measuring VO_2, 2 to 4 times per shift (during periods varying from 8 to 20 minutes, according to possibilities);
2. simultaneously recording heart rate values (HR);
3. determining, using linear regression, the general relationship between HR and VO_2 at the particular workplace and for that worker;
4. deriving for each minute of the period of observation the VO_2 value from the continuously recorded HR values;
5. converting these VO_2 values into metabolic rates (Wm^{-2}), assuming a metabolic rate of 338 watts for an oxygen consumption of 1 litre per minute.

As such VO_2 measurements were in practice impossible to perform in view of the work situations investigated, the UCL research team used an indirect method of measuring the metabolic rate, consisting of

1. recording elementary postures and movements of the worker, using a specially programmed HP 71B hand-held microcomputer;
2. deducing for each of these elementary activities a metabolic rate value, from the tables of Spitzer et al. (1982) used in ISO draft Standard 8996 on the estimation of metabolic rate;
3. computing the metabolic rate for each minute as a time-weighted mean of the elementary metabolic rates.

The three techniques described above are listed in order of decreasing accuracy. The first one raises again the problems of temporal division and task comparability but, as a rule, should provide a rather accurate estimate of the worker's energy expenditure.

The second method aims at eliminating the errors due to the deduction of metabolic rates from HR values, using a relationship derived at the workplace for the job performed and the worker observed (Nielsen and Meyer 1987).

These two methods require the use of an oxygen consumption measuring instrument. Such an instrument is seldom available in practice and such measurements are seldom feasible in the field, so that, use will have to be made of the third method described above.

The validity of this approach depends, perhaps more than for the two first methods, on the ability of the observer to recognize the different postures and movements and to estimate their relative load (for instance, moderately heavy work with both arms versus light work performed with the trunk). It also depends on the accuracy of the coding system - hence the need for automatic systems such as microcomputers - and on the relevance of the average metabolic rates set out in the reference tables. It is therefore not possible to describe in a general way the accuracy of this technique. It has proved, however, to be much more reliable than the pencil and paper technique of observation and provides accurate results when used by a trained observer (Horwat et al. 1988).

6. Industrial situations investigated

The workplaces analyzed according to the techniques described above and taken into consideration for the validation of thermal indices were as follows:

1. BUW study: 70 workplaces in the glass industry, observed for periods of 240 to 480 minutes. The study also used subsidiary data collected in the steel industry as well as data from laboratory experiments by Ilmarinen (1978).

2. INRS study: 11 workplaces, analyzed 5 times for 5 different workers over 4 hours; Five of them involved hot, humid conditions without radiation: the other 6 were characterized by high but generally steady radiation loads. In addition, 5 experiments were performed in a controlled environment to simulate a working condition with intense, intermittent radiation.
3. UCL study: 39 work sequences, 4 to 8 hours long, at 9 work stations in the steel industry. All had to be considered individually, since the climatic variations and variations in the nature of the work itself were so great from one observation to the next. These conditions involved almost exclusively high radiation and very intermittent work. In addition, 25 experiments were run in controlled conditions in order to simulate hot, humid conditions without radiation and with different types of clothing insulation.

For each working situation observed in all these three studies, climatic parameters (t_a, t_r, p_a, V) and individual parameters (M, I_{clo}) were recorded minute by minute according to the methods discussed above.

Table 2 gives the means and standard deviations of these input data for the computation of the indices, calculated over the whole set of minute-by-minute data.

It emphasizes the fact that

- the conditions investigated comprised mostly situations with low to medium heat stress;
- periods of exposure to high heat stress were of relatively short durations and workers usually had the opportunity to recover in comfortable thermal environments.

For information only - the purpose of the research being to study the representativeness of these indices - Table 3 gives the means and the standard deviations of the minute-by-minute values of the WBGT and the required sweat rate indices, as well as the percentages of the time during which these values exceeded the limit values $WBGT_L = 33.6 - M/21.67$ and $SW_{req} = 250\ Wm^{-2}$. The distribution of the primary parameters and of the values of the indices are not in fact of the Gauss type but show considerable positive skewness. These statistics confirm the high intermittency of exposure to heat. They also confirm, incidentally the fact that working for prolonged periods of time in very hot conditions has become rather rare and/or has been already adequately organized in practice.

7. Subjects and physiological measurement

7.1. *Characteristics of the subjects observed*

Table 4 gives the means and the standard deviations of the main characteristics of the workers studied by the three teams participating in the validation study in the field.

