The effects of Solar radiation on human thermoregulatory system: Experimental investigation into thermal strain caused by solar radiation

MARC B MCNEILL AND KEN C PARSONS

Department of Human Sciences, Loughborough University,
Loughborough, Leicestershire, LE11 3TU, UK

Keywords: Solar radiation; Standards; Heat Stress

Present methods for evaluating heat stress do not adequately accommodate for the effects of solar radiation. Heat stress whilst working outdoors in hot environments is a potential hazard, especially in industrially developing countries where a large proportion of workers are involved in agriculture. In order to conduct an ergonomics analysis of such working environments, methods that allow the short wave solar component of radiation to be incorporated should be considered. This paper thus considers solar radiation, its effects on the human thermoregulatory system and presents an experimental investigation into thermal strain caused by solar radiation. 6 Subjects performed a step test in outdoor conditions with a solar load, (t_a=21^{o}C, rh=46^{o}C, v=1.01m/s, $WBGT$=18.50^{o}C), repeating this in similar conditions in a thermal chamber with no solar load. The difference in sweat loss between the conditions was attributed to the increased load from solar radiaiton. In the conditions measured, with a cloudy sky and a low direct solar radiation the radiation incident on the human thermoregulatory system was 82W/m^2. Two existing models for solar radiation were validated and more accurate estimates for radiation in outdoor conditions were proposed

1. Introduction

1.1 Solar radiation

The emission of thermal radiation is governed by the temperature of the source. As the temperature increases the radiation changes in character as well as quantity. The peak wavelength steadily shortens as the emitter temperature increases (McIntyre, 1980). For the natural human thermal environment there are two principal sources of radiation and thermal exchanges occur with these in their two distinct bands, short wave and long-wave. The former is solar radiation, occurring in the range of 0.3*T*m, whilst the later is that which usually surround humans, radiation from surfaces below about 100°C occurring at about 0.7 to 150*T*m (Gonzalez 1993). Solar radiation thus constitutes an important heat load which can be treated somewhat differently from the long-wave heat exchanges that are usually considered in heat transfer calculations (Kerslake, 1972). This load can present a significant stress upon the human thermoregulatory system, indeed on a clear sunny day, the mean radiation incident on a human can amount to about 267W/m^2 (Burton and Edholm, 1955).

In calculating the amount of solar radiation absorbed by the human body, many factors must be considered. These include the solar intensity which will be affected by moisture and dust in the air and clouds, the surrounding terrain (for example diffuse radiation will be greater on sand than on grass), cloudiness; cross sectional area presented by the body to the sun's rays; solar incidence (azimuth and altitude of the sun); geographical location (altitude, latitude); and clothing (absorbance/radiance, thickness). Some of these factors will vary in opposite directions; for example when the sun is low the intensity will be low however the cross sectional area will be greater. (Burton and Edholm, 1955.)

When measuring stressful environments radiation is generally considered as the mean radiant temperature. This is calculated from the temperature of a standard matt black globe of standard size (150mm diameter). This however has limited validity in measuring solar radiation. It will overestimate the radiant temperature if the sun is the principal source of radiant heat (Gagge 1972). In such instances the globe should have the colour of the clothing or a correction made (Parsons 1993).

1.2 Sweat loss and Solar Load

According to the heat balance equation, heat transfer between the human and the environment must remain in equilibrium to maintain the body temperature between certain limits. Sweating mechanisms, facilitating evaporative heat loss, will respond to rises in environmental stresses. Hence evaporative heat loss is the best single physiological index of human environmental stress (Gagge 1972). If the thermoregulatory system is exposed to stress from a solar load, the sweat rate will consequently increase. Gagge (1972) cites studies by Gosselin (1947) who compared the average sweat rates of soldiers in the sun and in the shade in similar ambient conditions and found an average change of 165 g/h. From heat balance equations Gagge attributed this rise to the net radiant load on the body (i.e. the effective radiant temperature equals the sweat lost divided by the clothing area factor f_{cl}.) Making several assumptions, and using the increase in sweating, -E, to calculate the solar heat load Gagge was able to deduce from Gosselin's results the total incident irradiation from the sun.

The interaction between the effects of solar radiation, activity, clothing and posture on the sweat rate have been investigated by Givoni (1972.) Body surface area exposed to the solar load also has a significant effect on sweat loss due to solar radiation, (Table 1). Whilst clothing was found to reduce the sweat rate (Table 2), the effects of clothing on heat absorption is governed by a number of factors. These include the colour of clothing, which has small yet significant effect, (i.e. heat absorption in black garments is greater than in white garments, Nilson 1990); transparency of the surface material , and the insulation values of both the clothing and the air layer. For example additional heat absorbed by loose fitting black robes is lost through convection before it reaches the skin (Shkolnik et al., 1980). The wearing of a hat that intercepts the solar beam and similarly reduces the thermal solar load. Sen (1983) notes that the use of a wide brimmed hat, a 'Jhapi' creates a microenvironment which produces a significant decrease in the thermal strain of workers. Such a personal protective device however would have negligible effect in conditions with a large diffuse solar radiation component.

