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TITLE

DETERMINATION OF BODY HEAT STORAGE IN CLOTHING: CALORIMETRY VERSUS THERMOMETRY

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ORIGINAL ARTICLE

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Determination of body heat storage in clothing: calorimetry versus thermometry

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Abstract Two methods of estimating body heat storage were compared under differing conditions of clothing, training, and acclimation to heat. Six male subjects underwent 8 weeks of physical training [60–80% of maximal aerobic power ($\dot{V}O_{2max}$) for 30–45 min · day^{-1}, 3–4 days · week^{-1} at < 25 °C dry bulb (db)] followed by 6 consecutive days of heat acclimation (45–55% $\dot{V}O_{2max}$ for 60 min · day^{-1} at 40 °C db, 30% relative humidity)]. Nine other male subjects underwent corresponding periods of control observation followed by heat acclimation. Before and after each treatment, subjects walked continuously on a treadmill (1.34 m · s^{-1}, 2% grade) in a climatic chamber (40 °C db, 30% relative humidity) for an average of 118 min (range 92–120 min) when wearing normal light combat clothing and for an average of 50 min (range 32–68 min) when wearing protective clothing resistant to nuclear, biological, and chemical agents. The heat storage was determined calorimetrically (by the balance of heat gains and losses) and thermometrically [by the conventional equations, using one or two set(s) of relative weightings for the rectal temperature (T_{re}) to mean skin temperature ($\bar{T}_{sk}$) of 4 : 1 and 4 : 1, 2 : 1 and 4 : 1, or 2 : 1 and 9 : 1 in thermoneutral and hot environments, respectively]. $\bar{T}_{sk}$ was calculated from 12-site measurements, weighted according to the regional distribution of body surface area and the first eigenvectors of principal component analysis. There were only minor differences ($< 5\%$) between the heat storage values calculated by given weighting factors for T_{re} and $\bar{T}_{sk}$, whether the individual coefficients were derived from estimates of regional surface area or principal component methodologies. When wearing normal clothing, no significant differences were found between the two estimates of heat storage (calorimetry vs thermometry with an invariant relative weighting of 4 : 1) in any experimental condition, with one specific exception: when wearing protective clothing, thermometry underestimated the heat storage by 24–31%. This underestimation was attenuated by using two sets of relative weightings of 2 : 1 and 4 : 1 or 2 : 1 and 9 : 1. The results suggest that when subjects wearing protective clothing are transferred from thermoneutral to hot environments, the accuracy of thermometric estimates of heat storage can be improved by using two sets of weighting factors for T_{re} and $\bar{T}_{sk}$.

Key words Rectal temperature · Mean skin temperature · Mean body temperature Heat exchanges and balance · Exercise and heat stress

Introduction

Precise determinations of body heat storage by solution of the equations of thermal balance require the use of sophisticated climatic chambers that are available at only a few specialized centers. Accordingly, it is common practice to estimate changes of body heat content using a mean body temperature ($\bar{T}_b$) calculated from a weighted combination of rectal temperature (T_{re}) and average skin surface temperature ($\bar{T}_{sk}$). The appropriate weighting of rectal and skin readings has been estimated empirically, by relating experimental data to the changes in heat content calculated by thermal balance equations (Colin et al. 1971; Hardy and Stolwijk 1966).

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Unfortunately, the weighting factors (typically based on semi-nude young men resting or performing continuous moderate work in a hot environment) do not remain constant from one situation to another (Vallerand et al. 1992). For example, training and acclimatization each allow a subject to develop a greater skin blood flow in response to a given heat load, bringing the $\bar{T}_{sk}$ closer to that of the body core, especially in hot and humid environments (Armstrong and Pandolf 1988; Roberts et al. 1977; Wenger 1988). Likewise, protective clothing impedes the surface loss of heat, causing $\bar{T}_{sk}$ to rise very close to core values (Aoyagi et al. 1994, 1995; Goldman 1985).

The commonly adopted estimate of $\bar{T}_{sk}$ is also open to criticism, since it is based simply upon the respective surface areas of various body regions (Burton 1935; Hardy and DuBois 1938a; Ramanathan 1964; Teichner 1958; Vallerand et al. 1989). However, local protective devices such as a respirator or gloves (Goldman 1985) and inter-individual differences in subcutaneous fat distribution (Frim et al. 1990) could well change the contribution of individual thermocouple or thermistor readings to the true $\bar{T}_{sk}$.

In the present paper, we have explored the potential of a new approach to the estimation of $\bar{T}_{sk}$, based on principal component analyses of the usually chosen 12-site skin thermistor measurements. We have tested whether such an analysis indicates a common axis corresponding to $\bar{T}_{sk}$, whether individual weighting factors can be derived from such an axis, whether weighting coefficients change under different combinations of clothing, training and acclimation to heat, and how well the weighting factors derived from the principal component approach, in combination with the commonly used relative weightings for T_{re} to $\bar{T}_{sk}$ of 2:1, 4:1 and 9:1, predict the change in body heat content as derived from standard heat balance equations.

Methods

Experimental plan

Subjects

Fifteen males volunteered for the study following consent procedures established and approved by the Human Ethics Committees of the University of Toronto and the Defence and Civil Institute of Environmental Medicine. The subjects were clinically healthy, with the following characteristics [mean (range)]: age 27 (21–34) years; height (Ht) 1.76 (1.67–1.85) m; body mass (Wt) 81.8 (66.6–106.6) kg; body surface area (A_D; see Appendix) 1.98 (1.82–2.30) m^2; maximal oxygen consumption ($\dot{V}O_{2max}$; Aoyagi et al. 1994) 42.6 (34.3–50.9) ml$\cdot$kg$^{-1}\cdot$min^{-1}.

Protocol

Testing was conducted from November through March, so that subjects were not initially heat-acclimatized. Participants were arbitrarily allocated to one of two treatment sequences: (1) endurance training followed by heat acclimation (T_{ET+HA}; $n = 6$) or (2) a corresponding control period followed by heat acclimation (T_{C+HA}; $n = 9$).

Prior to undergoing any treatment, each subject completed two bouts of submaximal exercise in a climatic chamber maintained at 40 °C dry bulb (db) and 30% relative humidity (rh). These bouts were separated by no less than 48 h and differed in one respect (by the type of clothing worn). After donning in turn normal or protective clothing in a temperate laboratory environment (20 °C db), the subject entered the chamber and walked on a motor-driven treadmill at a speed of 1.34 m$\cdot$s^{-1} and a grade of 2% (1.15 °). The chosen work rate amounted to approximately 42% (range 33–50%) of the subject's $\dot{V}O_{2max}$ while wearing normal clothing and 45% (range 32–56%) while wearing protective clothing. Exposures averaged 118 min (range 92–120 min) when wearing normal clothing and 51 min (range 39–68 min) when wearing protective clothing.

