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Original articles

Solar heat load on man

Review of different methods of estimation

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Abstract. Different methods have been compared for the estimation of solar heat load on man. The comparison comprised several methods based on the calculation of absorbed solar radiation and one method for calculation of mean radiant temperature (*Mrt*). Regression analysis was carried out for predicted values and values calculated for a vertical cylinder, assumed as an analog model of a standing man. Regression of mean skin temperature, measured in 10 subjects exposed to solar radiation under a variety of climatic conditions, on predicted radiant heat load was also analysed. Mean skin temperature correlated best with *Mrt*, accounting for more than 50% of the variance. The results indicated that three methods provide a realistic estimation of the radiation heat load, whereas some methods show deviations of several hundred per cent.

Key words: Heat load – Mean skin temperature – Solar radiation – Clothing – Mean radiant temperature

Introduction

Solar radiation is an important source of heat gain in the field. Accurate methods of measurement or prediction are required for the analysis of conditions for human heat balance. Since no direct method of measurement is available yet for determination of the amount of solar heat gain by the body, this has to be calculated on the basis of general measures of solar radiation. During the last 30 years many different formulas have been proposed. They recalculate the intensity of solar radiation (global or direct, diffuse and reflected) measured at a plane horizontal or perpendicular to the sun, to a value representative for its effect on the human body. All equations consider, on a theoretical basis, the geometry of the human body and require only values for solar radiation and clothing thermal insulation (if applicable). The aims of the present study were to review prediction formulas for solar heat gain and validate them: (1) by comparing predicted values with measured thermal effects on the human body; and (2) by comparing predicted values with values calculated by a model derived from measured radiation heat gain of a vertical cylinder.

Review of formulas of solar heat gain

The general equation for the solar radiation heat balance of a clothed man can be expressed as follows:

$$R_{cl} = (\beta_1\, Q + \beta_2\, D + \beta_3\, Ref)\, \phi\, Cl \qquad (1)$$

where β_1, β_2, and β_3 are parameters used for the estimation of components of solar radiation, Φ is the skin reflectance coefficient and Cl is a clothing factor (for explanation of other symbols see Table 1). R_{cl} will also be called "absorbed solar radiation". Most authors evaluate absorbed solar radiation for a man in a standing relaxed posture and assume a vertical cylinder as an analog model of the human body.

Measurements of solar radiation at the surface normal to the sun are rather rare in meteorology. Methods based on such data (Aizenshtat 1986; Clark and Cena 1976), therefore, will not be considered. All methods based on solar radiation measured at the horizontal plane recalculate its intensity in relation to a man in upright posture, using different measures of solar geometry. Methods may be categorized in groups according to the principal parameters used for the prediction (Fig. 1). Comparisons are based on effects on nude subjects, since some of the models do not include a clothing factor.

The first group comprises methods using trigonometrical functions of sun altitude as a weighting factor of direct solar radiation reaching the human body. One

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Table 1. List of symbols and units