Table 1 Effect of posture on weight loss (g/h) due to solar radiation (Givoni, 1976)

Air Velocity (m/s)	Sitting	Walking
1	341	259
2.5	306	220

Table 2 Effects of solar radiation on elevation of sweat rate (g/h) in relation to clothing and work (From Givoni, 1976)

Activity	Semi-nude	Clothed	Difference
Sitting	324	132	192
Working	240	176	64
Ö	282	154	128

1.3 InternationaHeat stress Standards and solar radiation

International standards have been developed to evaluate thermal strain and allow modifications to be made to reduce the thermal stress. Solar load can present a significant stress on the human thermoregulatory system during outdoor work, yet the existing methods incorporated into international heat stress standards do not adequately account for the effects of solar radiation. For a heat stress standard to be valid for use in any hot environment as is intended, an additional requirement of it will be that it can be meaningfully used in all conditions where workers may be subjected to heat stress. In accordance with this, this project investigates solar heat load on the human thermoregulatory system; assessing methods for quantifying the thermal effects of solar radiation, evaluating existing methods of predicting such effects and proposing a practical way in which such effects can be quantified in outdoor applications.

ISO 7933 is based upon the heat balance equation predicting the amount of evaporation (E_{req}) required to maintain thermal equilibrium, hence:

$$E_{req} = M - W - C_{res} - E_{res} - C - R$$

Where;
M = metabolic power
W = mechanical power (usually taken to be zero)
C_{res} = respiratory heat loss by convection
E_{res} = respiratory heat loss by evaporation
C = heat exchange on the skin by convection
R = heat exchange on the skin by radiation

ISO 7933 was developed and validated using data from subjects in chamber trails (Vogt et al 1981, Wadsworth and Parsons 1986) and evaluated using data from industrial field conditions such as foundries and coal mines (CEC 1988). In their experiments investigating heat balance during exercise in the sun, Nielsen et al (1988) concluded that predictions of sweat loss based upon chamber experiments will under estimate values for outdoor exercise in the sun. Little work has been done on the validation of ISO 7933 for use in hot outdoor conditions. Following Nielsen et al’s conclusions, ISO 7933 may not be accurate in such environments where a short wave radiant load form the sun is present.

In its calculations for radiant heat transfer, ISO 7933 fails to accommodate for short wave radiation generated by the sun, the radiate heat transfer coefficient being estimated from data obtained from the black globe thermometer, the limitations of which have already been discussed. The scope of ISO 7933 recognises that in its present form the standard is not applicable to cases with high radiant temperature (ISO 7933). A method of estimation of the solar heat load that can be incorporated into heat transfer equations is thus required.

2. Review of different methods of Estimation of Solar load

There have been a number of studies attempting to estimate the effects of solar load on the human thermoregulatory system. These have either been based upon analogue results with measurements made from heated manikins or cylinders, or from physiological responses to solar radiation. They generally calculate the intensity of the solar radiation (direct, diffuse and albedo); the geometry of the human body (i.e. body surface area exposed) and clothing, both the thermal insulation and the absorbance/reflectance of its surface.. The following are models that are suitable for estimating solar radiation in a practical application.

2.1 Models based upon analogue results

2.1.1 Roller and Goldman, 1968

Roller and Goldman(1968), subsequently modified by Breckenbridge and Goldman (1972) presented a model for predicting the solar heat load on humans in a given radiant environment. The model was based upon measurements from an electrically heated copper manikin and considered the solar intensity, clothing characteristics, the persons size, position and orientation to the sun and wind speed. The calculations for predicting the solar heat load consisted of six equations, describing the separate heat loads resulting from absorption and transmission. Total solar heat load is the sum of these loads, respectively of direct sunlight, diffuse sky radiation and terrain reflected sunlight, thus *R* (W/m^2) is the sum of:

Transmitted direct load = $Af_a \gamma_p a \tau I$
Absorbed direct load = $Af_a \gamma_p a U I$

Transmitted diffuse load = $Af_{acl}\left[\gamma_z + \frac{\gamma_h}{2}\right]\tau D$

Absorbed diffuse load = $Af_{acl}\left[\gamma_z + \frac{\gamma_h}{2}\right]aUD$

Transmitted terrain load = $Af_{acl}\gamma_h \tau AL$

Absorbed terrain load = $Af_{acl}\gamma_h aUAL$

Where:

A= Nude (Dubois) surface area (m^2)
I= Direct solar intensity (W/m^2)
D= diffuse solar radiation (W/m^2)
AL= terrain albedo (W/m^2)
R= Solar Heat load
a= Absorbance of clothing (%)
\ = Transmittance of clothing (%)
U= reduction in heat dissipation from the skin with sunlight (dimensionless)
K_p, K_z, K_h, and f_a are dimensionless ratios expressing the projected or "silhouetted" areas.

2.1.2 Blazejczyk et al

Blazejczyk et al (1992) in their short paper present an equation for calculating solar heat load on the human. Their equation considers the 3 components of solar radiation (Direct, diffuse and albedo), absorbance, the insulation of clothing and the solar angle.

$$R = \left(\beta_1 \cdot Q_{direct} + \beta_2 \cdot Q_{diffuse} + \beta_3 \cdot Q_{reflected}\right)\alpha \cdot Cl$$

Where; J1, J2, J3 are weighting coefficients given as:

$$\beta_1 = \cot h(0.25 - 0.001h)$$

$$\beta_2 = 0.36$$

$$\beta_3 = (0.49 - 0.005h)$$

and;

R = Absorbed radiation (W/m^2)
Q = components of solar radiation (W/m^2)
Cl = clothing factor
h = Solar angle (degrees)

Whilst earlier methods of predicting solar radiation were based upon measurements from a vertical cylinder as an analogue model of the human body, the equation presented by Blazejczyk et al (1992) was based upon measurements from an ellipsoid. They found a strong correlation between their predictions of absorbed radiation and skin temperature. Although the method accounts for the solar angle, it does not consider the body posture and its orientation to the sun, similarly the colour of clothing is omitted from the calculations.