Following the first pair of heat-exercise trials, subjects assigned to the T_{ET+HA} group completed an 8-week endurance training program. Because endurance training improved the average fitness level (Aoyagi et al. 1994), the relative intensity of effort decreased by about 7% (range 2–10%) for both clothing ensembles, but average exposure times remained unchanged [120 min for all subjects in the T_{ET+HA} group when wearing normal clothing and an average of 47 min (range 40–56 min) when wearing protective clothing].

All subjects underwent 6 successive days of heat acclimation following the second pair of trials. The final pair of trials were completed in the first 96 h following heat acclimation. Heat acclimation did not change the relative intensity of exercise (although it may have helped to conserve the effects of endurance training in the T_{ET+HA} group), nor did it change average times of exposure [119 min (range 105–120 min) when wearing normal clothing and 50 min (range 32–60 min) when wearing protective clothing].

Experimental conditions

Clothing ensembles

Normal clothing was represented by light military combat kit, and clothing with limited vapor permeability was represented by military issue for protection against nuclear, biological, and chemical hazards (NBC clothing), as detailed in the accompanying paper (Aoyagi et al. 1995).

Endurance training

For a total of 8 weeks, subjects ran on a treadmill or an indoor running track at 60–80% $\dot{V}O_{2max}$ for 30–45 min$\cdot$day^{-1}, 3–4 days$\cdot$week^{-1} at an ambient temperature < 25 °C db.

Heat acclimation

For 6 consecutive days, subjects walked or ran on a treadmill for 60 min$\cdot$day^{-1} at a speed and elevation demanding 45–55% $\dot{V}O_{2max}$, under the environmental conditions (40 °C db, 30% rh.) adopted for the definitive heat-exercise trials.

Thermal analysis

Temperature measurements

T_{re} was measured using a flexible vinyl-covered probe (Pharmaseal APC 400 Series) inserted approximately 12 cm above the anal sphincter. Local skin temperatures were measured at 12 sites, using uncovered thermistors (Yellow Springs Instruments thermistor bead 44004). The $\bar{T}_{sk}$ was calculated from (1) weighting factors reflecting regional proportions of the total body surface area ($\bar{T}_{skA}$), according to the equation of Vallerand et al. (1989):

$$\begin{aligned}\bar{T}_{sk} = {} & 0.07 \cdot (\text{forehead}) + 0.085 \cdot (\text{chest}) + 0.065 \cdot (\text{calf}) \\ & + 0.085 \cdot (\text{abdomen}) + 0.14 \cdot (\text{lower arm}) + 0.05 \cdot (\text{wrist}) \\ & + 0.095 \cdot (\text{front thigh}) + 0.065 \cdot (\text{shin}) + 0.07 \cdot (\text{foot}) \\ & + 0.09 \cdot (\text{upper back}) + 0.09 \cdot (\text{lower back}) \\ & + 0.095 \cdot (\text{rear thigh}) \qquad (1)\end{aligned}$$

and (2) weighting factors derived from the first eigenvectors of principal component analyses ($\bar{T}_{skP}$) for each experimental condition. $\bar{T}_b$ was estimated from T_{re} and $\bar{T}_{skA}$ or $\bar{T}_{skP}$, using relative weightings of 2 : 1 [$\bar{T}_{bA(2:1)}$ or $\bar{T}_{bP(2:1)}$], 4 : 1 [$\bar{T}_{bA(4:1)}$ or $\bar{T}_{bP(4:1)}$], and 9 : 1 [$\bar{T}_{bA(9:1)}$ or $\bar{T}_{bP(9:1)}$]:

$$\bar{T}_{b(2:1)} = 0.67 \cdot T_{re} + 0.33 \cdot \bar{T}_{sk} \qquad (2)$$

$$\bar{T}_{b(4:1)} = 0.80 \cdot T_{re} + 0.20 \cdot \bar{T}_{sk} \qquad (3)$$

$$\bar{T}_{b(9:1)} = 0.90 \cdot T_{re} + 0.10 \cdot \bar{T}_{sk} \qquad (4)$$

Heat balance analysis

Six thermometric estimates of heat storage [$S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$, $S_{A(2:1,4:1)}$ or $S_{P(2:1,4:1)}$, and $S_{A(2:1,9:1)}$ or $S_{P(2:1,9:1)}$ in $\text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$] were calculated, using equations of the type (Burton 1935):

$$S = (c_p \cdot \text{Wt} \cdot A_D^{-1}) \cdot (\Delta \bar{T}_b \cdot \Delta t^{-1}) \qquad (5)$$

where c_p is the average specific heat of body tissues ($3.47\ \text{kJ} \cdot \text{kg}^{-1} \cdot {}^{\circ}\text{C}^{-1}$) and $\Delta \bar{T}_b \cdot \Delta t^{-1}$ is the rate of increase in mean body temperature (in $^{\circ}\text{C} \cdot \text{h}^{-1}$).

A parallel calorimetric estimate (S) was derived from the standard heat balance equation (all units are in $\text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$):

$$S = M \pm W \pm E_{res} \pm C_{res} \pm E_{sk} \pm R \pm C \pm K \qquad (6)$$

where M is the metabolic rate; W is the external work rate; E_{res} and C_{res} are the rates of latent (evaporative) and dry (convective) heat exchanges via the respiratory tract, respectively; E_{sk} and R, C, and K are the rates of evaporative and dry (radiant, convective, and conductive) heat exchanges between the clothed skin and the environment, respectively.

Metabolic heat production (M) was determined by the equation of Gagge and Nishi (1983), using oxygen uptake [$\dot{V}O_2$ in $\text{l} \cdot \text{min}^{-1}$, standard temperature and pressure, dry (STPD)] and respiratory quotient (RQ) values averaged over 15-min intervals (Aoyagi et al. 1995):

$$M = [(0.23 \cdot \text{RQ} + 0.77) \cdot 21.14] \cdot (60 \cdot \dot{V}O_2) \cdot A_D^{-1} \qquad (7)$$

where $(0.23 \cdot \text{RQ} + 0.77) \cdot 21.14$ is the energy equivalent of oxygen consumed (in $\text{kJ} \cdot \text{l}^{-1}$).

W was calculated from the treadmill walking speed (v_{tw}, $1.34\ \text{m} \cdot \text{s}^{-1}$) and slope ($\theta$, 1.15°):

$$W = 3.6 \cdot m_d \cdot g \cdot (v_{tw} \cdot \sin \theta) \cdot A_D^{-1} \qquad (8)$$

where m_d is the body mass when dressed (in kg); g is the acceleration due to gravity ($9.81\ \text{m} \cdot \text{s}^{-2}$); and $v_{tw} \cdot \sin \theta$ is the vertical distance risen ($0.03\ \text{m} \cdot \text{s}^{-1}$).

