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Prediction of mean skin temperature in warm environments

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Summary. The data collected by the authors in four experimental series have been analysed together with data from the literature, to study the relationship between mean skin temperature and climatic parameters, subject metabolic rate and clothing insulation. The subjects involved in the various studies were young male subjects, unacclimatized to heat. The range of conditions examined involved mean skin temperatures between 33°C and 38°C, air temperatures (T_a) between 23°C and 50°C, ambient water vapour pressures (P_a) between 1 and 4.8 kPa, air velocities (V_a) between 0.2 and 0.9 $m \cdot s^{-1}$, metabolic rates (M) between 50 and 270 $W \cdot m^{-2}$, and Clo values between 0.1 and 0.6. In 95% of the data, mean radiant temperature was within ±3°C of air temperature. Based on 190 data averaged over individual values, the following equation was derived by a multiple linear regression technique: $\bar{T}_{sk} = 30.0 + 0.138\,T_a + 0.254\,P_a - 0.57\,V_a + 1.28 \cdot 10^{-3}\,M - 0.553\,Clo$. This equation was used to predict mean skin temperature from 629 individual data. The difference between observed and predicted values was within ±0.6°C in 70% of the cases and within ±1°C in 90% of the cases. It is concluded that the proposed formula may be used to predict mean skin temperature with satisfactory accuracy in nude to lightly clad subjects exposed to warm ambient conditions with no significant radiant heat load.

Key words: Skin temperature — Heat stress — Exercise — Clothing

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Introduction

Skin temperature is a fundamental factor in heat exchanges between the body and its environment. The level of skin temperature directly affects the energy transfer by convection and radiation and also influences heat losses from sweat evaporation by determining the saturated vapour pressure at the skin surface. The assessment of skin temperature is thus of great importance for thermal balance evaluation in working man.

It is well known that temperature varies across the surface of the skin, so that an average skin temperature may only be obtained by taking the mean of local temperatures weighted according to the relative surface of the area they are supposed to characterize. The optimal number of measurement points, their location, and the weighting system most appropriate for estimating mean skin temperature have been discussed for many years (Teichner 1958; Ramanathan 1964; Olesen et al. 1972; Nadel et al. 1973; Lund and Gisolfi 1974).

Several heat stress indices use a fixed mean skin temperature for thermal balance calculations: this temperature is taken to equal 35° in the Heat Stress Index (Belding and Hatch 1956) and in the Index of Thermal Stress (Givoni 1969), while a figure of 36°C is adopted in the Required Sweat Rate Index (Vogt et al. 1981). This last figure can be very close to the actual average skin temperature observed during intermittent exposure to heat: however, it can underestimate skin temperature levels during the most severe periods of exposure and thus lead to important errors in heat balance calculations (Mairiaux et al. 1986).

Direct measurements of skin temperatures being often not possible in practice, some authors have tried to derive prediction equations from observed skin temperature data. Givoni (1967) reviewed published data and presented various formulae relating skin temperature to dry and wet bulb temperatures, air velocity, mean radiant temperature or metabolic rate. These relationships are valid for resting subjects only. Missenard (1973) reviewed data collected on nude subjects by other authors and proposed four equations relating skin temperature to air temperature, at four levels of air velocity. Several other relationships have been published by various authors, but most of these were obtained from a relatively small number of subjects and in a given set of conditions.

This study constitutes a further attempt of finding a reliable predictor of skin temperature variations in warm environments. The data used originated from four different studies carried out by the authors on clothed and nude subjects, both at rest and at work, at various levels of air temperature, humidity and air velocity.

Material and methods

Data sources

The results of four experimental series, all but one being published, constituted the main data base of this study. Details of the experimental procedures can be found in the referenced papers. The main features of each series are briefly summarized below.

Series I: five subjects wearing shorts and working on a bicycle ergometer were exposed to square pulse variations in air temperature (T_a: 23°C–50°C; 28°C–45°C) at constant metabolic rate ($M = 169\ W \cdot m^{-2}$) and to metabolic variations between $117\ W \cdot m^{-2}$ and $214\ W \cdot m^{-2}$ at constant T_a (36.5°C). The working period lasted 120 min (Mairiaux et al. 1983).