2.2 Models based upon Physiological results

2.2.1 Burton and Edholm (Thermal radiation increment)

Burton and Edholm (1955) considered a rational approach to solar heat gain, considering the effects of solar radiation as a correction to the air temperature to give an equivalent shade temperature. The factors for solar radiation that they considered were the absorbance of the clothing, a solar constant for radiation above the clouds and an estimation of "average cloudiness". Thus the magnitude of radiation energy is given in the following formula:

$$R = 58.12\left(4.6(1 - 0.9x) \times \frac{a}{100}\right)$$

Where; R= radiation (W/m^2)
x= average cloudiness
a= absorbing power of clothing (%) taken as 88% for black clothing, 57% khaki, 20 white clothing.

From this estimation for radiation energy, they proposed the thermal radiation increment (TRI) multiplying R by the insulation of the air I_a appropriate to the prevailing wind. hence:

$$TRI = 0.42(1-0.9x)aI_a \ {}^{o}C$$

The TRI is an "equivalent" temperature, correcting the effective temperature for the solar heat load. The TRI is added to the temperature to give the equivalent shade temperature. This TRI in full sunshine can amount to 2 or 3 times the resting metabolic rate (Youle et al, 1990) Burton and Edholm validated their TRI theory from physiological results of 3 semi-nude subjects sitting in direct sunlight; the difference between heat loss from evaporation and heat production being an estimate of heat loss by radiation once heat transfer from convection had been accounted for. Whilst the TRI is simplistic in that it does not account for the solar radiation area on the human body or any meteorological data relating to the solar intensity it has been incorporated by the BOHS (Youle et al, 1990) in their thermal environment technical guide for estimating a correction factor for solar radiation incident on the body.

2.2.2 Index of Thermal Strain (ITS)

In the ITS t_g is replaced with t_a and allowances made for solar load. The radiant heat load due to solar radiation is calculated using the following formula:

$$R=I_N K_{pe} K_{cl}\ [1—a(v^{0.2}-0.88)]$$

Where; R = solar radiation heat load (Kcal/hr)
I_N = normal solar intensity
K_{pe} = coefficient depending upon terrain and posture
K_{cl},,a = coefficients depending upon clothing
v= Air velocity (m/s)

2.2.3 Shapiro et al

Shapiro et al (1995) present a mathematical model to predict sweat loss that incorporates calculations for solar radiation. The initial model was based upon indoor laboratory studies (Shapiro et al 1982), however the predictions it generated were found to be inaccurate under outdoor conditions. Adjustments were therefore made to separately evaluate the radiative heat exchange, short wave absorption in the body and long wave emission from the body to the atmosphere. These were integrated into the E_{req} component to allow for a more accurate prediction of solar load.

The initial prediction of sweat loss (m_{sw}) was as follows (Shaprio et al, 1982):

$$m_{sw} = 27.9 E_{req} \left(E_{\max}\right)^{-0.455}$$

In calculating E_{req}, convective heat transfer was that proposed by Givoni and Goldman (1972) with the radiative heat transfer being adjusted to account for solar radiation. An additional correction was suggested to account for long-wave emission from body to the environment, hence:

$$E_{req}=M+H_c+H_r+H_1$$

Where;

$$H_r = 1.5 A_D \left(\frac{SL^{0.6}}{I_T} \right)$$

$$H_c = 6.45 \times A_D \times \left(\frac{T_a - T_{sk}}{I_T} \right)$$

$$H_1 = 0.047 A_D \times \frac{M_{e.th}}{I_T}$$

Where:

H_c	=	convective heat transfer coefficient (watt)
H_r	=	radiative heat transfer coefficient (watt)
H_1	=	correction for long-wave emission from body-environment (watt)
SL	=	Solar short-wave radiation (W/m^2)
I_T	=	Effective clothing insulation coefficient
A_D	=	body surface area (m^2)
$M_{e.th}$	=	Stephan Boltzman constant

(Symbols as used by Shapiro et al (1995))

2.3 Blazejczyk et al (1993) Review of different methods

Blazejczyk et al (1993) reviewed a number of methods of estimating the solar heat load on humans. Of the 10 methods reviewed, only 3 included a clothing factor in their calculations. Such methods are not considered here as they are not of a practical nature. Blazejczyk et al (1993) assessed the accuracy of the predictions using 10 subjects exposed to solar radiation and found the Roller and Goldman (1968) method to make the best predictions. They used mean skin temperature as an indicator of physiological strain, correlating it with predictions of solar heat load from the reviewed methods. This method is limited in so far as by itself, skin temperature does not give a valid evaluation of thermal physiological strain (ISO 9886).

