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Solar heat load: heat balance during exercise in clothed subjects

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Summary. Six subjects exercised for 60 min on a cycle ergometer. Their backs were exposed to an artificial 'sun' with a spectral distribution similar to sunlight and an intensity of 724 W m^{-2}. Each subject took part in four experiments in random order: wearing suits of polyester (insulation value = 0.5 clo), white (WP) or black (BP), or cotton (0.6 clo), white (WC) or black (BC). Measured by partitional calorimetry, the calculated heat losses and gains for the four conditions balanced within less than 10%. The differences between the short-wave radiation gains of subjects in white or black garments were small. This is due to the transparency of the white materials, which allows a larger percentage of the radiation to penetrate the clothing. The surface temperatures of the sun-exposed areas were very high, especially in the black suits. This promotes dry heat loss. Therefore the sweat loss in the black suits and the differences between the black and white clothes became relatively small. The physiological strain in steady-state exercise, as expressed by average heart rates, was 142 (WP), 154 (BP), 151 (WC), and 160 (BC) beats min^{-1}; the sweat losses were 649 (WP), 666 (BP), 704 (WC), and 808 (BC) g. For both of these measures values for white polyester were significantly less than those for black cotton.

Key words: Oesophageal temperature - Skin temperature - Sweat rate - Solar head load - Clothing

Introduction

In a recent study (Nielsen et al. 1988) we examined the physiological effects of the heat load from the sun in subjects exercising outdoors, dressed in only small, white shorts. Studies in natural environments with animals (Borut et al. 1979; Finch et al. 1980; Ellis 1980) and our above-mentioned study show that the solar heat load can be of considerable magnitude. The colour of the animal is very important for the strain: black fur or feathers lead to a greater heat absorption and to a larger evaporative heat loss. For humans the colour of the skin and clothing is also of importance for the reflectance and absorbance of the sun's radiation (e.g. Blume 1945; Clark et al. 1973; Clark and Cena 1978), but few studies have qualitative measurements of the heat balance and of the variations in physiological strain with the colour of the clothing. The purpose of the present study was to measure the heat load due to the sun's radiation in exercising subjects in black and white clothing. In addition the importance of the nature of the fabric (polyester or cotton material) was investigated.

Initial experiments were conducted outdoors, but the weather conditions were so unstable that the experiments had to be brought indoors, into the Technical University of Denmark, Thermal Insulation Laboratory. In their artificial sunshine, from solar simulators built to test solar conservation panels, the radiation intensity and wavelength spectrum were of the same magnitude as in our previous outdoor experiments (Nielsen et al. 1988).

Methods

Six subjects (three male and three female) each participated in four experiments, one in each of the garments: white polyester (WP), black polyester (BP), white cotton (WC), and black cotton (BC). The subjects had the following characteristics: age 25 (range 23-31) years, height 179 (range 167-188) cm, weight 70 (range 56-82) kg, surface area 1.86 (1.62-2.02) m^2, projected area 0.221 (0.175-0.246) m^2.

For a given subject all four trials were conducted in random order at the same time of day. Each subject was equipped with six skin thermocouples, an oesophageal probe, and electrodes (ECG) for heart rate recordings. Wearing only briefs they put on the selected garment (jogging suit with long sleeves, and loose, long pants) and sneakers. The clothes had been weighed before in a polyethylene bag and kept ready for use.

Thereafter the subject sat on the cycle ergometer. The mechanically braked ergometer (Stiga, Glostrup, Denmark) was suspended in a balance (Krogh and Trolle 1936) so that evaporative weight loss could be measured continuously. This apparatus was situated about 10 m from the artificial sun panel, a 1.5 × 2.5-m rack with 36 iodide lamps, which irradiated the subject from the back. The balance was adjusted and resting measurements were taken. Then the subject started to exercise at 60 rpm at an intensity of 108 W (65 W in one subject) and continued for 60 min. When the subject stopped the garment was quickly taken off and put back into the polyethylene bag so that it could be weighed for determination of its sweat content.

