PHYSIOLOGICAL RESPONSES TO TEMPERATURE AND HUMIDITY COMPARED WITH PREDICTIONS OF PHS AND WBGT.

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INTRODUCTION

The physiological strain resulting from thermal stress is influenced by six major variables: by the climatic parameters air temperature, humidity, wind velocity and thermal radiation as well as by the energy expenditure of a person and by the thermal properties of the clothing (thermal insulation, water vapour permeability), and is moreover modified by acclimatization status, hydration status, body posture, etc. (Kampmann 2000).

Accordingly an analysis should consider a six-dimensional space of input parameters for each of the predicted strain variables – in practice this will fail due to a lack of experimental data that show evenly distributed parameters for all six dimensions. In order to describe at least the mutual influence of air temperature and air humidity (i.e. at least for two input parameters) equivalence lines within the psychrometric diagram represent a well developed instrument of the systematic investigation of climatic effects on humans (e.g. Houghten & Yagloglou 1923).

Wenzel (1976) conducted series of exposures where only air temperature and humidity were varied and all other stress parameters (i.e. air velocity, thermal radiation, energy expenditure and clothing insulation) were fixed in order to determine equivalence lines of equal strain. Ilmarinen (1978) continued to record such series for varied levels of work intensity and different clothing insulations. We took the data from Ilmarinen's thesis (1978) for an evaluation of the predictions of the Predicted Heat Strain model (PHS, ISO 7933, 2004; Malchaire et al., 2001) and for comparing the heat strain resulting from different combinations of air temperature and humidity with the assessment performed by the Wet Bulb Globe Temperature (WBGT, ISO 7243, 1989).

The comparisons will not only be made for single data points but for a range of different values of temperature and humidity by means of equivalence lines. This allows to estimate the mutual influence of air temperature and humidity simultaneously as well as to diminish the problem of intra-individual variation of physiological strain by using regression approximations for complete series of exposures.

This may recall a method to compare assessment scales and thermoregulatory models to physiological data. We demonstrate the procedure for PHS and WBGT.

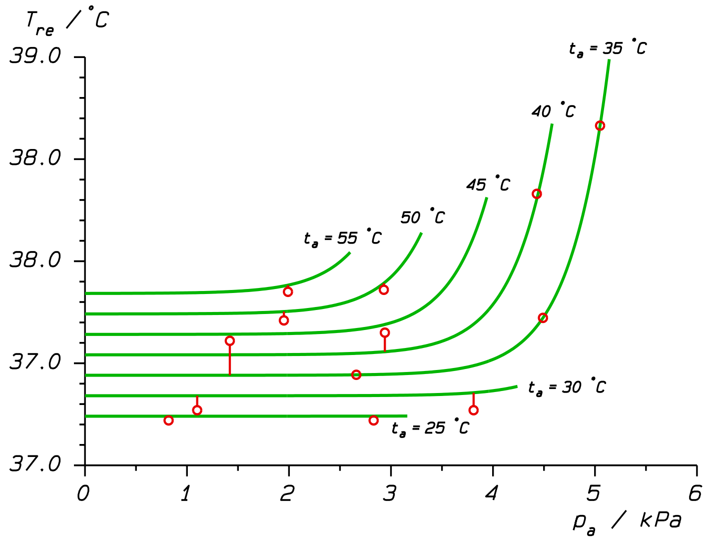

Figure 1: Body temperature of a single subject (Icl = 0.1 clo) depending on air temperature and humidity. - As the exposures were done within a 5 °C grid of ta, the respective lines are given explicitly.

METHODS

The following analysis is based on the experimental series of Ilmarinen (1978). Energy expenditure was 135 W/m^2 (walking on a treadmill at the level; 4 km/h); radiant temperature equalled air temperature; air velocity was va = 0.3 m/s. For three subjects there were series of exposures with as well Icl = 0.1 clo as Icl = 0.7 clo, each comprising 12 to 15 exposures with different values of air temperature (ta) and vapour pressure (pa). These six series of exposures were chosen for analysis, comprising a total of 81 exposures. For the rectal temperatures (Tre) and sweat rates (SR), mean values during the third hour of exposure were taken for analysis.

Regression surfaces were calculated for each of the six series of exposures and for the strain parameters considered (one result for Tre is given in Fig. 1). A computer program (Kampmann 2000) allowed to calculate lines of equivalent strain and to plot these lines within a psychrometric chart. For the comparison with the predictions of models (e.g. PHS) the regression planes of all three subjects included in the analysis were averaged linearly for the corresponding strain parameters (the resulting lines for Tre is given in Fig. 2).

This procedure was preferred to the calculation of a single regression surface using the data points of all subjects, because the non-linear response of the strain parameters looks different for the different subjects, and so the regression procedure may smooth out the nonlinearity of the stress-strain response. The usability of the aggregated diagram is restricted to the area covered by exposures of all three subjects, as indicated in Fig. 2.