2.4 Incorporating solar load into Required Sweat Rate Index

This investigation proposes to provide a simple method for estimating the solar load in the field and incorporating it into existing heat stress indices such as Sw_{req} (ISO 7933). The method for determining the solar load will be based upon Gagge's (1972) observations that using Partitional calirometry, the solar heat load can be deduced. If the amount of sweat produced is known under controlled conditions with no solar load, additional quantities of sweat produced in conditions under sunlight will be attributable to that solar load.

The first part of this project presents an experimental investigation into thermal strain caused by solar radiation. The aim was to quantify the thermal load caused by solar radiation in simulated outdoor work. The second part of the project aims to evaluate the existing prediction methods described above and to determine a practical method for predicting the solar effects on thermal strain.

3. Method

7 healthy male subjects (Table 3) took part in two one hour conditions, one outdoors with solar load and one ‘shaded’ in a thermal chamber. The chamber simulated all parameters except radiant temperature.

Table 3 Details of subjects who participated in investigation.

Subject	Age (Years)	Height (m)	Weight (Kg)
1	24	1.71	77.23
2	27	1.72	72.87
3	25	1.69	71.47
4	23	1.85	60.56
5	28	1.73	71.16
6	23	1.75	80.03
Ö	25	1.74	72.22
[	2.10	0.06	6.69

3.1 Experimental design

The first experiment took place on Thursday 1 August 1996 between 14:39-15:39 (solar time 14:28-15:28). This was conducted outdoors under a solar load (Solar altitude I= 44.36^{o}-36.40^{o}) with a significant cloud cover (due to the busy schedule of the Human Thermal Environmental Laboratory it was not possible to postpone the experiemtn until clouldless conditions were experienced. These ambient conditions were then simulated ‘in the shade’ in the thermal chamber at the same time the following week in order to prevent diurnal variation effects. (ISO 9886).

3.2 Environmental Measurements

Air temperature (t_a), radiant temperature (t_r), humidity (*rh*) and air velocity (*v*) were measured according to ISO 7726. The characteristics of each measuring instrument were within the range, accuracy and response time of *class s* (thermal stress.) Measurements were recorded using the Brüel & Kjær type 1213 indoor climate analyser at six minute intervals. WBGT values were recorded on a Grant Squirrel logger (Type SQ16-16U) using a wet bulb globe thermometer constructed according to specifications presented in ISO 7243. Total solar radiation was measured using an Skye pyranometer. Diffuse radiation was measured using an Skye pyranometer shielded with a custom shading ring with the suitable correction factor being applied (Drummond, 1956). Direct radiation was calculated from the global and diffuse radiation using formulae presented by Iqbal (1983).

3.3 Physiological measurements

Aural temperature (t_{au}), and mean skin temperature (t_{sk}) (using Ramanathan's four point weighting coefficient) were recorded at 1 minute intervals using Grant Squirrel datalogger (Type SQ16-16U and SQ32-16U.) Metabolic rate was estimated from step height and step speed using an adaptation of the equation presented in ACSM guidelines (ACSM, 1991):

$$M = \left(\left[Steps.\min^{-1} \times 0.35\right] + \left[StepHeight \times Steps.\min^{-1} \times 1.8\right]\right) \times \frac{1}{3.5} \times 58.15$$

Heart rates were taken using Polar Sports testers, and sweat loss was calculated from the body mass loss. Evaporative heat loss due to sweating was calculated from body mass loss, according to ISO 7933, 1W/m^2 = 2.6g/h (for a standard subject, 1.8m^2 of body surface).

3.4 Clothing

Subjects wore dark blue boiler suits with a clo value of 0.52 (ISO9920.) The transmittance was estimated to be 0.02 and absorbance 0.7. Light weight sun-visors were worn to protect the eyes from direct sunlight.

3.5 Experimental Procedure

The equipment was calibrated prior to each experiment. Subjects were briefed before the experiments on the objectives, procedures and potential hazards. They then completed a form consenting to participate in the experiment. It was explained that they were free to withdraw at any time without giving any reasons. Subjects were measured and weighed (semi-nude). Their clothes were weighed separately. Skin and aural thermistors and heart rate monitors were placed on the subjects in thermally neutral rooms (21 ^{o}C). They then exercised for one hour in an open space facing the sun, performing a step test in time to a metronome set at a rate of 60bpm on a vertical rise of 150mm. Each movement was cued by a pulse from the metronome. Subjects were advised to alter the choice of lead foot periodically to avoid unequal leg strain. At the end of the hour they were again weighed semi-nude and their clothes weighed separately. They repeated this procedure on their next visit to the laboratory in the thermal chamber. On completion of the two trials the subjects were paid £10 for their inconvenience. The difference between sweat lost in shade and solar conditions is attributable to the stress of the solar load. This differences were thus analysed using a Wilcoxon matched pairs statistical test.

Figure 1 Subjects in outdoor solar condition

Figure 2 Subjects in chamber "shade" condition

4. Results

4.1 Environmental Conditions

With the exception of air velocity and radiation, the environmental parameters were kept constant within the range of the measuring equipment between the two conditions (Table 4). During the outdoor experiment there was a thick cloud cover, subsequently diffuse radiation was considerably greater than direct radiation (Table 5).