Series II: six subjects exposed in the same experimental setting as that in series I. Conditions of exposure involved: constant metabolic rate ($169\ W \cdot m^{-2}$), square pulse variations of air temperature (T_a: 50°C–23°C; 45°C–28°C) or water vapour pressure (P_a: 4 kPa–2 kPa; 4.6 kPa–1.4 kPa), and a steady condition at $T_a = 36.5$°C and $P_a = 3$ kPa (Mairiaux et al. 1986).

Series III: five subjects working on a bicycle ergometer at constant load ($M = 143\ W \cdot m^{-2}$) either "nude" or "clothed". The duration of exposure was 150 min divided into two subperiods of 75 min. From one subperiod to another, three parameters could be varied: clothing, T_a between 21°C and 47°C, and mean radiant temperature ($\overline{T}_r$) between 18°C and 54°C (Vogt et al. 1983).

Series IV: the experiments (unpublished results) were carried out by five subjects and involved alternate periods of cycling exercise in a climatic chamber ($T_a = \overline{T}_r = 41.8$°C; $P_a = 3$ kPa; air velocity $(V_a) = 0.64\ m \cdot s^{-1}$) and resting periods outside the chamber ($T_a = \overline{T}_r = 28°C \pm 1°C$; $P_a = 0.9$ kPa). The duration of exercise was 20, 24 or 28 min depending on the metabolic rate ($243\ W \cdot m^{-2}$, $199\ W \cdot m^{-2}$ and $166\ W \cdot m^{-2}$ respectively) while rest periods lasted 15 min between the exercise bouts. The final recovery period lasted 30 min. The subjects were clothed (0.5 Clo) in three conditions and nude (0.1 Clo) in the two others. The clothing insulation was determined using the figures from Olesen and Nielsen (1983).

Additional data from other authors were also used in order to enlarge the diversity of the conditions taken into account. These data were in most cases averaged data over a small number of subjects; Hardy and Stolwijk (1966): 3 subjects; Stolwijk and Hardy (1966): 3 subjects; Gagge et al. (1969): 4 subjects; Chappuis et al. (1976): 11 subjects; Gonzalez et al. (1978): 5 subjects; Kobayashi et al. (1980): 5 subjects; Candas (1980): 5 subjects; Alber-Wallerstrom and Homer (1985): 6 subjects.

Subjects

The data collected by the authors are based on a sample of 18 male subjects, as 2 subjects took part in both series I and II, and another subject took part in series I and III. All subjects were in good health and unacclimatized to heat. Age ranged from 20 to 25 years for sixteen subjects; two subjects were 30 years old. Body weight was on average 71.4 kg (range: 60–84.8) while mean stature was 178 cm (range: 168–186). Fourteen subjects had their $\dot{V}_{O_{2max}}$ assessed: values ranged from 2.9 to $4.0\ l \cdot min^{-1}$ with an average $\dot{V}_{O_2} = 3.46\ l \cdot min^{-1}$.

The data from the literature involve a total sample of 41 male subjects with characteristics similar to our own: young subjects (33 with age <28 years; all below 38 years) with a good level of fitness and unacclimatized to heat.

Measurement techniques

In series I, II and III, ten local skin temperatures (foot, calf, thigh, hand, upper arm, abdomen, chest, back, subscapular and forehead) were recorded. Thermocouples were used in series I and II. In series III, thermistors were used and the measurement of forearm skin temperature was substituted for the subscapular location. Mean skin temperature ($\overline{T}_{sk}$) was determined by weighting each local measurement according to the Hardy and Dubois formula. In series IV, skin temperatures were recorded with thermistors at four locations: chest, upper arm, medial thigh, and leg; $\overline{T}_{sk}$ was determined using Ramanathan's expression (1964).

In the studies taken from the literature, the number of measurement locations ranged from 7 to 15 and thermocouples or thermistors were used in all but one study (Gagge et al. 1969) where measurements were taken with a radiometer.

Data selection and statistical analysis

Experimental series I to IV provided a minute by minute record of skin temperature. The purpose of this study being to examine the relationship between mean skin temperature and climatic parameters as well as metabolic rate and clothing insulation, we analysed the data observed at the end of each exposure period, that is 20, 25 or 30 min after the metabolic and/or climatic transient. When the periods of exposure were longer, as for instance in series III, we selected the conditions prevailing after 25 min and 60 min of exposure. The same rationale was used, when applicable, to select the data reported in the literature references. In series I, II and IV this provided a total of 629 sets of data: T_a, T_r, P_a, V_a, M, Clo, $\overline{T}_{sk}$, and rectal temperature (T_{re}). From these, were derived 127 "mean" conditions by averaging over the individual values for each experiment. With the data available from series III and from the literature, a set of 218 "mean" conditions was constituted.