For a comparison with the PHS index predictions of strain parameters were calculated using available software (Mehnert et al., 2002). Air temperature was increased between 20 and 50 °C with an increment of 1 K and relative humidity in steps of 5 % between 0% and 100 % to maximally 5 kPa water vapour pressure.

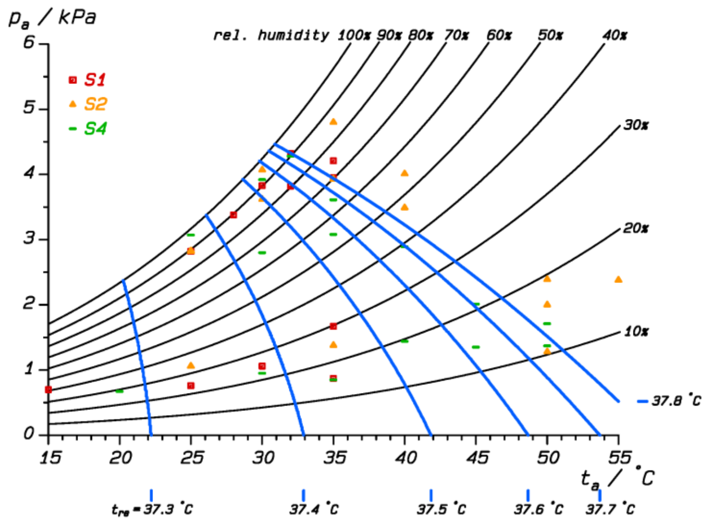

Figure 2: Equivalence lines for Tre averaged for three subjects with single exposures marked.

As for the experimental data, mean radiant temperature equalled air temperature, and air velocity was set to va = 0.3 m/s. Simulations were carried out with clothing thermal insulation values of 0.1 and 0.7 clo, respectively. The person was assumed to be acclimated with the energy expenditure being 135 W/m^2 corresponding to walking with 1.1 m/s.

Rectal temperatures (Tre) and sweat rates (SR) predicted by PHS after 3h of exposure time were smoothed over the grid of air temperature and humidity values (LOESS) and the resulting contour lines were compared to the equivalence lines derived from the empirical data.

The equivalence lines for Tre from the empirical data with Icl = 0.7 clo were further compared to the WBGT values obtained for the different combinations of air temperature and vapour pressure. For acclimated persons and a metabolic rate of 135 W/m^2, a limit value of WBGT = 28 °C is proposed (ISO 7243, 1989), assuming a reference clothing insulation of Icl = 0.6 clo.

RESULTS

In Fig. 3 the predictions of sweat rates by PHS look excellent for Icl = 0.1 clo at least for pa below 3 kPa and quite well for Icl = 0.7 clo (less than 200 g/h deviation within the whole range). This may be due to the fact that PHS was developed from SWreq (Required Sweat Rate - Index), taking in to account evaporation efficiency at different conditions etc. (cf. Malchaire et al., 2001). Body temperature was kept constant to 37.4 °C within PHS unless a thermoregulatory equilibrium no longer could be maintained. So the equivalence lines in Fig. 4 look shifted to the right, giving thermal strain approximately 0.4 °C too low.

In case of WBGT, the equivalence lines of physiological data and WBGT show a comparable slope (e.g. for WBGT = 28 °C or 30 °C) in humid conditions (Fig. 5), but the lines seem to be shifted to the left (i.e. safe!) side as for the WBGT, Tre = 38 °C is a limit criteria. For the given conditions the limit line of WBGT = 28 °C applies. Here the index overestimates Tre by 0.5 °C in humid conditions and by 0.4 °C in dry climatic conditions.