Symbol	Definition	Unit
Meteorological and environmental parameters:		
Q	Intensity of direct solar radiation on horizontal surface	W/m^2
D	Intensity of diffuse solar radiation on horizontal surface	W/m^2
Ref	Intensity of reflected solar radiation on horizontal surface	W/m^2
ag	Albedo of ground (=0.18)	
T_a	Air temperature	°C
T	Air temperature	K
v	Wind velocity	m/s
hsh	Ratio of the sky hemisphere unobstructed by any objects (=0.85)	
h	Sun altitude	degree
Mrt	Mean radiant temperature	°C
Physical parameters of heat exchange:		
s	Emissivity of radiating surface (=0.95)	
σ	Stefan-Boltzman constant ($=5.7\times10^{-8}$)	W/m^2 per K^4
h_c	Heat transfer coefficient $=0.04\ T_a-11.84$	W/m^2 per K
d	Coefficient of turbulent diffusion $=\sqrt{v}$	
Physiological parameters:		
T_s	Mean skin temperature	°C
a	Mean albedo of skin and clothing (=0.33)	
R_{cl}	Radiation balance of clothed man (solar radiation absorbed by clothed man)	W/m^2
R	Radiation balance of unclothed man (solar radiation absorbed by unclothed man)	W/m^2
R_p	Potentially absorbed solar radiation (solar radiation absorbed by vertical cylinder)	W/m^2
A_{du}	du Bois body surface area	m^2
A_{rad}	Radiant area $=0.725(1+0.15I_{cl})\ A_{du}$	m^2
A_{sh}	Shaded area $=4.27\ \exp[-0.0512(90-h)]$	
A_{sh}'	Shaded area $=7.57\ \exp[-0.0512(90-h)]$	
A_p	Projected area of cycling man (Table 2)	
fp	Projected area, according to Jendritzky (1990) $=0.308\cos[h(0.998-h^2/50000)]$	
A_i	Ratio of body area received solar radiation $=0.0429\sin h+0.3845\cos h$	
as	Absorbance of skin for solar radiation (=0.54)	
gp	Fraction of nude man area perpendicular to solar beams (Table 2)	
gz	Fraction of nude man area facing zenith (=0.1)	
gh	Fraction of nude man facing horizon (=0.6)	
f_{eff}	The effective radiation area $=0.7(1-A_c)$	
Clothing parameters:		
A_{cl}	Clothing area $=A_{rad}/0.725$	m^2
CLO	Clothing insulation	clo
I_{cl}	Clothing insulation	K/m^2 per W
I_a	Insulation of the boundary air layer (=0.105)	K/m^2 per W
A_c	Ratio of body area covered by clothing	
ac	Absorbance of clothing (=0.80)	
d'	Heat conductivity coefficient of clothing = 0.53/CLO	
I_{rc}	Resistance coefficient of radiant heat transfer by clothing $=h_c\,d'/(h_c\,d'+h_c\,d+4s\sigma\,T^3)$	
f_a	Ratio of clothed to nude projected area (=1.1)	
f_{acl}	Ratio of clothed to nude surface area, i.e. ratio of effective clothing area (=1.2)	
U	Reduction of solar heat load by clothing $=I_a/f_{acl}(I_{cl}+I_a/f_{acl})$	

of them is the equation proposed by Budyko and collaborators (Budyko 1959; Budyko and Tsytsenko 1960). Taking into consideration the authors' correction for radiation at the top of a cylinder model, absorbed solar radiation for a nude man (R) can be calculated as follows:

$$R=0.588[1.6(Q\cot h/\pi+D/2+Ref/2)+0.1(Q+D)](1-a) \quad (2)$$

The equation proposed by Lee (1980) has a slightly different form. He considered the sum of direct and diffuse radiation (defined as global solar radiation) rather than their individual contribution:

$$R=[(Q+D)(0.07+0.54\cot h)+0.85\cdot ag(Q+D)](1-a) \quad (3)$$

The second group contains methods using a "shaded area" factor (Ash). Terjung and collaborators (Burt et al. 1982; Terjung 1974; Terjung and Louie 1971; Terjung and O'Rourke 1983) proposed the following equation for the radiation balance of unclothed man:

$$R=(Q\cdot A_{sh}\cdot A_{cl}+D)(1-a) \quad (4)$$

Table 2. Values of A_p and gp coefficients for different sun altitude (from Nielsen et al. 1988; Breckenridge and Goldman 1972)

h	1	5	10	15	20	25	30	35	40	45	50	55	60
A_p	0.21	0.20	0.19	0.19	0.18	0.18	0.17	0.17	0.15	0.15	0.14	0.13	0.16
gp	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.24	0.23	0.22	0.21	0.20	0.18

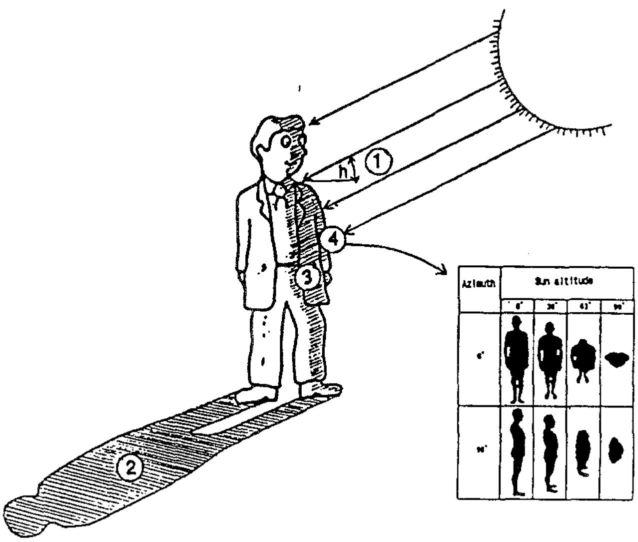

Fig. 1. Schematic representation of different parameters used for the estimation of direct solar radiation; *1*, trigonometric functions of solar angle; *2*, area of body shade cast on the ground surface; *3*, ratio of body area receiving solar beams; *4*, body area projected perpendicular to the sun beams (Underwood and Ward 1966)