Figure 3 Cloud cover during experiment

Table 4 Mean environmental conditions in both experiments

	Solar Conditions		Chamber Conditions		Difference
	Ö	[	Ö	[	
t_a	21.35 ^oC	0.58	21.31 ^oC	0.55	0.03^oC
rh	45.97 %	2.10	49.71 %	1.60	-3.75%
v	1.01 m/s	0.26	0.80 m/s	0.12	0.21 m/s
t_g	27.32 ^oC	1.13	21.79 ^oC	0.17	5.53^oC
tr	40.08 ^oC	3.89	22.78 ^oC	0.99	17.30^oC
WBGT	18.50 ^oC	0.38	17.60 ^oC	0.12	0.91^oC

Table 5 Mean Solar radiation during outside experiment

	Ö	[
Total	335.00W/m^2	63.17
Diffuse	327.21W/m^2	37.76
Direct	11.15W/m^2	51.56
Albedo	41.29W/m^2	5.50

4.1.1 Physiological Results

Whilst the heart rate (Figure 4), aural temperature (Figure 5) and four point mean skin temperature (Figure 6) were greater during the conditions with a solar load, the differences in the last 5 minutes of exposure were not significant. Mean sweat rates of 475.1g/h (182.7 w/m^2) in the solar condition and 262.4 g/h (100.9 w/m^2) were recorded with a mean difference in sweat lost between the two conditions of 212.7g (81.8w/m^2) (Figure 7), the difference being significant (P = 0.0277). The amount of sweat trapped in the clothing in both conditions was negligible.

From the aural temperatures it is apparent that there was no difference in the heat storage, the magnitude being constant between the conditions. Air temperature, metabolic rate, clothing, and relative humidity were the same in both conditions. Air velocity was slightly greater in the solar condition, resulting in an increase in heat loss by convection of approximately 5W/m^2 (from calculation ISO 7933). Radiation and sweat loss were the principle parameters that differed between the two conditions, from this, the increase in sweat loss in the outdoor conditions can be attributed to the increase in radiation.