Measurements. The *oxygen* consumption ($\dot{V}O_2$) was measured by the Douglas bag method at 15, 35, and 55 min. A Tissot spirometer was used for volume measurements, and the percentages of O_2 and CO_2 in the bags were determined with an Ametek O_2 analyser, Applied Electrochemistry (S-3A, Pittsburg, Pa, USA), and a Mogan infrared CO_2 analyser (Rainham, UK), respectively. *Heart rate* (HR) was recorded from the ECG, and monitored by an oscillosope (Siemens, Albertslund, Denmark) every 5 min.

The *body weight* loss during exercise was recorded continuously via a potentiometer attached to the lever arm of the Krogh balance. The potentiometer signal, reflecting the changes in position of the lever arm of the balance, was recorded on a two-channel, pen recorder (Linseis, Selb, FRG). The signal was calibrated by placing or removing known weights on the suspended ergometer. The accuracy of the weighing was ±10 g during exercise.

Temperatures, oesophageal (T_{es}) and skin (T_{sk}), were measured with thermocouples connected to an electrical thermometer (Ellab CTF84, Rødovre, Denmark) and recorded every 2–5 min. T_{es} was measured in the deep oesophagus, and the skin thermocouples were placed on the chest, abdomen, shoulder, lower back, forearm and front of the thigh. The surface temperature of the face and the clothing was measured every 10 min with a handheld radiometer (AGA thermopoint 80, Danderyd, Sweden). The surfaces of the frontal and dorsal side of the subject were scanned evenly from a distance of about 1 m. The built-in emission factor of the radiometer was set at $\varepsilon = 0.98$. The average skin temperature ($\overline{T}_{sk}$) was calculated as the simple sum of the six thermocouple readings and the face temperature (measured with the radiometer), divided by 7. The average surface temperature (measured with the radiometer) ($\overline{T}_{cl}$) was calculated as $\overline{T}_{cl} = [T_{face} + 2(5 \times T_{front} + 2 \times T_{back})]/15$. The weighting factors of Hardy and DuBois (1938), were used as basis for this estimation of relative areas.

The mean radiant infrared temperature ($\overline{T}_{r(ir)}$) was also measured with the radiometer. Walls, ceiling and floor were scanned every 10 min (emission factor 0.98) with equal weighting. The total 'solar' radiation (R_{tot}) was measured by a solarimeter (Kipp and Zonen, Delft, Holland) to the right and left of the subject in a plane parallel to the sun-exposed back, and on the right side also perpendicular to the radiation source at an angle of 22.5° to the horizontal, at the level of the back of the seated subject. The output of the solarimeter was recorded by the pen recorder (Linseis, LM 23, Selb, FRG).

The ambient air temperature (T_a) was measured with a mercury thermometer shielded with aluminium foil and placed in the 'shade' behind a cardboard shield (where the technician sat). Wind movement was measured with a hot-wire anemometer (Fues) and relative humidity with an aspiration psychrometer (Lambrecht, Göttingen, FRG). These environmental factors were measured three times during an experiment.

The projected area (A_p) for each subject was measured twice by planimetry of photos of the subject in the exercise position, taken with a camera placed in the mid-sagittal plane of the subject at the same angle to the horizontal as the solar radiation (22.5° angle).

The water vapour pressure under the suit was measured by drawing air (400 ml min^{-1}) sampled in front of the chest through the O_2 analyser. A registered fall in O_2 partial pressure was due to the addition of water vapour to the sample (Holmér and Elnäs 1981):

$$P_{O_2} = \text{barometic pressure} - P(\text{other dry gasses}) - P\ H_2O$$

Some physical properties of the garments were determined (Table 1). The insulation value ('clo value') was measured on a heated mannikin (Olesen and Madsen 1983). The short-wave radiation heat load (R) was calculated from measurements of the total radiation that impinged on the garment and the percentage of this that was reflected (r) from the surface measured by a pyranometer (S-15-SO-3, Sensors Inc.). The absorbed heat load was taken to be $(100-r)$% of R_{tot}. The radiation transmitted through the clothing was measured by covering the solarimeter in the position parallel to the back of the subject with a single layer of the fabric corresponding to that worn by the subject and recording the percentage decrease in output.