E_{res} and C_{res} were calculated from the values for M, according to the equation presented by Fanger (1970), allowing for the average temperature of around 38 °C and corresponding saturated water vapor pressure of around 49 Torr in the upper respiratory tract:

$$E_{res} = 0.0023 \cdot M \cdot (49 - P_a) \qquad (9)$$

$$C_{res} = 0.0014 \cdot M \cdot (38 - T_a) \qquad (10)$$

where P_a is the ambient water vapor pressure (16.6 Torr, given 30% saturation at 40 °C db) and T_a is the ambient temperature (40 °C db).

E_{sk} was determined from the rate of sweat evaporation (SE, $\text{g} \cdot \text{h}^{-1}$), calculated from clothed weight loss [which was corrected for the losses due to evaporation of water (m_e in $\text{g} \cdot \text{h}^{-1}$) and exchange of gases (m_r in $\text{g} \cdot \text{h}^{-1}$) in the respiratory tract; see Appendix]:

$$E_{sk} = \lambda \cdot \text{SE} \cdot A_D^{-1} \qquad (11)$$

where λ is the energy equivalent of sweat evaporated ($2.43\ \text{kJ} \cdot \text{g}^{-1}$).

The combination of dry heat gains by radiation and convection (R + C) was predicted from the equation of Oohori et al. (1984):

$$\text{R} + \text{C} = (F_{cl} \cdot f_{cl} \cdot h) \cdot (\bar{T}_{sk} - T_a). \qquad (12)$$

F_{cl} is Burton's thermal efficiency factor (non-dimensional), calculated as:

$$F_{cl} = (1 + 0.043 \cdot I_{clo} \cdot f_{cl} \cdot h)^{-1} \qquad (13)$$

in which I_{clo} is the average thermal resistance of the clothing (a value of 1.4 clo for normal clothing and 2.4 clo for protective clothing at wind speeds $< 0.4\ \text{m} \cdot \text{s}^{-1}$; $1\ \text{clo} = 0.043\ \text{m}^2 \cdot \text{h} \cdot {}^{\circ}\text{C} \cdot \text{kJ}^{-1}$); f_{cl} is the ratio of the surface area of the clothing layer to the DuBois skin surface area (a value of approximately 1.2 for normal clothing and 1.4 for protective clothing; Gagge and Nishi 1983); and h is a combined dry heat transfer coefficient ($44\ \text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot {}^{\circ}\text{C}^{-1}$) as described for the semi-nude case by a combination of radiation (h_r, $18\ \text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot {}^{\circ}\text{C}^{-1}$; see Appendix) and convection (h_c, $26\ \text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot {}^{\circ}\text{C}^{-1}$; see Appendix).

Another variable, K, was assumed to be negligible, given the limited contact between the body and external objects.

Statistical procedures

Data are presented as mean values and standard errors of the mean (SEM). Principal component analysis without varimax rotation (Statistical Analysis System) was used to determine the weighting coefficients of individual skin temperatures and to assess the preponderance of some skin temperature readings over others. Student's t-tests for paired samples were used to compare the two estimates of $\bar{T}_{sk}$ or $\bar{T}_b$ (regional surface area vs principal component methodologies). Paired t-tests, adjusted for multiple comparisons by the relatively conservative Bonferroni method, were used to locate significant differences between the several estimates of heat storage. The level of statistical significance was set at $P < 0.05$, and the critical t values after application of the Bonferroni procedure were 3.21 for the T_{C+HA} group and 3.32 for the T_{ET+HA} group.

Results

Principal component analysis

The eigenvalues (EV) indicate that two or at most three components provide a good summary of the variance in T_{sk} for both normal clothing (Table 1) and protective clothing (Table 2); two components accounted for 59–87% of the standardized variance and three components explained 71–94% of the total. In no case did

Table 1 Data from principal component analyses showing loading of 12 local skin temperatures at the initial (*I*) and at the final (*F*) stages of heat-exercise challenge before (*B*) and after (*A*) endurance training (*ET*) or control (*C*) and heat acclimation (*HA*) while wearing normal clothing. $n = 9$ for the control and heat acclimation (T_{C+HA}) group and $n = 6$ for the endurance training and heat acclimation (T_{ET+HA}) group. (*EV* eigenvalue, *PVE* proportion of variance explained, *P1, P2, P3* first, second and third principal components)