A similar formula was used by Morgan and Basket (1974):

$$R=(Q\cdot A_{sh}+D\cdot A_{sh}+Ref\cdot A_{sh})\,(1-a) \qquad (5)$$

as well as by Tuller (1975):

$$R=(1.05\cdot Q\cdot A_{sh}'+D/2+ag(Q+D)/2)\,(1-a) \qquad (6)$$

The third group of methods considers two kinds of parameters, i.e. trigonometrical functions and a "projected area" coefficient. The area is derived from pictures taken of the body at various solar angles and azimuth. The "shaded area" or the "ratio of body area receiving solar beams" to total area of skin surface may also be used. The method proposed by Höppe (1982) is relatively simple; the following equation was derived by the authors from the original equations in Höppe's study:

$$R=(Q\cdot \sin h\cdot A_{sh}+D+Ref)\,(1-a) \qquad (7)$$

Nielsen et al. (1988) observed a clear relationship between solar radiation intensity and skin temperature measured for 10 subjects during bicycle work. They considered global solar radiation, rather than direct and calculated radiation balance of unclothed man using the following formula:

$$R=A_p\cdot as\frac{Q+D}{\sin h}+D/2\sin h+f_{eff}\cdot as\cdot D/2 \qquad (8)$$

The projected area of cycling persons was estimated empirically by photographic investigations.

de Freitas and Ryken (1989) studied the heat balance of 10 unclothed subjects during running. They used the following equation to estimate solar heat load:

$$R=1.12\cdot A_i\frac{Q}{\sin h}+0.45\,D+0.34\cos h\cdot ag(Q+D) \qquad (9)$$

Breckenridge and Goldman (1971, 1972, 1977) tried to solve the problem of solar heat load in another way. They considered fractions of body parts with different solar exposure in relation to total body surface area. Their formula has the following form:

$$R=[gp\cdot fa\cdot Q+f_{acl}\,D(gz+gh/2)+gh\cdot f_{acl}\cdot Ref]\;ac \qquad (10)$$

The method of mean radiant temperature (*Mrt*) has a different approach. The method estimates the directional solar heat load in terms of a uniform surface temperature of an imaginary enclosure surrounding the person. Mean radiant temperature is used to express the intensity of radiant heat load in climatic chambers or in buildings (Fanger 1970). Its application to investigations performed in urban areas was proposed by Jendritzky and Nübler (1981). The *Mrt* index was also applied to an open area conditions by Jendritzky (1990). Including solar radiation intensity, mean radiant temperature may be calculated as follows:

$$Mrt=\{[(sT_i^4+(1-a)(D+Ref)/(s\cdot\sigma)+273] +(1-a)fp\cdot Q/(s\cdot\sigma)\}^{0.25}-273 \qquad (11)$$

where T_i is the temperature of the *i*th surface of the environment, assumed as equal to air temperature.

A comparison of examined methods shows differences connected not only with parameters estimating direct solar radiation but also coefficients used to express other solar fluxes (Table 3). Some authors (Breckenridge and Goldman 1971; Budyko and Tsytsenko 1960; de Freitas and Ryken 1989; Tuller 1975) assumed that 50% of diffuse radiation is received by man, whereas others use the total amount of this solar flux (Höppe 1982; Morgan and Baskett 1974; Terjung and O'Rourke 1983). The same consideration applies to Lee's method (Lee 1980), which examined global solar radiation. Nielsen's equation (Nielsen et al. 1988) includes diffuse radiation in three different ways, as a part of global radiation and separately with different parameters: sin h and effective radiation area. Reflected solar radiation is not considered with the Nielsen and Terjung methods (Nielsen et al. 1988; Terjung and O'Rourke 1983). This compo-