For each study, these workers were in good health and in acceptable physical conditions on the basis of a medical examination. They were usually employed at the particular workplace and were therefore fully conversant with the work procedures. As far as possible, the subjects selected were of average height and weight. All workers volunteered for the study, after being fully informed about the aims, the methodology and the physiological measurements that were going to be made. In the case of the BUW research, the subjects were considered as acclimatized. For the INRS and UCL studies, on the other hand, they were assumed to be non-acclimatized, although the acclimatization process might have taken place to a certain extent.

7.2. *Physiological measurements*

Table 5 gives the main characteristics of the physiological measurements performed by the three teams.

Heart rate was continuously recorded either by telemetry or using a portable recorder carried by the worker. The mean HR values were determined either by counting the ECG R waves or averaging the RR intervals over each minute. Oral temperature (T_{bu}) was systematically used in view of its simplicity, its acceptance by the workers and its representativeness (as it is better correlated to oesophageal temperature and to the temperature of the thermoregulatory system than, for instance, rectal temperature). Measurements were taken as systematically as possible at regular intervals, but generally during breaks in order to reduce interference with work. This might raise problems regarding the validity of some measurements, as it is known that this parameter is a good indicator of core temperature only when the ambient air temperature is higher than 25°C, and that it becomes meaningless for t_a lower than 18°C (Mairiaux et al. 1983).

Weight loss measurements were taken in similar conditions and were corrected for variations due to ingestion, excretion and changes of clothing.

The parameters recorded and the methods used are very close to what can be recommended for general practice. The measurement criteria are be described in the ISO Standard 9886 "Evaluation of thermal stress using physiological measurements".

Table 6 gives the means and standard deviations of all the values for the following three physiological parameters:

1. HR: the HR increase by comparison to the resting HR during work (BUW and UCL teams) or during the 4th minute of recovery (_ FC_4) (INRS);
2. T_{bu}: the T_{bu} absolute values (BUW) or its increase with respect to the initial value (INRS) or the maximum increase in T_{bu} during each observation period (UCL);
3. Weight loss (SR): the mean value of weight loss (weight loss divided by the time interval).

It can be seen that the level of these three physiological variables remained moderate and in most cases lower than the generally accepted limit values, namely an increase in HR due to heat of 30-40 bpm, an increase of 0.8 - 1°C in core temperature and a total sweat loss of approximately 1 litre per hour (WHO 1969).

8. Conclusion

The present study confirm that work in hot conditions is typically intermittent, due either to the variations of climatic parameters - mainly radiation - or to the fact that the worker is constantly moving away from heat in order to avoid discomfort and heat stress.

Heat stress is thus caused more by short bursts of intense exposure, separated by relatively long recovery periods in cold, comfortable or slightly warm conditions, than by prolonged exposure.

It therefore appears essential firstly to use a methodology of observation and instruments suitable for this intermittency and secondly to calculate heat stress indices in a way taking these fluctuations into account.

Two methods of investigation have been presented and discussed: the zone method appears adequate for situations with slight temporal and spatial climatic variations; the ambulatory method, on the other hand, must be preferred for situations with substantial climatic heterogeneities.

Appropriate instruments are not yet systematically available for the measurement of radiation and air velocity or for recording climatic variations.

Metabolic rate can be best estimated by measuring oxygen consumption during selected work phases. In all likelihood, however, it will have to be derived from observations of postures and movements: simple observation methods are not always systematically available here either.

Physiological measurements will include heart rate, oral temperature and weight loss; simple methods are now available for recording these parameters.

As mentioned above, the situations encountered comprise typically (mainly BUW and UCL) relatively short phases of severe exposure, separated by phases in environments which come close to being comfortable. The quality of the prediction of heat strain, and hence the predictive value of the indices, depends mainly on the accuracy of the measurements taken during the phases of severe exposure, but it is here that the greatest errors will be made: errors regarding energy expenditure, scale of the pumping phenomenon and therefore error regarding the thermal insulation of clothing, errors in the measurements of radiation and air velocity, etc.

It is impossible to assess these errors, either theoretically or in practice. We feel, however, that their potential size is such that any attempt at validation based on such data is doomed to failure: the prediction may be wrong not because the model is incorrect but because the input data are inaccurate. We will therefore have to confine ourselves to determining the degree of reliability of the predictions in the case of the industrial situations encountered, while the index will have been validated from basic data - usually obtained in the laboratory.

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