Group	Condition			EV	PVE (%)	Eigenvector											
						Fore-head	Chest	Calf	Abdo-men	Lower arm	Wrist	Front thigh	Shin	Foot	Upper back	Lower back	Rear thigh
T_{C+HA}	B	I	P1	0.8	67	0.24	0.30	0.30	0.30	0.33	0.27	0.23	0.31	0.29	0.32	0.30	0.25
			P2	1.8	15	−0.49	−0.19	0.08	−0.06	−0.01	−0.17	0.57	0.13	−0.19	−0.19	0.15	0.50
			P3	0.8	7	0.31	−0.44	0.48	−0.28	0.25	0.23	0.11	−0.17	−0.44	0.02	0.16	−0.17
		F	P1	7.4	61	0.15	0.25	0.33	0.31	0.30	0.28	0.32	0.34	0.32	0.22	0.26	0.33
			P2	1.4	12	−0.07	−0.49	−0.20	0.32	0.34	0.35	−0.29	−0.26	0.13	−0.04	0.42	−0.15
			P3	1.2	10	0.52	−0.14	−0.08	0.02	−0.18	−0.41	0.08	−0.05	0.07	0.57	0.31	−0.25
	A(C)	I	P1	8.1	67	0.08	0.25	0.31	0.33	0.33	0.33	0.33	0.22	0.25	0.29	0.32	0.32
			P2	1.5	12	0.60	0.28	0.04	−0.08	−0.21	−0.19	0.17	−0.30	−0.40	0.38	0.21	−0.12
			P3	0.9	8	0.59	−0.41	0.22	−0.24	0.05	0.07	−0.07	0.55	0.07	−0.01	−0.21	−0.06
		F	P1	8.0	67	0.21	0.19	0.32	0.31	0.25	0.33	0.34	0.34	0.30	0.25	0.26	0.30
			P2	1.5	13	−0.54	0.55	−0.15	0.14	0.20	−0.01	0.14	−0.10	−0.28	0.14	0.34	−0.29
			P3	1.0	8	0.07	0.18	−0.18	−0.39	0.55	0.19	−0.17	−0.16	0.09	0.43	−0.44	0.06
	A(HA)	I	P1	7.6	63	0.26	0.33	0.30	0.30	0.28	0.30	0.33	0.29	0.13	0.23	0.34	0.32
			P2	1.7	14	−0.15	−0.19	−0.22	0.25	−0.09	−0.13	−0.04	−0.35	0.67	0.44	0.20	0.04
			P3	1.0	8	0.12	−0.03	−0.40	−0.45	0.61	0.43	−0.16	−0.08	0.08	0.13	0.01	−0.10
		F	P1	4.7	39	0.19	0.29	0.13	0.30	0.41	0.18	0.09	0.30	0.29	0.42	0.29	0.37
			P2	2.4	20	0.35	−0.32	0.59	−0.25	−0.10	0.03	0.54	−0.19	0.10	0.08	−0.05	0.06
			P3	1.5	12	−0.27	−0.28	0.14	−0.37	0.29	0.60	−0.11	0.29	−0.05	−0.12	0.26	−0.26
T_{ET+HA}	B	I	P1	5.8	48	−0.01	0.34	0.16	0.27	−0.24	−0.34	0.38	0.29	−0.08	0.35	0.39	0.32
			P2	2.3	19	0.56	0.27	−0.34	0.13	−0.48	0.26	−0.23	−0.20	0.07	0.22	0.09	−0.17
			P3	2.2	18	0.11	−0.03	0.50	−0.28	−0.17	0.26	−0.13	0.41	0.60	−0.01	0.11	−0.02
		F	P1	7.7	64	0.21	−0.12	0.33	0.31	0.03	0.36	0.36	0.32	0.33	0.21	0.32	0.34
			P2	2.2	18	0.54	0.43	−0.07	−0.20	−0.57	−0.03	0.10	−0.05	0.06	−0.32	0.13	0.13
			P3	1.3	11	0.12	0.59	0.18	0.17	0.29	−0.02	0.00	−0.38	−0.20	0.41	0.32	−0.20
	A(ET)	I	P1	9.4	78	0.27	0.30	0.31	0.30	0.31	0.29	0.30	0.30	0.18	0.28	0.31	0.28
			P2	1.0	9	−0.06	0.25	−0.22	0.26	−0.02	−0.17	−0.24	−0.14	0.75	0.15	0.09	−0.34
			P3	0.8	7	−0.58	−0.31	0.21	0.01	−0.06	−0.22	0.14	−0.02	0.21	0.48	−0.17	0.38
		F	P1	6.7	55	0.06	0.30	0.37	0.25	0.29	0.33	0.33	0.37	0.29	0.01	0.26	0.34
			P2	2.7	23	0.56	−0.33	0.15	−0.18	−0.25	0.26	0.29	0.03	−0.20	0.51	0.04	−0.07
			P3	1.6	13	−0.08	0.24	−0.07	0.54	−0.29	−0.12	−0.14	−0.04	−0.12	0.31	0.56	−0.31
	A(HA)	I	P1	6.6	55	0.20	0.32	0.27	0.33	0.24	0.14	0.36	0.37	0.05	0.35	0.35	0.29
			P2	2.2	18	0.41	0.17	−0.04	−0.18	−0.09	0.50	−0.12	−0.14	0.62	0.18	−0.18	−0.19
			P3	1.9	16	−0.34	−0.36	0.22	−0.23	−0.52	0.29	−0.02	0.06	0.14	0.12	0.26	0.44
		F	P1	6.8	56	0.17	0.04	0.33	0.28	0.35	0.34	0.37	0.33	0.33	−0.05	0.25	0.36
			P2	2.4	20	0.55	0.10	0.09	−0.09	−0.09	0.20	0.10	−0.24	0.09	0.61	−0.42	0.01
			P3	1.8	15	−0.17	0.62	−0.28	0.46	0.25	0.22	0.11	−0.22	−0.23	0.08	0.02	−0.26

a fourth component describe as much as 10% of residual variance (not shown).

The first component (P1) may be presumed a measure of overall T_{sk}, since with a few specific exceptions the first eigenvector loads approximately equally on all variables. The second (P2) and third eigenvectors (P3) show high positive or negative loadings on specific regions of the body surface; they may thus tentatively be identified as one of the following: (1) the temperature in regions that are highly insulated by the protective clothing (such as the forehead, wrist and/or foot); (2) the "torso" temperature, heavily loaded by data for the chest, abdomen, upper and/or lower back(s); (3) the "leg" temperature, heavily loaded by data for the shin, calf, front and/or rear thigh(s); and (4) other combinations of specific sites.

Weighting factors for local T_{sk}

When the local weighting factors for T_{sk} were based upon the respective contributions of individual readings to the variance of the first component of the analysis, the coefficients for the various conditions tested became as shown in Table 3. When wearing protective clothing, there was a tendency to an increment in coefficients for "highly insulated regions" with increasing heat-exercise stress, regardless of treatment status.

Calculation of $\bar{T}_{sk}$ and $\bar{T}_b$

$\bar{T}_{sk}$ values estimated from regional surface area and principal component methodologies differed from each

Table 2 Data from principal component analyses showing loading of 12 local skin temperatures while wearing protective clothing. (Abbreviations as in Table 1)