Table 1. Physical properties of clothing

Property	Polyester		Cotton	
	White	Black	White	Black
Insulation clo units I_{Cl} (K m^2 W^{-1})	 0.48 0.074		 0.62 0.096	
Transmittance % of R_{tot}	57.8	35.6	32.0	12.8
Reflectance r (% of R_{tot})	40	26	45	25
Absorptance $\alpha = (1-r)$ (% of R_{tot})	60	74	55	75
Sweat in suit after 60 min (g) ($n = 6$) SE	 36 ±8	 32 ±6	 130 ±42	 167 ±48
Water vapour difference over clothing ΔP H_2O (mm)	8.6	12.6	10.3	9.9
	10.1 range (6–13.8)		10.6 (2.2–19.5)	

Thermal sensation was assessed by the subjects at 20, 40 and 60 min on a seven-point scale (Fanger 1970).

Calculations. The values in the heat-balance equation $M \pm W \pm C \pm R \pm E \pm L \pm S = 0$ were calculated for the last 15 min of the exercise, when the thermal state of the subject should have approximated a steady state most closely, and expressed in watts.

M, the metabolic free-energy liberated, was calculated from the measured $\dot{V}_{O_2}$ using 333 W l O_2^{-1} min^{-1} as the conversion factor.

W, the external work, was measured by the bicycle ergometer, from the load and revolutions per minute (52.74 J kg^{-1} revolution of the pedals^{-1}).

C, the convective heat loss, was determined from measurements of average surface temperature $\overline{T}_{cl}$ and T_a according to the formula $C = A_s f_{cl} h_c (\overline{T}_{cl} - T_a)$, where A_s is the DuBois surface area, f_{cl} the increase in surface area due to the clothing: 1.15 for the polyester and 1.2 for the cotton (Fanger 1970), and h_c the convection coefficient, $= 8.3\sqrt{\bar{v}}$, W m^{-2} (Kerslake 1972). The average wind velocity, $\bar{v}$, in the experimental hall was 0.22 m s^{-1}. With the extra convection due to the cycling we used $\bar{v} = 0.5$ m s^{-1} for the calculations of C.

R, the radiation heat exchange was calculated as follows:

R_s, short-wave heat gain $= R_{tot} \alpha A_p$

where A_p = projected area (m^2; see Table 2); R_{tot} = radiation intensity measured normal to the source by the solarimeter (W m^{-2}); α = absorptance of the surface for solar radiation (see Table 1) = $(1-r)$.

Table 2. Environmental factors, average and range for all conditions

T_a	25.3° C, range 23.3-27.2° C
$\bar{T}_{r(ir)}$	28.9° C, range 27.7-30..4° C
$\bar{v}$	0.2-0.4 m s^{-1}
P H_2O	7.9 mm Hg, range 6.8-8.9 mm Hg (≈1.05 kPa) (range: 30%-50%)
R_{tot}	724 W m^{-2}, range 697-754 W m^{-2}

R_l, the long-wave radiation heat loss = $\varepsilon\sigma A_{seff}[\bar{T}_{cl})^4 - (\bar{T}_{r(ir)})^4]$

where ε = the emittance of the skin and clothing: 0.98; σ = Stefan-Boltzmann's constant: 5.67×10^{-8} W m^{-2} K^{-4}; A_s = DuBois surface area; A_{seff} = the effective area for radiation exchange, 70% of A_s; $\bar{T}_{r(ir)}$ = mean radiant infrared temperature, K.

E, the evaporative heat loss due to sweating, was calculated from the weight loss corrected for weight changes due to the respiratory gas exchange and respiratory evaporation (1 kg h^{-1} = 675 W). The sweat content in the clothing was measured as mentioned by weighing the garments before and after exercise. The total sweat loss was obtained by adding the two.

L, the respiratory evaporative heat loss (in watts) was calculated (Fanger 1970) as $L = M \times 0.0014(34 - T_a)$.

S, the storage of body heat, was calculated as S = body weight ΔT_b 3474 s^{-1} W

where ΔT_b, the change in mean body temperature, was calculated over the time period 45-60 min as $0.8\Delta T_{es} + 0.2\Delta T_{sk}$ (Stolwijk and Hardy 1966).