Table 3. Comparison of parameters used in particular methods

Method	Solar fluxes	Estimated parameters	Clothing factor	Skin absorbance	Posture	Analog model
Budyko	Q	cot h	I_{rc}	$1-a$	Standing	Cylinder
	D	0.5				
	Ref	0.5				
Lee	Q_{global}	cot h	$I_{cl}/(I_{cl}+I_a)$	$1-a$	Standing	Cylinder
	Ref	0.85				
Terjung	Q	Shadow area	No	$1-a$	Standing	–
	D	1.0				
Morgan	Q	Shadow area	No	$1-a$	Standing	–
	D	Shadow area				
	Ref	Shadow area				
Tuller	Q	1.05 shadow area	No	$1-a$	Standing	–
	D	0.5				
	Ref	0.5				
Nielsen	Q_{global}	sin h, projected area	No	as	Cycling	–
	D	0.5 sin h, radiation area				
Höppe	Q	sin $h\times$ shadow area	No	$1-a$	Standing	Cylinder
	D	1.0				
	Ref	1.0				
de Freitas	Q	1.12 sin $h\times$ body area factor	No	No	Running	Cylinder
	D	0.45				
	Ref	0.34 cos h				
Breckenridge	Q	Fractions of body area	U	ac	Standing	Cylinder
	D	Fractions of body area $\times 0.5$				
	Ref	Fractions of body area				
Mrt	Q	Projected area	No	$1-a$	Standing	–
	$D+Ref$	–				

nent of the radiation balance is, however, very small and may be significant only in some specific kinds of environment, e.g. sand areas and snow cover. For the purpose of comparison of predictions by the various equations, the results of the experimental studies of the solar radiation balance of a vertical cylinder made by Krys and Brown (1990) were used. Net solar radiation of the cylinder, defined as "potentially absorbed solar radiation" (R_p) is expressed by the following formula:

$$R_p=[Q\cdot s\cdot \tan(90-h)/\pi+D\cdot hsh + D(1-hsh)\,ag]\,(1-ag)\,(1-a) \quad (12)$$

Absorbance of solar radiation by the body surface strongly depends on clothing. Nielsen (1990) measured the intensity of solar radiation with a pyranometer covered by layers of clothing material. She observed that the transmittance of solar radiation through clothing was 13–58% and dependend on type, colour and thermal insulation of the material. Unfortunately, only three of the methods presented above include the resistance to heat transfer by clothing (Table 3). With Budyko's method clothing is considered by the I_{rc} coefficient (Liopo and Tsytsenko 1971), with the Breckenridge equation by the U coefficient and with Lee's model by $I_{cl}/(I_{cl}+I_a)$. The detailed formulas of I_{rc} and U coefficients are found in Table 1.

Materials and methods

The quantity of solar radiation absorbed by unclothed man was estimated for all compared equations using observation data collected during outdoor bioclimatological investigations performed in northeast Poland in the summer of 1989. All meteorological parameters including solar radiation fluxes as well as skin temperature of subjects were measured simultaneously every hour form 6.00 a.m. to 8.00 p.m. Skin temperatures of 10 healthy volunteers (5 male and 5 female) with a normal weight to height ratio and within the age category of 25–45 years were measured at five points of the body surface (forehead, palm, chest, thigh and calf). Subjects were facing north and wore sport's cotton clothing with a basic thermal insulation of about 1 clo and a mean albedo of about

Table 4. Characteristics of subjects

Subject	Sex	Age (years)	Body mass (kg)	Height (cm)
1	Female	28	53	157
2	Female	32	48	153
3	Female	35	62	163
4	Female	39	57	160
5	Female	43	53	155
Average		35.4	54.6	157.6
6	Male	25	80	182
7	Male	35	72	167
8	Male	37	70	165
9	Male	40	74	172
10	Male	45	82	181
Average		36.4	75.6	173.4

30%. Table 4 contains some physiological characteristics of the subjects. Mean skin temperature was calculated using the following formula (Blazejczyk and Krawczyk 1991):

$$T_s = 0.07\ T_{foreh} + 0.05\ T_{palm} + 0.5\ T_{chest} + 0.18\ T_{thigh} + 0.2\ T_{calf} \quad (12)$$

The following three types of analysis were undertaken. (1) The dependence of mean skin temperature on climatic factors were analysed by stepwise multiple regression. (2) Mean skin temperature was used as an indicator of physiological strain and correlated with calculated value for absorbed solar radiation using the different equations. (3) The calculated values were correlated with values obtained with the cylinder method of Krys and Brown (1990).