Group	Condition			EV	PVE (%)	Eigenvector											
						Forehead	Chest	Calf	Abdomen	Lower arm	Wrist	Front thigh	Shin	Foot	Upper back	Lower back	Rear thigh
T_{C+HA}	B	I	P1	4.4	37	0.28	0.39	0.25	0.30	0.26	0.05	0.29	0.26	− 0.0	0.45	0.37	0.22
			P2	2.8	23	− 0.03	− 0.24	0.36	− 0.42	0.24	0.49	0.20	0.20	0.41	0.01	− 0.25	0.16
			P3	1.6	13	0.37	0.02	− 0.13	− 0.07	0.45	0.33	− 0.49	− 0.35	0.05	0.15	0.12	− 0.36
		F	P1	8.2	69	0.24	0.32	0.30	0.25	0.27	0.33	0.32	0.33	0.31	0.28	0.24	0.24
			P2	1.3	11	0.22	0.19	− 0.28	0.22	− 0.40	− 0.05	− 0.22	0.00	0.03	0.38	− 0.46	− 0.48
			P3	0.9	7	− 0.69	− 0.02	− 0.05	0.38	− 0.08	− 0.17	0.05	0.00	− 0.09	− 0.05	0.46	0.34
	A(C)	I	P1	7.1	59	0.05	0.25	0.32	0.35	0.35	0.29	0.34	0.27	0.08	0.24	0.34	0.36
			P2	2.0	16	0.60	0.43	0.07	− 0.18	− 0.00	− 0.32	− 0.03	− 0.09	− 0.42	0.34	− 0.06	0.02
			P3	1.0	8	− 0.02	− 0.02	− 0.27	0.02	0.32	− 0.21	− 0.38	− 0.00	0.47	0.54	0.23	− 0.25
		F	P1	7.0	58	0.23	0.21	0.29	0.33	0.33	0.36	0.31	0.24	0.35	0.25	0.23	0.28
			P2	2.3	19	0.43	0.48	− 0.27	0.17	− 0.03	0.11	− 0.36	− 0.44	0.11	0.14	0.12	− 0.32
			P3	1.2	10	− 0.33	− 0.24	− 0.36	0.10	0.12	− 0.00	− 0.08	0.18	− 0.16	0.63	0.42	− 0.23
	A(HA)	I	P1	5.3	44	0.88	0.30	0.33	0.31	0.27	0.23	0.35	0.28	− 0.07	0.34	0.34	0.37
			P2	2.4	20	− 0.50	0.11	− 0.26	− 0.36	0.39	0.22	0.12	0.10	0.54	− 0.01	− 0.08	0.16
			P3	1.8	15	0.42	0.42	− 0.24	0.09	0.15	− 0.06	− 0.35	0.55	0.11	− 0.04	− 0.34	− 0.08
		F	P1	7.3	61	0.30	0.31	0.22	0.32	0.16	0.35	0.22	0.23	0.34	0.32	0.30	0.32
			P2	2.0	17	− 0.29	− 0.13	0.29	− 0.21	0.46	− 0.13	0.49	0.45	− 0.02	− 0.16	− 0.25	0.09
			P3	1.1	9	− 0.20	0.30	0.57	− 0.27	− 0.43	− 0.09	− 0.21	0.29	− 0.26	0.21	0.18	− 0.08
T_{ET+HA}	B	I	P1	6.0	50	0.29	0.32	0.22	0.36	0.23	0.06	0.37	0.22	0.01	0.36	0.38	0.36
			P2	2.1	17	0.10	− 0.17	0.49	− 0.29	− 0.43	− 0.28	− 0.00	0.56	0.11	− 0.13	− 0.01	0.19
			P3	2.0	17	0.45	− 0.13	0.06	− 0.10	− 0.16	0.54	− 0.01	− 0.09	0.59	0.04	0.12	− 0.28
		F	P1	7.6	63	0.34	0.31	0.30	0.17	− 0.01	0.35	0.22	0.32	0.35	0.30	0.33	0.26
			P2	1.9	16	0.09	0.35	− 0.24	0.30	0.35	0.10	− 0.45	− 0.27	0.15	0.08	0.24	− 0.48
			P3	1.4	12	− 0.20	− 0.10	0.32	0.35	0.63	− 0.14	0.39	0.04	0.07	− 0.39	0.00	− 0.05
	A(ET)	I	P1	7.3	61	0.19	0.29	0.32	0.32	0.29	0.23	0.32	0.32	0.11	0.35	0.32	0.31
			P2	2.7	22	0.51	− 0.32	0.18	− 0.26	− 0.35	0.47	0.05	− 0.08	0.26	0.12	− 0.29	0.16
			P3	1.3	11	0.11	0.23	− 0.22	0.18	− 0.18	− 0.11	− 0.31	0.37	0.72	− 0.08	0.02	− 0.23
		F	P1	7.1	59	0.05	0.23	0.35	0.20	0.36	0.36	0.34	0.34	0.32	0.25	0.27	0.23
			P2	2.2	19	0.19	− 0.48	0.21	0.21	− 0.07	− 0.07	0.19	0.10	0.13	− 0.41	− 0.42	0.46
			P3	1.4	12	0.72	− 0.18	− 0.13	− 0.25	0.03	0.15	− 0.16	− 0.02	0.40	0.28	− 0.18	− 0.24
	A(HA)	I	P1	6.7	55	0.37	0.35	0.05	0.36	0.31	− 0.34	0.26	0.36	0.11	0.27	0.31	0.14
			P2	2.6	22	0.03	0.15	0.53	0.18	− 0.22	0.18	− 0.44	0.11	0.56	0.04	0.03	− 0.25
			P3	1.6	14	− 0.25	− 0.26	0.29	− 0.14	− 0.04	0.21	0.09	0.03	0.08	0.53	0.09	0.65
		F	P1	92	77	0.27	0.31	0.28	0.31	0.29	0.32	0.12	0.29	0.31	0.28	0.32	0.30
			P2	1.2	10	0.20	− 0.19	− 0.13	0.10	− 0.06	0.11	0.83	0.04	0.09	− 0.39	− 0.14	0.04
			P3	0.8	7	0.53	0.15	− 0.40	0.04	0.38	0.09	− 0.02	− 0.24	− 0.35	0.08	0.15	− 0.41

other by 0.1–0.4°C in all experimental conditions except one, significantly so in the majority (19 out of 24) of experimental conditions (Table 4). However, as might be expected, the two $\bar{T}_b$ estimates tended to converge as the relative weighting of $\bar{T}_{sk}$ to T_{re} was decreased.

Predictions and comparisons of heat storage

With any given clothing assembly, the variable(s) M and/or E_{sk} changed with alterations of S (Table 5). In contrast, there were negligible variations (0–5 kJ · $m^{-2} \cdot h^{-1}$) in the remaining parameters (W, E_{res}, C_{res}, and R + C) from one experimental condition to another.

For any given weightings of T_{re} and $\bar{T}_{sk}$, there were generally only minor differences ($<$ 5%) between the thermometric estimates of heat storage, irrespective of whether $\bar{T}_{sk}$ was based on regional surface area or principal component methodologies (Table 6). However, paired t-tests showed significant differences between thermometric estimates based on invariant and variable weightings for T_{re} and $\bar{T}_{sk}$ under all experimental conditions except post-acclimation in the T_{ET+HA} group.

There were relatively large discrepancies between calorimetric and thermometric estimates of heat storage (Table 6). If the relative weighting of T_{re} to $\bar{T}_{sk}$ was increased from the beginning of the heat-exercise challenge to its end, the discrepancy tended to increase when wearing normal clothing but to decrease when wearing protective clothing. In the T_{C+HA} group, significant differences were found between calorimetry and thermometry with two sets of relative weightings of 2 : 1 and 4 : 1 or 9 : 1 [S vs $S_{A(2:1,4:1)}$, $S_{P(2:1,4:1)}$, $S_{A(2:1,9:1)}$, or $S_{P(2:1,9:1)}$] when wearing normal clothing and between calorimetry and thermometry with an invariant

Table 3 Weighting coefficients for 12 local skin temperatures, derived from the respective eigenvectors of P1 while wearing normal or protective clothing. (Abbreviations as in Table 1)