Results

The environmental conditions were the same in all experiments (Table 2): air temperature (T_a) = 25.3° C, SE 0.17; mean radiant infrared temperature ($\bar{T}_{r(ir)}$) = 28.9, SE 0.13; wind velocity ($\bar{v}$) = 0.22 m s^{-1}. The relative humidity was approximately 40%, i.e. the water vapour pressure was 7.9 mm Hg, SE 0.22. The solar irradiation was approximately 724 W m^{-2} normal to the source at the distance of the exposed back of the subjects. The physiological strain varied with the colour of the clothing (Table 3). The T_{es}, $\bar{T}_{sk}$, HR and sweat rates were higher in the black clothing compared to the white of similar material and the differences were significant between the white polyester and black cotton. However, it must be borne in mind that the insulation value of the cotton was also higher, 0.62 clo, compared to the 0.48 clo of the polyester.

Table 3. Means and SE of measurements taken between 50th and 60th min of exercise, of oesophageal temperature (T_{es}), average skin temperature under the clothing ($\bar{T}_{sk}$), and of clothing surface ($\bar{T}_{cl}$), heart rate (HR) from 45-60 min of exercise, and total sweat loss (Sw) including the sweat retained in the clothes, and rate of sweat loss

Parameter	WP	BP	WC	BC	
T_{es} (° C)	38.2	38.3 (5)	38.3	38.4	NS
SE	0.1	0.2	0.1	0.3	
$\bar{T}_{sk}$ (° C)	34.8	35.1	34.9	36.1	WP≠BC, WC≠BC
SE	0.3	0.2	0.4	0.3	
$\bar{T}_{cl}$ (° C)	29.8	32.7	30.1	34.2	WP≠BC, WC≠BC
SE	1.1	0.5	0.6	0.4	
HR (beats min^{-1})	142	154	151	160	WP≠BC
SE	6	8	8	8	WP≠BC
Sw (g) total loss	649	666	704	808	
SE	49	54	80	98	WC≠BC
Sw rate (g h^{-1})	687	743	646	736	
SE	55	70	57	58	

Significant differences <5% level are indicated as ≠. White polyester (WP), black polyester (BP), white cotton (WC), black cotton (BC)

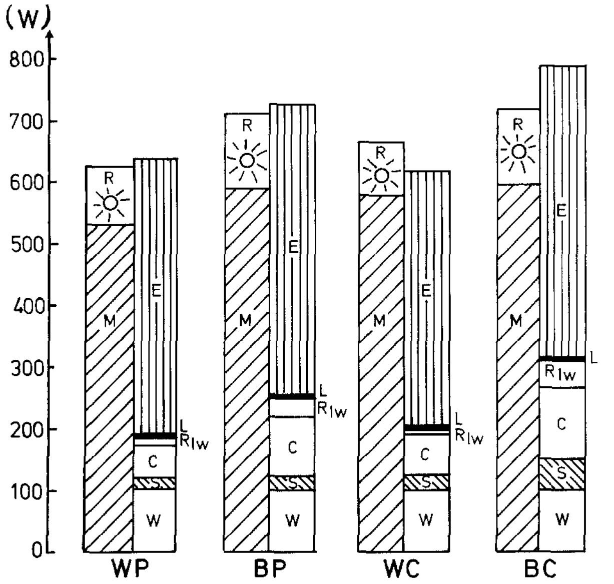

Fig. 1. Heat balances for subjects exercising in four different suits: *WP*, white polyester; *BP*, black polyester; *WC*, white cotton; *BC*, black cotton. Heat gains: metabolic energy liberation (*M*) and short-wave radiation (*R*), are balanced by storage (*S*) and losses: work (*W*), convection (*C*), long-wave radiation (R_{lw}), sweat evaporation (*E*), and evaporation from the lungs (*L*). (Averages from six subjects)

The calculated heat balances for the four trials are presented in Fig. 1. The heat exchange values (lost and gained) were within 10% of each other in each experimental condition.