Results

Mean skin temperature depended firstly on air temperature ($r = 0.739$), as well as on solar radiation (0.743; Table 5, Fig. 2). Relationships between skin temperature and other meteorological parameters were lower, e.g. correlation coefficient for water vapour pressure was 0.67 and for wind speed −0.13. The multiple correlation coefficient of skin temperature and air temperature plus global solar radiation was 0.827. Addition of any other factor did not increase the predictive power.

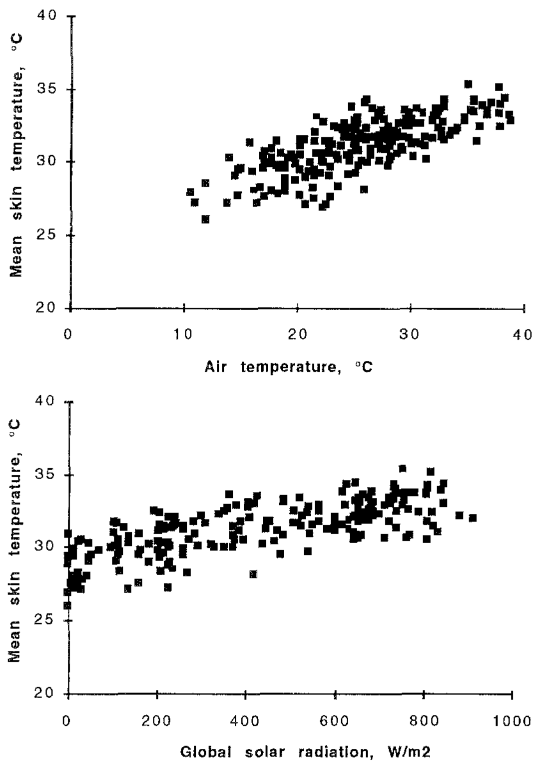

Fig. 2. Simple regression relationships of mean skin temperature (T_s) and air temperature (T_a) and global solar radiation (Q_{global}), respectively

Table 5. Stepwise, multiple linear regression of mean skin temperature and several measures of the ambient climate ($n = 214$, $P \leq 0.05$)

Factor	Correlation coefficient (r)
Global solar radiation	0.743
Air temperature	0.739
Water vapour pressure	0.669
Wind speed	−0.129
Cloudiness	−0.353
Solar radiation/air temperature	0.827
Solar radiation/air temperature/vapour-pressure/wind speed	0.829

Table 6. Statistical relations between mean skin temperature (T_s) and different indices of incoming solar radiation (R_{cl}, R or R_p) as well as mean radiant temperature (Mrt)

Method	Correlation coefficient	SEE
Methods including clothing factor (R_{cl}):		
Budyko	0.68	1.24
Breckenridge	0.69	1.25
Lee	0.51	1.49
Methods not including clothing factor (R):		
Budyko	0.69	1.23
Breckenridge	0.69	1.25
Lee	0.51	1.49
Terjung	0.67	1.28
Morgan	0.64	1.34
Tuller	0.57	1.42
Höppe	0.62	1.36
Nielsen	0.67	1.28
de Freitas	0.61	1.37
Krys (R_p)	0.68	1.26
Mean radiant temperature (Mrt):	0.72	1.20

SEE, Standard error of estimation

Table 7. Comparison of potential absorbed solar radiation (R_p) with solar radiation incoming to the standing man (R) and mean radiant temperature (Mrt)

Method	R/R_p proportion			Correlation coefficient	SEE	
	Mean	Min.	Max.		W/m^2	%
Budyko	1.04	0.72	1.58	0.93	25.0	21
Terjung	0.79	0.17	3.84	0.72	45.4	37
Morgan	0.69	0.03	4.09	0.75	43.3	36
Tuller	0.58	0.08	1.91	0.50	56.8	47
Breckenridge	1.06	0.35	1.91	0.93	23.4	19
Lee	2.51	0.75	17.66	0.62	51.4	42
Nielsen	1.61	1.18	9.45	0.97	14.5	12
de Freitas	1.44	0.96	2.70	0.78	40.6	33
Höppe	1.51	0.33	2.78	0.91	27.8	23
Mrt	–	–	–	0.93	24.1	20