Clothing	Group	Condition		Forehead	Chest	Claf	Abdomen	Lower arm	Wrist	Front thigh	Shin	Foot	Upper back	Lower back	Rear thigh
Normal	T_{C+HA}	B	I	0.06	0.09	0.09	0.09	0.11	0.08	0.05	0.09	0.09	0.11	0.09	0.06
			F	0.02	0.06	0.11	0.09	0.09	0.08	0.10	0.12	0.10	0.05	0.07	0.11
		A(C)	I	0.01	0.06	0.10	0.11	0.11	0.11	0.11	0.05	0.06	0.09	0.10	0.10
			F	0.04	0.04	0.10	0.09	0.06	0.11	0.11	0.12	0.09	0.06	0.07	0.09
		A(HA)	I	0.07	0.11	0.09	0.09	0.08	0.09	0.11	0.08	0.02	0.05	0.12	0.11
			F	0.03	0.08	0.02	0.09	0.17	0.03	0.01	0.09	0.08	0.18	0.08	0.13
	T_{ET+HA}	B	I	0.00	0.12	0.03	0.07	0.06	0.11	0.14	0.08	0.01	0.13	0.16	0.10
			F	0.04	0.01	0.11	0.10	0.00	0.13	0.13	0.10	0.11	0.04	0.10	0.12
		A(ET)	I	0.07	0.09	0.10	0.09	0.09	0.08	0.09	0.09	0.03	0.08	0.10	0.08
			F	0.00	0.09	0.14	0.06	0.08	0.11	0.11	0.14	0.08	0.00	0.07	0.12
		A(HA)	I	0.04	0.10	0.07	0.11	0.06	0.02	0.13	0.13	0.00	0.12	0.12	0.08
			F	0.03	0.00	0.11	0.08	0.12	0.11	0.14	0.11	0.11	0.00	0.06	0.13
Protective	T_{C+HA}	B	I	0.08	0.15	0.06	0.09	0.07	0.00	0.08	0.07	0.00	0.21	0.14	0.05
			F	0.06	0.11	0.09	0.06	0.07	0.11	0.10	0.11	0.10	0.08	0.06	0.06
		A(C)	I	0.00	0.06	0.10	0.12	0.12	0.09	0.12	0.07	0.01	0.06	0.12	0.13
			F	0.05	0.04	0.08	0.11	0.11	0.13	0.10	0.06	0.12	0.06	0.06	0.08
		A(HA)	I	0.01	0.09	0.11	0.10	0.07	0.05	0.12	0.08	0.01	0.12	0.12	0.14
			F	0.09	0.10	0.05	0.10	0.02	0.12	0.05	0.05	0.12	0.10	0.09	0.11
	T_{ET+HA}	B	I	0.08	0.10	0.05	0.13	0.05	0.00	0.14	0.05	0.00	0.13	0.15	0.13
			F	0.12	0.10	0.09	0.03	0.00	0.12	0.05	0.10	0.12	0.09	0.11	0.07
		A(ET)	I	0.04	0.08	0.10	0.10	0.09	0.05	0.10	0.10	0.01	0.12	0.10	0.09
			F	0.00	0.05	0.12	0.04	0.13	0.13	0.12	0.11	0.10	0.06	0.07	0.05
		A(HA)	I	0.13	0.12	0.00	0.13	0.10	0.11	0.07	0.13	0.01	0.07	0.10	0.02
			F	0.08	0.10	0.08	0.10	0.09	0.10	0.01	0.08	0.10	0.08	0.10	0.09

Table 4 Thermal data while wearing normal or protective clothing. Values are mean (SEM) in°C. [T_{re} rectal temperature, $\bar{T}_{skA}$ or $\bar{T}_{skP}$ mean skin temperatures, calculated by weighting coefficients derived from regional surface area or principal component methodologies, respectively, $\bar{T}_{bA(2:1)}$ or $\bar{T}_{bP(2:1)}$, $\bar{T}_{bA(4:1)}$ or $\bar{T}_{bP(4:1)}$, and $\bar{T}_{bA(9:1)}$ or $\bar{T}_{bP(9:1)}$ mean body temperatures, calculated from T_{re} and $\bar{T}_{skA}$ or $\bar{T}_{skP}$ using relative weightings as indicated in inferior parentheses, respectively]. Other abbreviations as in Table 1

Clothing	Group	Condition		T_{re}	$\bar{T}_{skA}$	$\bar{T}_{skP}$	$\bar{T}_{bA(2:1)}$	$\bar{T}_{bP(2:1)}$	$\bar{T}_{bA(4:1)}$	$\bar{T}_{bP(4:1)}$	$\bar{T}_{bA(9:1)}$	$\bar{T}_{bP(9:1)}$
Normal	T_{C+HA}	B	I	37.4 (0.1)	32.1 (0.3)	32.0 (0.3)	35.6 (0.1)	35.6 (0.1)	36.3 (0.0)	36.3 (0.0)	36.9 (0.1)	36.9 (0.0)
			F	38.8 (0.1)	36.9 (0.2)	37.1 (0.2)*	38.2 (0.1)	38.2 (0.1)*	38.4 (0.1)	38.5 (0.1)*	38.6 (0.1)	38.7 (0.1)*
		A(C)	I	37.3 (0.1)	32.5 (0.3)	32.3 (0.3)*	35.7 (0.1)	35.7 (0.1)*	36.3 (0.1)	36.3 (0.1)*	36.8 (0.1)	36.8 (0.1)*
			F	38.7 (0.1)	37.1 (0.2)	37.2 (0.2)*	38.2 (0.1)	38.2 (0.1)*	38.4 (0.1)	38.4 (0.1)*	38.6 (0.1)	38.6 (0.1)*
		A(HA)	I	37.2 (0.1)	32.1 (0.2)	32.2 (0.2)*	35.5 (0.1)	35.5 (0.1)*	36.2 (0.1)	36.2 (0.1)*	36.7 (0.1)	36.7 (0.1)*
			F	38.4 (0.1)	36.6 (0.2)	36.5 (0.2)*	37.8 (0.1)	37.8 (0.1)*	38.1 (0.1)	38.0 (0.1)*	38.2 (0.1)	38.2 (0.1)*
	T_{ET+HA}	B	I	37.3 (0.1)	31.8 (0.2)	31.9 (0.2)	35.5 (0.0)	35.5 (0.0)	36.2 (0.1)	36.2 (0.1)	36.7 (0.1)	36.7 (0.0)
			F	38.8 (0.2)	36.9 (0.2)	37.1 (0.3)*	38.2 (0.2)	38.3 (0.2)*	38.4 (0.2)	38.5 (0.2)*	38.6 (0.2)	38.6 (0.2)*
		A(ET)	I	37.3 (0.1)	32.2 (0.5)	32.3 (0.5)*	35.6 (0.2)	35.6 (0.2)*	36.3 (0.2)	36.3 (0.2)*	36.8 (0.1)	36.8 (0.1)*
			F	38.6 (0.1)	36.7 (0.2)	36.9 (0.2)*	38.0 (0.1)	38.0 (0.1)*	38.2 (0.1)	38.3 (0.1)*	38.4 (0.1)	38.4 (0.1)*
		A(HA)	I	37.2 (0.1)	32.6 (0.3)	32.8 (0.3)	35.7 (0.1)	35.7 (0.1)	36.2 (0.0)	36.3 (0.0)	36.7 (0.0)	36.7 (0.0)
			F	38.6 (0.1)	36.5 (0.2)	36.7 (0.2)*	37.9 (0.1)	37.9 (0.1)*	38.1 (0.1)	38.2 (0.1)*	38.3 (0.1)	38.4 (0.1)*
Protective	T_{C+HA}	B	I	37.4 (0.1)	32.8 (0.2)	33.2 (0.3)*	35.9 (0.1)	36.0 (0.1)*	36.5 (0.1)	36.6 (0.1)*	37.0 (0.1)	37.0 (0.0)*
			F	38.9 (0.1)	38.1 (0.2)	38.2 (0.2)*	38.6 (0.1)	38.7 (0.1)*	38.7 (0.1)	38.8 (0.1)*	38.8 (0.1)	38.8 (0.1)*
		A(C)	I	37.3 (0.1)	33.3 (0.2)	33.3 (0.2)	36.0 (0.0)	36.0 (0.1)	36.5 (0.0)	36.5 (0.0)	36.9 (0.1)	36.9 (0.1)
			F	38.8 (0.1)	38.1 (0.1)	38.2 (0.1)*	38.5 (0.1)	38.6 (0.1)*	38.6 (0.1)	38.7 (0.1)*	38.7 (0.1)	38.7 (0.1)*
		A(HA)	I	37.2 (0.1)	32.6 (0.2)	32.7 (0.2)	35.7 (0.1)	35.7 (0.1)	36.3 (0.1)	36.3 (0.1)	36.8 (0.1)	36.8 (0.1)
			F	38.7 (0.2)	37.8 (0.1)	37.9 (0.1)*	38.4 (0.2)	38.4 (0.2)*	38.5 (0.2)	38.5 (0.2)*	38.6 (0.2)	38.6 (0.2)*
	T_{ET+HA}	B	I	37.2 (0.1)	31.9 (0.3)	32.2 (0.3)*	35.5 (0.1)	35.6 (0.1)*	36.2 (0.1)	36.2 (0.1)*	36.7 (0.1)	36.7 (0.1)*
			F	38.9 (0.1)	38.1 (0.1)	38.4 (0.2)*	38.7 (0.1)	38.7 (0.1)*	38.8 (0.1)	38.8 (0.1)*	38.8 (0.1)	38.9 (0.1)*
		A(ET)	I	37.3 (0.1)	33.1 (0.3)	33.3 (0.3)*	35.9 (0.1)	36.6 (0.1)*	36.4 (0.1)	36.5 (0.1)*	36.9 (0.1)	36.9 (0.1)*
			F	38.9 (0.1)	38.0 (0.2)	38.2 (0.2)*	38.6 (0.1)	38.6 (0.1)*	38.7 (0.1)	38.7 (0.1)*	38.8 (0.1)	38.8 (0.1)*
		A(HA)	I	37.1 (0.1)	32.7 (0.2)	32.9 (0.2)*	35.6 (0.1)	35.7 (0.1)*	36.2 (0.1)	36.2 (0.1)*	36.6 (0.1)	36.7 (0.1)*
			F	38.7 (0.2)	37.9 (0.2)	38.1 (0.2)*	38.4 (0.2)	38.5 (0.2)*	38.5 (0.2)	38.6 (0.2)*	38.6 (0.2)	38.6 (0.2)*