The "mean" conditions were reviewed to assess the normality of the distribution of the different parameters. We excluded data sets in which any parameter was markedly outside the 95% confidence limits of its distribution. This led to the suppression of 18 sets of data from the literature and of 10 sets corresponding to high and low radiant heat load exposures in experimental series III (Vogt et al. 1983). This last step of selection left for statistical analysis a total of 190 "mean" conditions, among which 151 corresponded to nude subjects and 39 to clothed subjects. "Nude" and "clothed" data were considered together as they were recorded in subjects exposed to the same conditions in the nude and in the clothed condition.

A stepwise multiple linear regression analysis was conducted on the 190 "mean" data, the skin temperature being the dependent variable, T_a, $\bar{T}_r$, P_a, V_a, M and Clo being the independent variables. In a separate analysis, rectal temperature was also taken as an additional independent variable. A skin temperature prediction equation was derived which included the variables bearing a significant contribution to the regression. Predicted skin temperatures were then computed for the "mean" data and for the individual data. The level of agreement between observed and predicted skin temperatures was calculated as the percentage of cases where the difference between observed and predicted values was within given limits.

Results

Table 1 gives the mean, standard deviation and range of ambient and physiological parameters considered in this study. Ambient temperatures ranged from the neutral to the warm zone, most of them being above 27°C. No significant radiant heat load was present and T_a and $\bar{T}_r$ were broadly in the same range. The data studied did not include high air velocities. The ranges of ambient humidity levels and metabolic rates were fairly large. The rectal temperature levels observed in the data suggest that most of the conditions studied did not put an excessive thermal strain on the subjects.

Table 1. Mean value, standard deviation and range of each variable considered in the statistical analysis (*n* data = 190)

Variable	Mean	SD	Range
T_a, °C	35.2	7.7	22.9– 50.6
$\bar{T}_r$, °C	34.6	6.5	24.1– 49.5
P_a, kPa	2.2	1.1	0.8– 4.8
V_a, $m \cdot s^{-1}$	0.33	0.22	0.2– 0.9
M, $W \cdot m^{-2}$	124.9	63.1	46.4–272
Clo	0.19	0.18	0.1– 0.6
T_{re}, °C	37.4	0.38	36.6– 38.4
$\bar{T}_{sk}$, °C	35.3	1.3	32.7– 38.4

Table 2 gives the successive results of the stepwise multiple linear regression of mean skin temperature (190 mean values) on the independent variables. The last line of this table gives the regression coefficients when also including rectal temperature. As can be seen, the most significant parameters for the prediction of $\bar{T}_{sk}$ are, in decreasing order, air temperature, ambient partial vapour pressure and clothing insulation. Due to the strong correlation between $\bar{T}_r$ and T_a ($R = 0.95$), the effect of the mean radiant temperature is confounded with the effect of air temperature and the regression coefficient for $\bar{T}_r$ is not statistically significant. To a lower extent, P_a and V_a were also related to air temperature variations in the conditions studied ($R = 0.40$ and 0.39 respectively). Metabolic rate was significantly correlated with rectal temperature ($R = 0.50$). The contribution of metabolic rate to the prediction was not significant ($p < 0.05$) when rectal temperature was taken into account and was at the limit of significance when T_{re} was excluded. For practical purposes, a prediction equation including T_{re} would be of limited interest, and therefore T_{re} was not considered in the final proposal.

The validation procedure was thus based on the following prediction equation:

Table 2. Stepwise multiple linear regression equations of mean skin temperature on the independent variables: air temperature (T_a), water vapour pressure (P_a), thermal insulation of clothing (Clo), absolute air velocity (V_a), metabolic rate (M), mean radiant temperature ($\bar{T}_r$) and rectal temperature (T_{re}). Regression coefficients in parentheses are not statistically significant ($p < 0.05$).