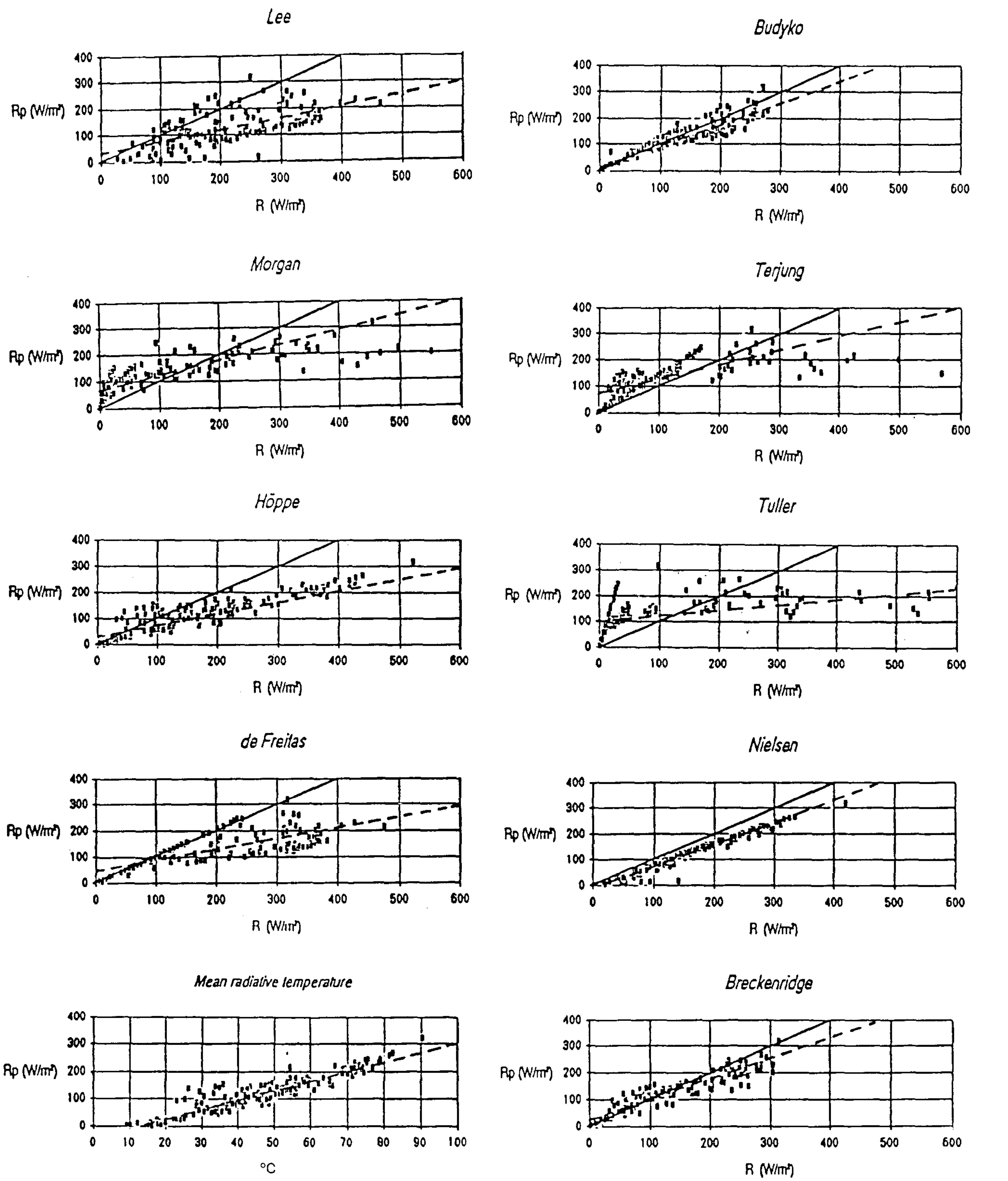

Fig. 3. Simple regression relationship of potential absorbed solar radiation (R_p) and solar radiation absorbed by unclothed man (R) at different methods of estimation as well as mean radiant temperature (*Mrt*); regression lines are *dotted* and lines of identity are *solid*

Solar heat load defined by the mean skin temperature was best explained by the mean radiant temperature index (Table 6). The correlation coefficient was 0.72 and the standard error of estimation was 1.20. Corresponding values for the Budyko and Breckenridge methods were slightly lower (0.69) and their SEE were 1.24 and 1.25, respectively. The correlation coefficient with the Lee method was considerably lower (0.51) and SEE was higher (1.49). The quantity of absorbed solar radiation of clothed man (R_{cl}) was similar for the Budyko and Breckenridge formulas and did not exceed 80 and 120 W/m^2, respectively. However R_{cl} values obtained by the Lee equation reached 300 W/m^2.