*Significantly different from corresponding mean skin or body temperature value [$\bar{T}_{bkA}$, $\bar{T}_{bA(2:1)}$, $\bar{T}_{bA(4:1)}$, or $\bar{T}_{bA(9:1)}$] ($P < 0.05$)

Table 5 Components of heat balance while wearing normal or protective clothing. [S rate of heat storage estimated by resolving the heat balance equation, M rate of metabolic heat production, W rate of external work, E_{res} rate of evaporative heat loss from the respiratory tract, C_{res} rate of convective heat gain through the respiratory tract, E_{sk} rate of evaporative heat loss from the clothed skin, $R + C$ rate of combined dry (radiant and convective) heat gain through the clothed skin]. Other abbreviations as in Table 1

Clothing	Group	Condition	S	M	W	E_{res}	C_{res}	E_{sk}	R + C
Normal	T_{C+HA}	B	153 (23)	909 (24)	41 (1)	57 (2)	8 (0)	716 (32)	51 (1)
		A(C)	154 (18)	899 (27)	42 (1)	57 (2)	8 (0)	703 (29)	49 (2)
		A(HA)	125 (18)	865 (19)	41 (1)	55 (1)	7 (0)	705 (24)	54 (1)
	T_{ET+HA}	B	156 (17)	904 (26)	40 (1)	57 (2)	8 (0)	709 (35)	50 (2)
		A(ET)	116 (24)	900 (27)	40 (1)	57 (2)	8 (0)	745 (41)	50 (2)
		A(HA)	55 (29)	868 (25)	40 (1)	55 (2)	7 (0)	777 (48)	51 (2)
Protective	T_{C+HA}	B	521 (38)	985 (33)	43 (1)	62 (2)	8 (0)	397 (15)	30 (1)
		A(C)	539 (28)	989 (18)	43 (1)	62 (1)	8 (0)	382 (19)	29 (1)
		A(HA)	528 (34)	992 (30)	43 (1)	63 (2)	8 (0)	398 (24)	31 (1)
	T_{ET+HA}	B	595 (22)	1021 (33)	42 (1)	64 (2)	9 (0)	360 (13)	32 (1)
		A(ET)	579 (20)	1029 (34)	42 (1)	65 (2)	9 (0)	379 (21)	28 (1)
		A(HA)	541 (30)	1005 (22)	42 (1)	63 (1)	8 (0)	397 (31)	30 (1)

Table 6 Body heat storage as estimated by calorimetry and thermometry while wearing normal or protective clothing. [$S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$, $S_{A(2:1,4:1)}$ or $S_{P(2:1,4:1)}$, and $S_{A(2:1,9:1)}$ or $S_{P(2:1,9:1)}$ rates of heat storage calculated from T_{re} and $\bar{T}_{sk}$ based on regional surface area or principal component methodologies, using the predictive equations with one or two set(s) of relative weightings as indicated in inferior parentheses, respectively]. Other abbreviations as in Table 1

Clothing	Group	Condition	S	$S_{A(4:1,4:1)}$	$S_{P(4:1,4:1)}$	$S_{A(2:1,4:1)}$	$S_{P(2:1,4:1)}$	$S_{A(2:1,9:1)}$	$S_{P(2:1,9:1)}$
Normal	T_{C+HA}	B	153 (23)	160 (9)	165 (9)	213 (12)*,**	220 (13)*,**	227 (12)*,**	223 (13)*,**
		A(C)	154 (18)	158 (10)	162 (10)	204 (11)*,**	211 (11)*,**	217 (11)*,**	223 (12)*,**
		A(HA)	125 (18)	143 (10)	141 (10)	193 (10)*,**	191 (10)*,**	207 (10)*,**	206 (10)*,**
	T_{ET+HA}	B	156 (17)	162 (4)	170 (3)	212 (4)*,**	227 (12)*,**	226 (4)*,**	241 (16)*,**
		A(ET)	116 (24)	138 (6)	138 (6)	184 (11)*,**	184 (11)*,**	197 (11)*,**	196 (11)*,**
		A(HA)	55 (29)	132 (7)*	134 (8)*	173 (10)*	174 (12)*	188 (11)*	186 (12)*
Protective	T_{C+HA}	B	521 (38)	396 (15)*	381 (17)*	503 (18)**	480 (19)**	518 (19)**	493 (20)**
		A(C)	539 (28)	388 (17)*	393 (18)*	487 (20)**	492 (22)**	502 (21)**	504 (23)**
		A(HA)	528 (34)	387 (12)*	388 (12)*	496 (13)**	497 (13)**	511 (13)**	510 (13)**
	T_{ET+HA}	B	595 (22)	428 (13)*	426 (13)*	543 (18)*,**	534 (19)*,**	557 (20)*,**	544 (21)*,**
		A(ET)	579 (20)	402 (16)*	400 (15)*	500 (23)*,**	494 (22)*,**	515 (24)*,**	507 (23)*,**
		A(HA)	541 (30)	375 (17)*	371 (17)*	471 (19)*,**	461 (21)*,**	483 (18)**	472 (21)*,**