Discussion

The heat load received by the human body in full sun during outdoor activities can amount to values equal to or even greater than the resting metabolic rate. Therefore, it is an important factor in the heat balance of persons in natural, outdoor environments (Adolph 1938; Adolph et al. 1947; Burton and Edholm 1955; Beckenridge and Goldman 1971). Nielsen et al. (1988) determined that 100 W direct, short-wave radiation was absorbed by a 'naked' subject exercising on a bicycle with either the back or the front exposed to the sun.

Heat balance studies on animals (Borut et al. 1979;

Ellis 1980) demonstrate the importance of the colour of the fur or feathers for the heat load. Similarly for humans the colour of the skin and clothing is decisive for the absorption and reflection of solar radiation (Blum 1945; Adolph et al. 1947; Jacques et al. 1955; Beckenride and Goldman 1971; Roller and Goldman 1968; Kerslake 1972; Clark and Cena 1978). Addition problems with clothes arise from the quantity of heat transmitted through the clothing to the skin and added to the heat load, how much of this is reflected back out, and how much is lost directly to the environment from the surface of the clothing. This depends on the insulation of the clothing, and the insulation of the air layer in contact with the surface, which in turn depends on the wind velocity around the person (Burton and Edholm 1955).

We have tried to calculate these heat exchanges from physical measurement of the reflectance of the fabrics (cf. Table 1), the argument being, that all radiation that is *not* reflected will add to the heat load on the subject, and must be dissipated. In steady states the evaporative heat loss can be used as a measure of the absorbed radiation. In conditions where the skin (or surface) temperature is constant, and a subject is exposed to changes in radiative heat loads, the sweat rate changes by the same magnitude (Adolph 1938; Gagge and Hardy 1967; Berglund et al. 1987).

Similarly in our present study the differences in the sweat rates between black and white garments should indicate the difference in total heat load. However, since the surface temperature of the black and white suits became different in the 'sun' - the black being 3°-4° C warmer - then the heat loss by convection and radiation was also (significantly) larger in the black suits, and the evaporative sweat loss less than what could be expected from the measured absorbance of the materials. The results show that the physiological strain, measured as sweat rate, HR and $\overline{T}_{sk}$ under the suits in the last 10 min of the exercise, was increased in the black as compared to the white outfits (Table 3). The subjects also felt warmer in the black suits, judging from their 'comfort scores' (Fanger 1970).

The differences in the heat stress in the four different suits were smaller than expected from the initially measured absorbances and clo values of the fabrics. This was due to an additional physical property of the fabrics; the light penetration in the material. This factor has been discussed previously in relation to furs and feathers (Ellis 1980; Borut et al. 1979) and Beduin clothing in black and white (Burton and Edholm 1955).

While the reflectance was nearly the same in the present study for both cotton and polyester, about 45% is reflected from white, 28% from black fabrics, there was a difference in the percentage of the radiation that could be measured under one layer of the material. The polyester was more transparent: even black polyester allowed the passage of 36% of the total intensity compared to only 13% in the black cotton (Table 1). How much of this heat is absorbed by the skin or reflected back through the material cannot be quantified. By measuring the total short-wave reflectance, we have presumed that the rest of the total irradiation is contributing the short-wave heat load on the subject.

This transparency of the polyester material to sun radiation and the corresponding heat gain under the clothes may be one reason for the discomfort many people feel in polyester garments outdoors. In our study the suits became totally wet and clinging to the skin and the water vapour pressure measured under the garments over the chest was equal (Table 1) and corresponded to 100% saturation at T_a in all the four suits.

The measurements of the environmental parameters, surface temperatures on the exercising subjects and physical factors of the clothing materials were used to calculate the dry heat exchanges by convection and radiation (see Subjects and methods). These values and the measured metabolic heat production, evaporative heat loss, and calculated heat storages were used in the heat balance equation. The results are shown in Fig. 1. The heat gain and loss balance is within 10% for all four garments. This indicates that the assumptions for the calculations are valid and that partitional calorimetry can also be used on clothed subjects exercising in the sun.

The wind speed in our study was low. At higher air velocities, as in natural outdoor cycling, the surface temperature will be lower (Burton and Edholm 1955) and the difference between black and white clothing surfaces less. We observed this in the model experiments (Table 4). With greater wind speed the sweat loss in the black garment would probably differ more from that in the white and to a greater extent than seen in the present study.