# variables	Constant term	T_a °C	P_a kPa	Clo	V_a $m \cdot s^{-1}$	M $W \cdot m^{-2}$	$\bar{T}_r$ °C	T_{re} °C	R^2
1	30.0	0.149							0.770
2	30.0	0.136	0.246						0.805
3	30.1	0.139	0.200	−0.811					0.816
4	30.0	0.141	0.256	−0.580	−0.512				0.820
5	30.0	0.138	0.254	−0.553	−0.571	$1.28 \cdot 10^{-3}$			0.823
6	30.2	0.161	0.293	−0.544	−0.603	$1.41 \cdot 10^{-3}$	(−0.032)		0.825
7	14.1	0.159	0.283	−0.600	−0.497	($5.58 \cdot 10^{-5}$)	(−0.030)	0.434	0.837

$$\overline{T}_{sk} = 30.0 + 0.138\,T_a + 0.254\,P_a - 0.571\,V_a + 1.28 \cdot 10^{-3}\,M - 0.553\,Clo$$

where T_a was in °C, P_a in kPa, V_a in $m \cdot s^{-1}$, M in $W \cdot m^{-2}$.

This equation was used to compute skin temperature from the data ($n = 629$) collected in individual subjects. Figure 1 illustrates the relationship between observed and predicted skin temperatures. The corresponding equation of regression was:

$$\overline{T}_{sk\,obs} = 0.94\,\overline{T}_{sk\,pred} + 2.15 \quad (R = 0.863)$$

A few data points in the figure corresponded to observed skin temperatures well below the predicted values. All these values originated from experimental series IV either from nude subjects during the resting periods or from clothed subjects after more than one hour exposure. This point will be discussed below.

The frequency of agreement between observed and predicted $\overline{T}_{sk}$ values is described in Table 3. The prediction error was within 0.6° C in 70% of the cases, and remained within 1° C in 90% of the cases, when considering individual data. As expected, the agreement was better when the mean data were compared. In the 14 subjects for whom individual data were available, the mean difference between observed and predicted values ranged from −0.82° C to +0.59° C. No relationship was found between this mean difference and the subject's $\dot{V}_{O_{2\,max}}$ or mean skinfold thickness. Individual data were also examined regarding the effect of exposure time of day on the prediction. The observed $\overline{T}_{sk}$ during the thermoneutrality period before the start of each exposure was on average 0.36° C (SD 0.35° C) below the predicted value in morning exposures, while only 0.02° C (SD 0.34° C) above the predicted value in afternoon exposures. This difference was highly significant (Student $t = 4.02$ with 58 df). A similar trend was observed when considering $\overline{T}_{sk}$ values recorded during the rest of the exposure but it was not significant (Student $t = 1.83$ with 58 df).

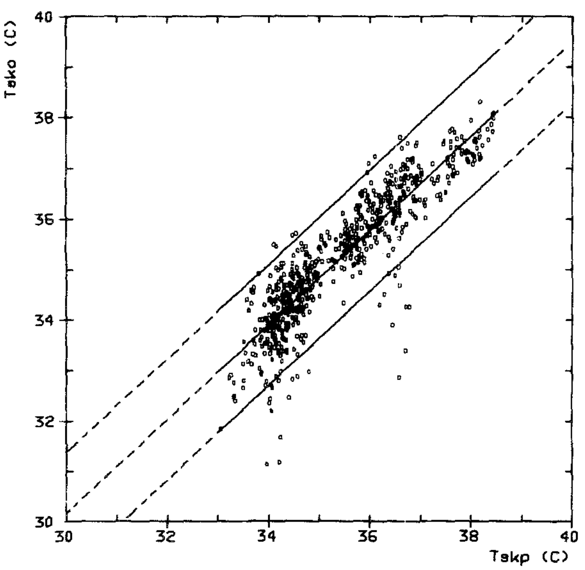

Fig. 1. Mean skin temperatures observed in 629 individual data plotted as a function of predicted skin temperatures. Regression line ($y = 0.94x + 2.15$) with 95% confidence limits

Table 3. Frequency of agreement between observed and predicted skin temperatures

Percentage of observed-predicted $\overline{T}_{sk}$ differences within	Mean data ($n = 190$)	Individual data ($n = 629$)
±0.2° C	33%	33%
±0.4° C	57%	54%
±0.6° C	77%	70%
±0.8° C	93%	83%
±1.0° C	95%	90%
±1.2° C	96%	95%
±1.4° C	98%	97%

Discussion

This study was based on results collected in various laboratories, with different experimental protocols and using various methods of mean skin temperature determination. By analysing together these various sets of data, it was hoped that the prediction formula to be derived could be relevant to an increased range of ambient conditions and to a significant part of the working population.