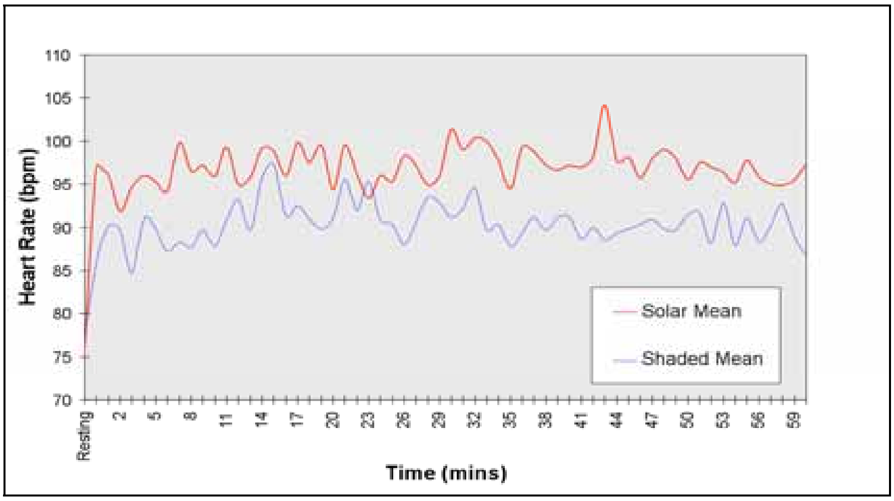

Figure 4 Mean heart rate of all subjects in solar and shade conditions

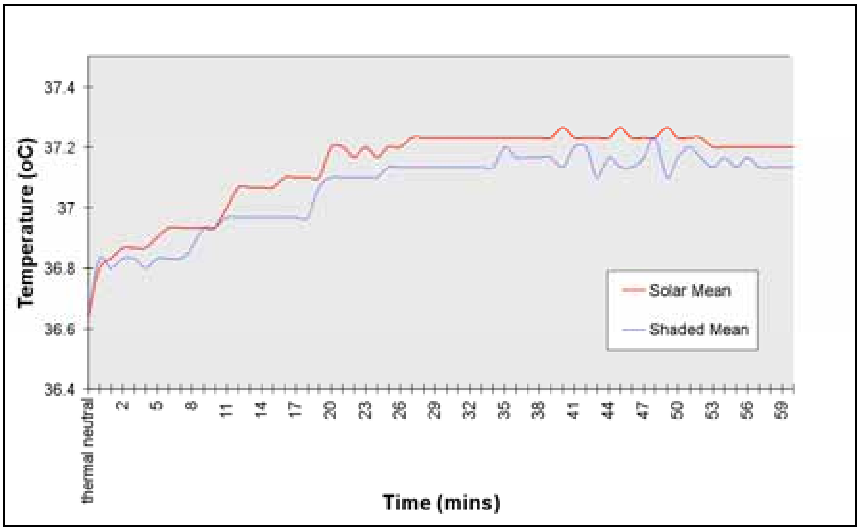

Figure 5 Mean aural temperature of all subjects in solar and shade conditions

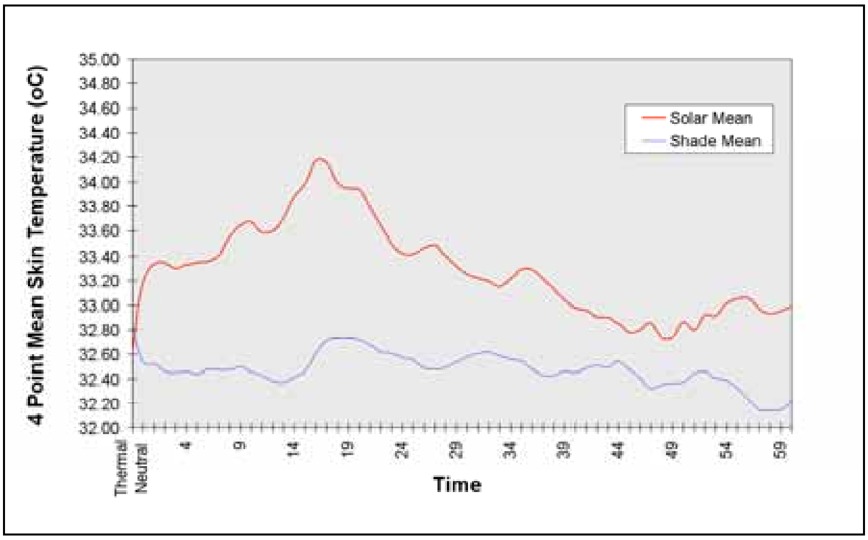

Figure 6 Mean four point mean skin temperature in solar and shade conditions

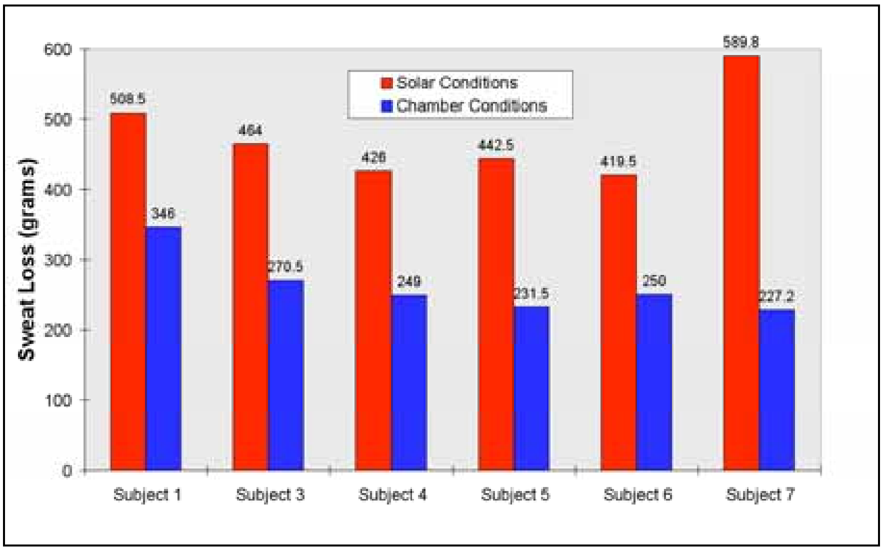

Figure 7 Sweat loss for all subjects in solar and shade conditions

5. Discussion

From the results it can be seen that the stress from work in outdoor conditions is greater than that from conditions similar in all but solar radiation. Even without direct sunlight, the load on the human thermoregulatory system from the various components of solar radiation is significant. For the conditions investigated this amounted to a mean of 82W/m^2.

In order to maintain heat balance, changes in sweat loss occur in response to changes in the stresses on the thermoregulatory system. With the exception of the radiant heat load, the stresses in the field conditions and chamber conditions were the same. The change in sweat loss was thus directly attributable to the solar load. This is consistent with Gagge and Hardy's (1967) findings that where the ambient temperature is constant, the change in evaporative loss caused by sweating may be used to measure radiation. From the heat balance equation, the sweat rate can therefore be used to measure quantitatively the solar radiant heat load with the solar radiation equating with the difference between sweat lost in the field conditions and sweat lost in the chamber conditions, hence:

$$R_{sun} - R_{shade} = \Delta E$$

It must be noted that the mean air velocity in the chamber was less than that in the field, where gusting winds prevented a constant air velocity to be measured. At higher velocities, the surface temperature of the clothing will be lower (Burton and Edholm 1955) and consequently sweat loss would be reduced, the difference in sweat loss between field and chamber trials may therefore be slightly exaggerated, however when convection is calculated according to ISO 7933 the differences between the two conditions is minor.

Using the heat balance equation it is possible to validate the results by entering values into the equation. The heat balance equation as follows can be adjusted where storage is zero and E_{req} can be assumed to be the measured sweat rate as there was no sweat trapped in the clothing.

$$E_{req} = M - W - C_{res} - E_{res} - C - R$$

Metabolic rate was estimated to be 176.7 W/m^2. Convection, was calculated according to the following equation:

$$C = h_c . F_{cl} (t_{sk} - t_a)$$

Where

$$h_c = 3.5 + 5.2\, v_{ar} \quad (v_{ar} < 1 \text{ m/s})$$
$$h_c = 8.7\, v_{ar}^{0.6} \quad (v_{ar} \geq 1 \text{ m/s})$$

and

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

Where

$$h_r = \sigma\, \varepsilon_{sk}\, A_r / A_{Du}\, [(t_{sk} + 273)^4 - (t_r + 273)^4] / (t_{sk} - t_r)$$

and

$$f_{cl} = 1 + 1.97\, I_{cl}$$

C_{res} and E_{res} were estimated using the following equations where T_{ex} is equal to 35°C and P_{ex} is equal to 5.624Kpa:

$$C_{res} = 0.014M\,(t_{ex} - t_a)$$

$$E_{res} = 0.0173\,M\,(p_{ex} - p_a)$$

Thus inputs to the heat balance equation were as follows:

Input	Solar Condiitons	Shaded Condiitons
E	182.7	100.9
M	176.7	176.7
C	63.0	57.0
Cres	3.4	3.4
Eres	13.3	13.3

Hence for the shade condition:

$$R=(M-W)-C-C_{res}-E_{res}-E$$

$$R=(176.7-0)-57.0-3.3-13.3-100.9$$

$$R=2.0W/m^2$$

A negligable result, i.e. there was no solar radiation.

For the solar condition,

$$R=(176.7-0)- 63.0-3.4-13.3-182.7$$

$$R=-85.7W/m^2$$

This corresponds with the solar heat load measured to be $82W/m^2$.

5.1.1 Comparison with Estimations

The models presented by Roller & Goldman (1968), Blazejczyk et al (1993) Givoni (1976) and Shapiro et al (1995) were run with the environmental results from the solar conditions. The predictions are shown in Table 6 against the actual result. For the conditions of this experiment, with the exception of Roller and Goldman (1968) prediction, all the models overestimated the solar load. The results are consistent with Blazejczyk et al (1993) findings; the Roller and Goldman (1968) model provided a realistic estimation of the radiation heat load.

For Shapiro's (1995) model, E_{max} was calculated using ISO 7933, this model also provided a fairly accurate prediction.

Table 6 Predictions of solar load and actual load measured

Method	Prediction (W/m^2)
Roller & Goldman	99
Blazejczyk	121
Givoni	49
Shapiro	102
Actual	82

As anticipated, ISO 7933 underestimated the radiation incident on subjects in the outdoor condition, calculating it to be 15.5W/m^2. This resulted in a predicted required evaporation of 112.2 W/m^2. This is considerably less then the actual evaporation measured of 182.7W/m^2. However when R is adjusted to be 82W/m^2, (the solar heat load measured in this study), a more accurate prediction of 179W/m^2 is made by the model.

6. Conclusions

To conclude, it has been shown that even without a direct solar load, the radiation incident on the human thermoregulatory system can be considerably more than in a shaded condition with no solar load. In the conditions measured, the load on the body from solar radiation amounted to a mean of 82Wm^2.

ISO 7933 underestimates radiation in conditions with a solar load. Given this shortcoming, a more valid calculation for estimating heat flow by radiation at the surface of the skin is required. This study has identified and validated two predictive models that provide this. For estimating the solar heat load on the human thermoregulatory system, in the conditions investigated, the models presented by Roller and Goldman (1968) and Shapiro et al (1995) provide fairly accurate predictions that may be incorporated into the standard for use in environments with solar radiation.

To conclude, it has been shown that even without a direct solar load, the radiation incident on the human thermoregulatory system can be considerably more than in a shaded condition with no solar load. In the conditions measured, the load on the body from solar radiation amounted to a mean of 82Wm^2. This study has identified and validated two predictive models; for the conditions investigated the models presented by Roller and Goldman (1968) and Shapiro et al (1995) for estimating the solar heat load on the human thermoregulatory system provide fairly accurate predictions.

The actual radiation incident on subjects in outdoor conditions has been shown to exceed measurements made by existing tools. For example the black globe has limited validity for use conditions with solar load, t_r as calculated from t_g in the solar conditions was measured to be 27.3°C. Using ISO 7933, the radiant load was calculated to be 15.8W/m^2, resulting in a predicted sweat rate of 268.3 W/m^2. This is considerably less then the actual sweat rate measured of 182.7W/m^2. However when R is adjusted to be 82W/m^2, (the solar heat load measured in this study), the sweat rate from ISO 7933 is accurately predicted to be 185.1W/m^2.

These results show that the existing methods for measuring radiation are inadequate for conditions with a solar load. Considering this, and from Roller & Goldman (1968), using hypothetical predictions of solar radiation, a simple estimation for solar radiation according to differing cloud covers is proposed (Table 7). These figures are for subjects working facing the sun, wearing dark clothing, and a solar angle of 45°C. The magnitude of radiation will differ for different altitude and azimuths to the sun and colour of clothing, however these estimations allow a more accurate value for radiation to be incorporated into ISO 7933 than is presently available.

Table 7 Estimation of solar load for different cloud covers

Cloud cover	Radiant Heat Load (W//m^2)
Total Cloud	80
Partial Cloud	160
Clear sky	240

7. References

BLAZEJCZYK K., NILSSON, H., and HOLMÉR, I., 1992, A modified equation for the calculation of solar heat load in man, in Lotens, W. A. and Havenith, G. (ed.), *Proceedings of the Fifth International Conference on Environmental Ergonomics*, 82-83.

BLAZEJCZYK K., NILSSON, H., and HOLMÉR, I., 1993, Solar heat load on man; Review of different methods of estimation International Journal of Biometeorology **37** 125-132.