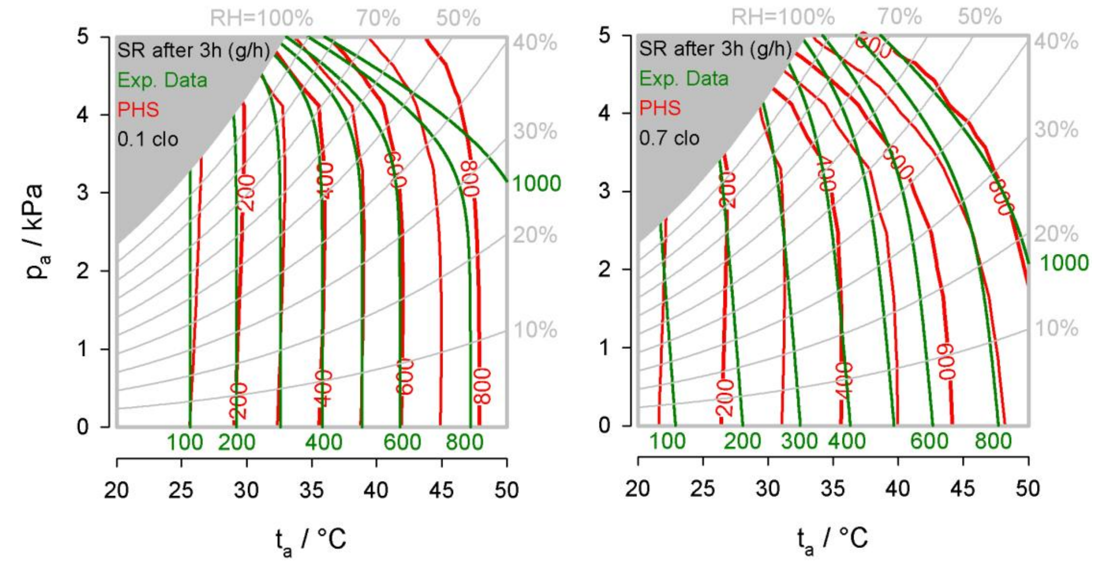

Figure 3: Lines of equivalent sweat rates (SR) from experimental data and predicted by PHS after 3h exposure to combinations of air temperature (ta) and vapour pressure (pa) for two clothing conditions.

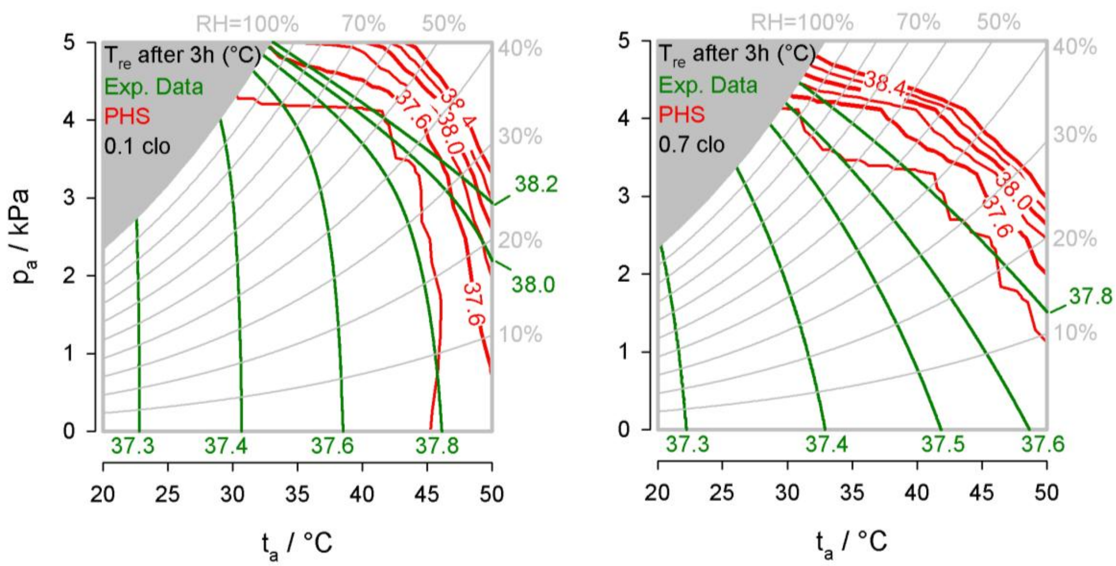

Figure 4: Lines of equivalent rectal temperatures (Tre) from experimental data and predicted by PHS after 3h exposure to combinations of air temperature (ta) and vapour pressure (pa) for two clothing conditions.

CONCLUSIONS

The method recalled to take physiological data as a benchmark for assessment scales and models of thermoregulation concerning the mutual impact of temperature and humidity. Its usability depends on characteristics of the available data like number of subjects and range of stress parameters. It would be desirable to enlarge such databases in order to enable validation studies also for more than two parameters. This would provide for a valuable contribution to the validity of newly developed models of thermoregulation and of heat or cold strain.

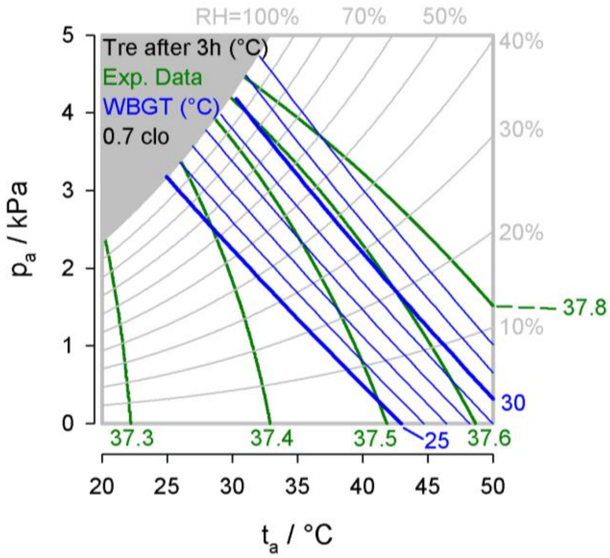

Figure 5: Lines of equivalent rectal temperatures (Tre) from experimental data with Icl = 0.7 clo and for WBGT limit criteria.

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