The overall agreement observed in these conditions between observed and predicted skin temperatures can only be compared with the figures reported by Meyer (1981). In his study, based on 29 subjects involved in various experiments in the same laboratory, 82% of the calculated values were within ±0.85° C of the observed values and 95% of the calculated values were within ±1.42° C of the observed ones. This level of agreement is similar to that obtained in the present study (see Table 3).

Several factors could have contributed to the difference between predicted and observed skin temperatures. The prediction errors observed for the data from series IV may be in part related to characteristics specific to this series, as for instance the use of only four points of skin temperature measurement. Besides these particular factors, a more general source of prediction error could be the circadian variation in thermoregulatory functions. In series I and II, which involved both morning and afternoon experiments, the difference between the observed and predicted skin temperatures during the initial resting period was significantly affected by the time of day while this was not the case during heat exposure. This observation must however be considered with caution, as a circadian variation in mean skin temperature has been reported during heat exposure but not at thermal neutrality (Marotte and Timbal 1982). Individual factors such as physical fitness or subcutaneous fat may also have contributed to the variance in $\bar{T}_{sk}$ prediction. Both the level of training and the subject's $\dot{V}_{O_{2\,max}}$ have been shown to affect skin temperature variations in response to heat exposure (Gisolfi and Robinson 1969; Drinkwater et al. 1982). The heat storage observed during the exposure to heat may be another source of prediction inaccuracies as the skin temperature variation exhibits some relationship with heat storage or rectal temperature (Houdas et al. 1972). A relationship between $\bar{T}_{sk}$ and T_{re} was observed in series I, II, and III, which involved continuous exercise in the heat ($R = 0.40$ with 100 df) but not in series IV which involved alternate periods of exercise and rest ($R = 0.21$ with 43 df). In similar work-rest alternations, Saltin et al. (1968) did not observe a $\bar{T}_{sk}$—T_{re} relationship. In the present study, the results showed that the inclusion of rectal temperature in the prediction model would have improved the accuracy of the prediction.

The regression coefficients determined for each independent variable can be compared with those reported in other studies. Among the ambient variables considered, air temperature was the best single predictor of $\bar{T}_{sk}$. The relationship had the form: $\bar{T}_{sk} = 30 + 0.149\,T_a$, with $R = 0.88$. In ambient conditions, with T_a ranging from 10° C to 35° C, Missenard (1973) reported $\bar{T}_{sk} - T_a$ relationships with slopes ranging from 0.35 to 0.45, and constant terms between 23 and 19.5 depending on the relative air velocity. In another study with air temperatures ranging from 10° C to 40° C, $\bar{T}_{sk}$ was related to T_a by $\bar{T}_{sk} = 27 + 0.22\,T_a$ (Saltin et al. 1972). For air temperatures between 30° C and 50° C, few data are available. For T_a above 34° C, Meyer (1981) reported slopes of 0.15 and 0.11, and constant terms of 29° C and 31.5° C at rest and at work respectively. When air temperature rises above 30—35° C, the increase in $\bar{T}_{sk}$ per unit change in T_a is thus lower than that observed in neutral to cold conditions. This confirms the non-linearity of the relationship, when $\bar{T}_{sk}$ increases close to the level of core temperature (Gagge et al. 1937; Houdas et al. 1972). In the range of data examined in this study, the parabolic trend of the relationship was found not significant.

The influence of ambient water vapour pressure on $\bar{T}_{sk}$ depends on the type of thermoregulatory exchanges between the skin and the environment. Its influence is only significant when body cooling requires the evaporation of sweat at the skin surface. The increase in $\bar{T}_{sk}$ with the increase in P_a observed in this study was thus expected, for most of the ambient conditions analysed involved regulatory sweating. The slope of the observed $\bar{T}_{sk} - P_a$ relationship (0.25) is in agreement with the figures reported by others in comparable ambient conditions (Candas 1980; Meyer 1981).

Variations in air velocity may affect skin temperature through increases in convective exchange and evaporative heat losses. Depending on the difference between air and skin temperatures, a change in air velocity could either decrease or increase the skin temperature. In the conditions in this study, a decrease in $\bar{T}_{sk}$ was observed with the increase in air velocity. This inverse relationship may probably be ascribed to an increase in evaporative cooling in the conditions studied.