In conclusion, the heat absorption due to sunlight in black garments is greater than in white. Whether or not this leads to a larger heat strain of the wearer depends on a number of factors: for example, the transparency of the surface material, the insulation value of the clothing and thus the number of layers of clothing and air under the surface, and the insulation of the air layer on the surface (which depends on wind speed). In the present study of exercising subjects in one-layer clothing the subjects sweated more (100 g h^{-1}) and had a higher HR (10 beats min^{-1}) in black as compared to white suits. It is possible to measure the heat balance by partitional calorimetry, and to obtain measurement of the short-wave radiative heat gain. However, per-

Table 4. Temperature difference from air temperature measured on an unheated manikin-'thigh' covered (tightly) by one layer of polyester trousers and exposed to the artificial sun. Effect of air velocity and color

Wind speed (m s^{-1})	Temperature above T_a (° C)	
	White	Black
0	15	26
1	3.5	6.5
3	2.3	5.2
5	1.8	5.2

haps a more direct measure of the difference in *heat strain* due to variations in colour of the clothing can be obtained by precise measurement of sweat rate and HR in steady-state, standardized exercise in an outdoor environment.

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References

Adolph EF (1938) Heat exchanges of man in the desert. Am J Physiol 123:486-499

Adolph EF, Brown AG, Goddard DR, Gosselin RE, Kelly JJ, Molnar GW, Rahn H, Rothstein A, Towbin EJ, Wills JH, Wolf AW (1947) Physiology of man in the desert. Interscience, New York

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

Berglund LG, Fashena D, Su X, Gwosdow A (1987) Evaporative weight loss as a measure of absorbed thermal radiation in the human. Proceedings of the 13th Annual North East Bioengineering Conference. Foster KR (ed) Institute of electrical and electronic engineers, Inc., New York, pp 507-510

Blum HF (1945) The solar heat load: its relationship to total heat load and its relative importance in the design of clothing. J Clin Invest 24:712-721

Borut AR, Dmi'el R, Shkolnik A (1979) Heat balance of resting and walking goats: comparison of climatic chamber and exposure in the desert. Physiol Zool 52:105-112

Burton AC, Edholm OG (1955) Man in a cold environment. Arnold, London

Clark, JA, Cena K (1978) Net radiation and heat transfer through clothing: the effects of insulation and colour. Ergonomics 21:691-696

Clark, JA, Cena K, Monteith JL (1973) Measurements of the local heat balance of animal coats and human clothing. J Appl Physiol 35:751-754

Ellis HI (1980) Metabolism and solar radiation in dark and white herons in hot climate. Physiol Zool 53:358-372

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

Finch VA, Dmi'el R, Boxman R, Shkolnik A, Taylor CR (1980) Why black goats in hot deserts? Effect of coat color on heat exchanges of wild and domestic goast. Physiol Zool 53:19-25

Gagge AP, Hardy JD (1967) Thermal radiation exchange of the human body by partitional calorimetry. J Appl Physiol 23:248-258

Hardy JD, DuBois EF (1938) The technique of measuring radiation and convection. J Nutr 15:461-475

Holmér I, Elnäs S (1981) Physiological evaluation of the resistance to evaporative heat transfer by clothing. Ergonomics 24:63-74

Jacques JA, Huss J, McKeehan W, Dimitrof JM, Kuppenheim HF (1955) Spectral reflectance of human skin in the region 0.7 μ-2.6 μ. J Appl Physiol 8:297-299

Kerslake DMck (1972) The stress of hot environments. Cambridge University Press, Cambridge

Krogh A, Trolle C (1936) A balance for the determination of insensible perspiration in man and its use. Scand Arch Physiol 73:159-162

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

Olesen BW, Madsen TL (1983) Measurements of thermal insulation of clothings by a movable manikin. Proceedings of the International Conference on Medical and Biophysical Aspects of Protective Clothing. Henane R (ed) Institute des Santes Armees, Lyon, pp 205-213

Roller WL, Goldman RF (1968) Prediction of heat load on man. J Appl Physiol 24:717-721

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