The smallest deviations of R values from R_p values were observed with the Budyko method. R values were, on the average, about 4% higher than R_p values and varied from −28 to +58%, only (Table 7). The mean deviation of R values was slightly greater (+6%) with the Breckenridge method; the range was −65 to +91%. Deviations of R values calculated by the use of other methods were considerably higher and varied from −97 to +1666%. The highest correlation coefficient of R and R_p values was observed with the Nielsen method (0.97) and the standard error of R estimation was only 14.5. However R values were always higher than R_p values; mean deviation was +61% and minimum and maximum values +18 and +845%, respectively. High r coefficients for R_p and R values (0.91–0.93) were also noticed with the Budyko, Breckenridge and Höppe methods. A similar correlation (0.93) was observed for mean radiant temperature. For other methods the r-values were considerably lower (0.50–0.78). Figure 3 shows that the best fit of regression and identity lines occurs with the Budyko, Breckenridge, Nielsen and mean radiant temperature methods.

Discussion

As expected, mean skin temperature was highly correlated to both air temperature and solar radiation and, in particular, the combination of these parameters (0.827). Thus about 68% of variation could be explained by changes of T_a and Q_{global}; for solar radiation, only, the value was 55%. The low correlation of skin temperature and wind speed was caused by the fact that temperature of the body surface was measured on clothed subjects. The high correlation coefficient for global solar radiation was remarkable, as skin temperature and air temperature were considerably higher in the second half of the day. Thus with the same intensity of solar radiation, showing a symmetrical distribution around midday, skin temperature may be higher or lower depending on the time of day.

Because skin temperature, which depends on absorbed solar radiation, was measured on clothed subjects, a full analysis of solar heat load was possible only with the Budyko, Breckenridge and Lee methods. It was noticed, however, that with the methods including a clothing factor, correlation coefficients with skin temperature were just the same for R and R_{cl} values (Table 6). The resistance to heat transfer by clothing is a constant in the equations. Thus despite different absolute values, the relationships of R_{cl} and R with skin temperature will be the same. The above remark allows us to confirm relations of T_s and R values for other methods also. Relatively high r-values were observed with the Krys, Nielsen and Terjung methods (0.67–0.68). However it is necessary to mention that with Terjung's method the skin temperature was rising faster within a low R range than at the high one.

As described in the section "Review of formulas of solar heat gain", almost all methods estimate absorbance of solar radiation (R) using theoretical principles of solar geometry. Only the formula of Krys and Brown (1990) was elaborated on the base of experimental measurements. The best agreement between R_p and R was found with the Budyko, Breckenridge, Nielsen and Höppe methods; mean R errors did not exceed 23%. However with the last two methods deviations could sporadically, reach 200–800%. With other methods R-values were unrealistically high and could reach 900 W/m^2. It seems that poor agreement in these cases is connected with inadequate estimation of direct or diffuse solar radiation quota. For example, with the Terjung and Morgan methods the authors used total amount of diffuse radiation. Also, the coefficients for the estimation of direct solar flux, used by the Terjung, Tuller, Morgan, Lee and de Freitas equations, appear inadequate. Their approaches do not consider in a realistic way the radiation effect on the human body.

Taking into consideration the thermal insulation properties of clothing, we noticed that the best T_s to R_{cl} conformity was achieved by the Budyko and Breckenridge equations. Calculated absorbed solar radiation was similar to those measured by Nielsen (1990). R_{cl} values calculated by the use of the Lee method were considerably too high (200–300 W/m^2). This probably results from the differences in the coefficients for resistance to radiant heat transfer by clothing. With the Budyko and Breckenridge methods, calculated radiant transmittance for clothing (1 clo) was similar to values observed by Nielsen for cotton material, i.e. 27 and 37%, respectively. This value was calculated at 60% with the Lee method. Budyko's I_{rc} and Breckenridge's U coefficients probably provide the best expression, so far, of the resistance to radiant heat transfer by clothing. It is necessary to mention that solar heat transfer by clothing is not a static process but depends on air and subject movement. Unfortunately, only one of the compared clothing coefficients includes a dynamic factor, Budyko's I_{rc} index.