Conflicting results have been reported concerning the influence of metabolic rate on skin temperature. In cool or neutral environments, a drop in skin temperature has frequently been reported at the start of exercise, sometimes followed by a subsequent and progressive increase with the continuation of exercise (Saltin et al. 1968; Nakayama et al. 1977; Adams 1977). Fanger's comfort equation (1970) is based on the assumption of a decrease in skin temperature with activity level. In warm environments, some authors reported a $\bar{T}_{sk}$ increase with metabolic rate (Nelson, cited by Givoni 1967) while others found that $\bar{T}_{sk}$ was independent of the level of activity (Missenard 1973). These apparent discrepancies between results reflect the complex interactions between work and skin temperature. The body movements associated with working activities increase the relative air velocity at the skin surface and, as Adams (1977) has shown, two activities requiring the same metabolic rate may induce different skin temperatures, due to differences in relative air velocity. In the present study, the exercise mode was uniformly a cycling exercise and therefore the relative air velocity could be affected by the pedalling rate but not by variations in metabolic rate. When relative air velocity was taken into account, Missenard (1973) did not find any effect of metabolic rate. On the other hand, muscular exercise is associated with a vasoconstrictor drive and this explains in part the drop in skin temperature already mentioned (Christensen and Nielsen 1942). Moreover, metabolic rate constitutes a major component of the total heat lead and thus of heat storage in a given ambient condition. In the present study, this contribution seems to have played the main role as rectal temperature was not correlated to any climatic parameter but was related to activity level. The metabolic rate contribution to the $\overline{T}_{sk}$ prediction was therefore only significant providing T_{re} variations were not taken into account in the model, and even so the effect was slight. Our results thus support the assumption that metabolic rate has per se little effect on skin temperature level.

The effect of clothing on skin temperature reflects the interferences that this insulation factor puts on insensible and sensible heat exchanges with the environment. Depending on the ambient conditions, cool or warm, clothing may be associated with respectively an increase or a decrease in skin temperature (Vogt et al. 1983). In warm conditions associated with regulatory sweating, the evaporative heat transfer coefficient is reduced and a saturated microclimate may develop under the clothing, so inducing a rise in skin temperature. However, in these conditions, the unevaporated sweat may accumulate in the clothing and have a marked cooling effect (Craig 1972). In the conditions of the present study, the significant $\overline{T}_{sk}$ reduction observed among the subjects when clothed may be ascribed on the one hand to the reduction in convective heat load and on the other hand, to the full wetting of the clothing observed in experimental series IV, especially during the resting periods spent in a dry climate ($P_a = 0.9$ kPa).

Besides the various parameters considered so far, the subject state of heat acclimatisation is another factor which can significantly affect the magnitude of skin temperature variations. During exposure to heat, heat acclimatised subjects exhibit higher sweat rates together with higher skin wettedness and lower mean skin temperature than those observed in unacclimatised subjects (Candas 1980). This important factor in $\overline{T}_{sk}$ variation should not be neglected when application of the prediction formula is considered.

In conclusion, the present results allow the prediction of mean skin temperature in warm climates, with satisfactory accuracy, from the main ambient parameters (T_a, P_a, V_a), activity level M and clothing insulation. Due to the range of conditions analysed in this study, these conclusions are valid for nude or lightly clad unacclimatised subjects exposed to ambient temperatures above 27°C under minimal radiant heat load.

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References

Adams WC (1977) Influence of exercise mode and selected ambient conditions on skin temperature. Ann NY Acad Sci 301:110–127

Alber-Wallerström A, Holmer I (1985) Efficiency of sweat evaporation in unacclimatized man working in a hot humid environment. Eur J Appl Physiol 54:480–487

Belding HS, Hatch TF (1956) Index for evaluating heat stress in terms of resulting physiological strains. ASHRAE Trans 62:213–228

Candas V (1980) Influence de la mouillure cutanée sur l'évolution du débit sudoral et des températures corporelles chez l'homme. Thèse Dr. Etat Sciences, Université Louis Pasteur, Strasbourg

Candas V, Libert JP, Vogt JJ (1979) Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. J Appl Physiol: Respirat Environ Exercise Physiol 47:1194–1200

Chappuis P, Pittet P, Jéquier E (1976) Heat storage regulation in exercise during thermal transients. J Appl Physiol 40:384–392

Christensen EH, Nielsen M (1942) Investigations of the circulation in the skin at the beginning of muscular work. Acta Physiol Scand 4:162–170

Craig FN (1972) Evaporative cooling of men in wet clothing. J Appl Physiol 33:331–336