BRECKENBRIDGE, J. R. and GOLDMAN, R. F., 1972, Solar Heat Load, *ASHRAE Trans.*, **78**, 110-119.
BURTON, A. C. and EDHOLM, O. G., 1955, *Man in a Cold Environment* Edward Arnold, London.
CEC, 1988, *Heat Stress Indices Proceedings 25th & 26th October 1988*, Commission of the European Communities, Health and Safety Directorate, Luxembourg.
DRUMMOND, A. J., 1956, On the measurement of sky radiation, *Arch. Meterol. Geophys. Bioklimatol. Ser.* B**7** (3/4), cited in Iqbal, M., 1983, An introduction to solar radiation, Academic Press, Toronto.
GAGGE, A. P. and HARDY, J. D., 1967, Thermal radiation exchange of the human by Partitional calorimetry, *Journal of Applied Physiology* **23**, 2, 248-258.
GAGGE, A. P., 1972, Partitional Calorimetry in the Desert in Yousef, M. K., Horvath, S. M., and Bullard, R. W., (ed.) *Physiological Adaptations Deserts and Mountain*, Academic Press, New York, 23-51.
GONZALEZ, R. R., 1993, Biophysics of heat transfer and clothing considerations, in Pandolf, K.B, Sawka, M. N., and Gonzalez, R. R., (ed.,) *Human performance physiology and environmental medicine at terrestrial extremes* Brown and Benchman, Massachusetts.
GOSSELIN, R. E., 1947, Rates of sweating in the desert, in Adolph, E. F., (ed.,) *Physiology of Man in the Desert*, Wiley, (Interscience,) New York, Cited in Gagge, A. P., 1972, Partitional Calorimetry in the Desert in Yousef, M. K., Horvath, S. M., and Bullard, R. W., (ed.) *Physiological Adaptations Deserts and Mountain*, Academic Press, New York, 23-51.
GIVONI, B. 1976, *Man, Climate and Architecture*, Applied Science Publishers Ltd., London.
GIVONI, B. and GOLDMAN, R.F., 1972, Predicting rectal temperature response to work, environment and clothing, *Journal of applied Physiology*, **32**, 812-822.
IQBAL, M., 1983, *An introduction to solar radiation*, Academic Press, Toronto.
ISO 7243, 1989, Hot environments- Estimation of heat stress on working man based on the WBGT-index (wet bulb globe temperature,) ISO, Geneva.
ISO 7726, 1985, Thermal environments-Instruments and methods for measuring physical quantities, ISO, Geneva.
ISO 7933, 1989, Hot environments Analytical determination and interpretation of thermal stress using calculation of required sweat rate, ISO, Geneva.
ISO 9886,1992, Evaluation of thermal strain by physiological measurements, ISO, Geneva.
ISO 9920, 1995 Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble, ISO, Geneva.
KERSLAKE, D.MCK., 1972, *The Stress of Hot Environments*, Cambridge University Press.
MCINTYRE, D. A., 1980, *Indoor Climate*, Applied Science Publishers, Essex.
NIELSEN, B., KASSOW, K., and ASCHENGREEN, F. E., 1988, Heat balance during exercise in the sun, *European Journal of Applied Physiology*, **58**, 189-196.
NIELSEN, B., 1990, Solar heat load: heat balance during exercise in clothed subjects, *European journal of Applied Physiology*, **60**, 452-456.

PARSONS, K. C., 1993, *Human thermal environments*, Taylor and Francis, London.
ROLLER, W. L. and GOLDMAN, R. F. 1968, Prediction of solar heat load on man, *Journal of Applied Physiology*, **24** 5 717-721.
SEN, R. N., 1983, Tea leaf plucking—workloads and environmental studies, *Ergonomics,* **26**, 887-893.
SHAPIRO, Y., PANDOLF, K. B. and GOLDMAN, R. F., 1982, Predicting sweat loss response to exercise, environment and clothing, *European Journal of Applied Physiology*, **48**, 83-96.
SHAPIRO, Y., MORAN, D., EPSTEIN, Y., STROCSCHEIN, L., and PANDOLF, K. B., 1995, Validation and adjustment of the mathematical prediction model for human sweat rate responses to outdoor environmental conditions, *Ergonomics*, **38**, 5, 981-986.
SHKOLNIK, A, TAYLOR, C. R. AND FINCH, V., 1980, Why do Bedouins wear black robes in hot deserts? *Nature*, **283**, 24, 373-375.
VOGT, J. J., CANDAS, V., LIBERT, J. P. and DAULL, F., 1981, *Required sweat rate as an index of thermal strain in industry*, in Cena, K. and Clark, J. A., (eds.) *Bioengineering, Thermal physiology and Comfort*, Elsevier, Amsterdam, 99-110.
WADSWORTH, P. M., and PARSONS, K. C., 1986, Laboratory evaluation of ISO DIS 7933 (1983)Analytical determination of heat stress, in Osborne, D. J., (ed.), *Contemporary Ergonomics*, Taylor and Francis, London, 193-197.
YOULE, A., COLLINS, K. J., CROCKFORD, G. W., FISHMAN, D. S., PARSONS, K. C. and SYKES, J., 1990, *The Thermal Environment*, BOHS Technical Guide No. 8, Science Reviews Ltd., Leeds.