In conclusion, the results showed that solar heat load on a standing man was best expressed by use of the Budyko, Breckenridge and mean radiant temperature methods. However, restrictions apply to most of the methods discussed:

they use a vertical cylinder as an analog model of the human body;

clothing heat transfer characteristics apply to static conditions only; and

effects of body motion and postural changes are not sufficiently accounted for.

In order to improve the general application and the predictive power of the models, more sophisticated expressions need to be developed to include other analog models of man as well as dynamic conditions of heat transfer.

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References

Aizenshtat BA (1986) Health and the heat balance of the human body. Proceedings of Symposium on Climate and Human Health, Leningrad, pp 170–181

Blazejczyk K, Krawczyk B (1991) Influence of climatic conditions upon heat balance of the human body. Int J Biometeorol 35:103–106

Breckenridge JR, Goldman RF (1971) Solar heat load in man. J Appl Physiol 31:659–663

Breckenridge JR, Goldman RF (1972) Human solar heat load. Proceedings of ASHRAE Semiannual meeting, New Orleans, pp 65–69

Breckenridge JR, Goldman RF (1977) Effect of clothing on bodily resistance against meteorological stimuli. In: Tromp WS (ed) Progress in human biometeorology. Sweits & Zeitlinger, Amsterdam, pp 194–208

Budyko MI (1959) About heat balance of living organisms (in Russian). Izv An SSSR Ser Geogr 2:29–35

Budyko MI, Tsytsenko GV (1960) Climatic factors of thermal sensations on man (in Russian). Izv An SSSR Ser Geogr 3:3–11

Burt JE, O'Rourke PA, Terjung WH (1982) The relative influence of urban climates on outdoor human energy budgets and skin temperature. I. Modelling considerations. Int J Biometeorol 26:3–23

Clark JA, Cena K (1976) Solar and thermal radiative heat loads in the energy balance of man. Int Mech Eng 5:75–78

de Freitas CR, Ryken MG (1989) Climate and physiological heat strain during exercise. Int J Biometeorol 33:157–164

Fanger PO (1970) Thermal comfort. Danish Technical Press, Copenhagen

Höppe P (1982) Physikalische Prinzipien in der Biometeorologie. Promet Meteorol Fortbild 3/4:4–9

Jendritzky G (1990) Bioklimatische Bewertungsgrundlage der Räume am Beispiel von mesoskaligen Bioklimakarten. In: Schirmer H (ed) Methodik zur räumlichen Bewertung der thermischen Komponente im Bioklima des Menschen. Akad für Raumforschung und Landesplanung, Hannover, pp 7–69

Jendritzky G, Nübler W (1981) A model analyzing the urban thermal environment in physiologically significant terms. Arch Met Geophys Biokl B29:313–326

Krys SA, Brown RD (1990) Radiation absorbed by a vertical cylinder in complex outdoor environment under clear sky conditions. Int J Biometeorol 34:69–75

Lee DHK (1980) Seventy-five years of search for a heat index. Environm Res 22:331–356

Liopo TN, Tsytsenko GV (1971) Climatic conditions and thermal state of man (in Russian). Leningrad

Morgan DL, Baskett RL (1974) Comfort of man in the city. An energy balance model of man-environment coupling. Int J Biometeorol 18:184–198

Nielsen B (1990) Solar heat load: heat balance during exercise in clothed subjects. Eur J Appl Physiol 60:452–456

Nielsen B, Kassow K, Aschengreen FE (1988) Heat balance during exercise in the sun. Eur J Appl Physiol 58:189–196

Terjung WH (1974) Energy balance between atmosphere and living organisms. In: Tromp WS (ed) Progress in biometeorology. Elsevier, Amsterdam, pp 55–58

Terjung WH, Louie SS-F (1971) Potential solar radiation climates of man. Ann Assoc Am Geogr 61:481–500

Terjung WH, O'Rourke PA (1983) Energy budget changes caused by varying solar angles, cloud scenarios, and air temperature in contrasting landscape. Int J Biometeorol 27:3–16

Tuller SE (1975) The energy budget of man: variations with aspect in a downtown urban environment. Int J Biometeorol 19:2–13

Underwood CR, Ward EJ (1966) The solar radiation area of man. Ergonomics 9:155–168