Drinkwater BL, Bedi JF, Loucks AB, Roche S, Horvath SM (1982) Sweating sensitivity and capacity of women in relation to age. J Appl Physiol: Respirat Environ Exercise Physiol 53:671–676

Fanger PO (1970) Thermal comfort. New York, Mc Graw-Hill

Gagge AP, Herrington LP, Winslow CEA (1937) Thermal interchanges between the human body and its atmospheric environment. Am J Hyg 26:84–102

Gagge AP, Stolwijk JAJ, Saltin B (1969) Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. Environ Res 2:209–229

Gisolfi C, Robinson S (1969) Relations between physical training, acclimatization, and heat tolerance. J Appl Physiol 26:530–534

Givoni B (1967) Estimation of the mean skin temperature. Report to the US Dept of Health, Education and Welfare. Israel Institute of Technology, Haïfa

Givoni B (1969) Man, climate and architecture. Elsevier, Amsterdam

Gonzalez RR, Berglund LG, Gagge AP (1978) Indices of thermoregulatory strain for moderate exercise in the heat. J Appl Physiol: Respirat Environ Exercise Physiol 44:889—899

Hardy JD, Stolwijk JAJ (1966) Partitional calorimetric studies of man during exposures to thermal transients. J Appl Physiol 21:1799—1806

Houdas Y, Colin J, Timbal J, Boutelier C, Guieu JD (1972) Skin temperatures in warm environments and the control of sweat evaporation. J Appl Physiol 33:99—104

Kobayashi K, Horvath SM, Diaz FJ, Bransford DR, Drinkwater BL (1980) Thermoregulation during rest and exercise in different postures in a hot humid environment. J Appl Physiol: Respirat Environ Exercise Physiol 48:999—1007

Lund DL, Gisolfi CV (1974) Estimation of mean skin temperature during exercise. J Appl Physiol 36:625—628

Mairiaux Ph, Sagot JC, Candas V (1983) Oral temperature as an index of core temperature during heat transients. Eur J Appl Physiol 50:331—341

Mairiaux Ph, Libert JP, Candas V, Vogt JJ (1986) Prediction of strain for intermittent heat exposures. Ergonomics 29:913—923

Marotte H, Timbal J (1982) Circadian rhythm of thermoregulating responses in man exposed to thermal stimuli. Chronobiologia 9:375—387

Meyer JP (1981) Prévision de la température cutanée moyenne. Thèse Dr Med, Université Louis Pasteur, Strasbourg

Missenard FA (1973) Température moyenne de la peau humaine en fonction de l'activité et de l'ambiance. CR Acad Sci Paris 277, D:1557—1559

Nadel ER, Mitchell JW, Stolwijk JAJ (1973) Differential thermal sensitivity in the human skin. Pflügers Arch 340:71—76

Nakayama T, Ohnuki Y, Niwa K (1977) Fall in skin temperature during exercise. Jpn J Physiol 27:423—437

Olesen BW, Nielsen R (1983) Thermal insulation of clothing measured on a movable thermal manikin and on human subjects. Technical University of Denmark, Lyngby, Denmark

Olesen S, Fanger PO, Bassing JJ (1972) Physiological comfort conditions at sixteen combinations of activity, clothing, air velocity and ambient temperature. ASHRAE Trans 78:199—204

Ramanathan NL (1964) A new weighting system for mean surface temperature of the human body. J Appl Physiol 19:531—533

Saltin B, Gagge AP, Stolwijk JAJ (1968) Muscle temperature during submaximal exercise in man. J Appl Physiol 25:679—688

Saltin B, Gagge AP, Bergh U, Stolwijk JAJ (1972) Body temperature and sweating during exhaustive exercise. J Appl Physiol 32:635—643

Stolwijk JAJ, Hardy JD (1966) Partitional calorimetric studies of responses of man to thermal transients. J Appl Physiol 21:967—977

Teichner WH (1958) Assessment of mean body surface temperature. J Appl Physiol 12:169—176

Vogt JJ, Candas V, Libert JP, Daull F (1982) Required sweat rate as an index of thermal strain in industry. In: Cena K, Clark JA (ed) Bioengineering, thermal physiology and comfort. Elsevier, Amsterdam, pp 99—110

Vogt JJ, Meyer JP, Candas V, Libert JP, Sagot JC (1983) Pumping effects of thermal insulation of clothing worn by human subjects. Ergonomics 26:963—974

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