*Significantly different from S value ($P < 0.05$), **significantly different from $S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$ value ($P < 0.05$)

relative weighting of 4:1 [S vs $S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$] when wearing protective clothing. In the T_{ET+HA} group, all calorimetric and thermometric estimates of heat storage differed significantly from each other, except S versus $S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$ before heat acclimation when wearing normal clothing and except S versus $S_{A(2:1,9:1)}$ after heat acclimation when wearing protective clothing.

Discussion

Many thermal physiologists have adopted invariant weightings of T_{re} and $\bar{T}_{sk}$ (commonly, $\Delta\bar{T}_b = 0.8 \cdot \Delta T_{re} + 0.2 \cdot \Delta\bar{T}_{sk}$) when estimating the change of $\bar{T}_b$ under hot conditions. This is true whether the subjects have worn shorts (Hardy and DuBois 1938b; Stolwijk and Hardy 1966) or full protective clothing (Holmér and Elnäs 1981; Vallerand et al. 1991). However, the body heat storage thus calculated is sometimes underestimated relative to values obtained by solution of the heat balance equation, especially if subjects move from thermoneutral to hot environments (Colin et al. 1971; Snellen 1966). In the present investigation, the underestimation was substantial (approximately −30%) when wearing protective clothing, as reflected by the discrepancy between S and $S_{A(4:1,4:1)}$ or $S_{P(4:1,4:1)}$ (a difference of 125–179 $kJ \cdot m^{-1} \cdot h^{-1}$; Table 6). This could reflect an inappropriate weighting of local T_{sk} and/or an inappropriate weighting of the respective contributions of core and T_{sk} to the overall T_b.

Influence of T_{sk}

The principal component analyses revealed that type of clothing, endurance training, heat acclimation, and heat-exercise exposure all modified the contribution of individual thermistor readings to the first component (which we presume reflects an overall $\bar{T}_{sk}$ trend). For instance, when wearing the protective clothing, the loading coefficients of "highly insulated regions" such as the forehead, wrist, or foot tended to increase as heat-exercise stress was increased, causing the weighting of T_{sk} to become more uniform. Nevertheless, the discrepancies (always $< 5\%$) between heat storage estimates based on regional surface area and principal component methodologies had little practical significance.

The small size of any differences reflects in part the low weighting of $\bar{T}_{sk}$ relative to that of T_{re}. The impact of changes in individual coefficients may also have been offset by opposing effects among the various weighting coefficients. Mitchell and Wyndham (1969) argued that if $\bar{T}_{sk}$ was calculated from at least 12 measurement points, it was for practical purposes immune to variations in the respective weighting coefficients. Uniformity of T_{sk} is more evident in the clothed than in the nude case. Teichner (1958) and Goldman (1985) have both claimed that when wearing full protective clothing in the heat, T_{sk} become remarkably uniform. In such a situation, it may even be sufficient to measure a single lateral or medial thigh temperature (which is unlikely to be influenced by direct impingement of solar or other radiant heat sources; Goldman 1985).

Relative influence of core temperature and T_{sk}

The usual method of determining appropriate coefficients of T_{re} and $\bar{T}_{sk}$ is a stepwise multiple linear regression analysis (Colin et al. 1971; Vallerand et al. 1992). However, even if such an approach yields optimal weightings, the values obtained only apply to a limited range of conditions. Another approach is to make an arbitrary comparison of the different weighting systems proposed by various investigators (Mitchell and Wyndham 1969; Teichner 1958). In theory, an unlimited number of comparisons are possible; however, if the weighting for $\bar{T}_{sk}$ equals or exceeds that for T_{re}, $\bar{T}_b$ becomes unrealistically low. The present study thus compared three combinations of commonly used relative weightings for thermoneutral and hot environments: 4:1 and 4:1, 2:1 and 4:1, or 2:1 and 9:1.

When wearing normal clothing, the heat storage calculated by the fixed 4:1 weighting matched calorimetric estimates quite well. However, these results should be accepted with some caution, since the calorimetric estimate may have been biased by methodological errors. E_{sk} can be overestimated, due to external dripping from the clothing. In the present study, such losses were quite small, since most of the secreted sweat soaked into garments which covered almost the entire skin surface. The decrease in efficiency of evaporative cooling with an increase in the water content (wetted area) of the clothing cannot be predicted exactly (Craig and Moffitt 1974), but a comparison of differences in heat storage estimates between the three treatment conditions for the T_{ET+HA} group (Tables 5, 6) implies that when the sweat evaporation rate reached 650 $g \cdot h^{-1}$ ($777\ kJ \cdot m^{-2} \cdot h^{-1} \div 2.43\ kJ \cdot g^{-1} \times 1.98 m^2$), there was a significant overestimation of E_{sk} (possibly as large as 30–40 $kJ \cdot m^{-2} \cdot h^{-1}$, corresponding to the evaporation of 24–33 $g \cdot h^{-1}$ of sweat with no cooling effect).

When wearing protective clothing and using invariant coefficients (0.8, 0.2), there was a substantial discrepancy between the heat storage calculated by calorimetry and the figure obtained by thermometry. However, the discrepancy was decreased at least 20% ($100\ kJ \cdot m^{-2} \cdot h^{-1}$) by the expedient of using two sets of weighting factors (0.67, 0.33 before exposure and either 0.8, 0.2 or 0.9, 0.1 after exposure). Only minor differences ($< 3\%$) in estimated heat storage were observed between these last two options. These calculations show that the choice of initial weighting factors is at least as critical as that of the final ones; this is not surprising, since the gradient between T_{re} and $\bar{T}_{sk}$ is larger initially than in the final stages of a heat-exercise stress challenge. The apparent underestimation of heat storage by thermometry may relate to the sluggish variation of T_{re}. In our study, the average overall exposure time of 50 min when wearing protective clothing may have been too short to yield an equilibrium $\sum T_{re}$ and thus to give a reliable estimate of heat storage. In cases where the exposure time is < 60 min, other more rapidly responding indicators of core temperature such as the esophagus or the tympanic membrane (Sawka and Wenger 1988; Vallerand et al. 1992) can be used, but this is not always convenient. The alternative option of using T_{re} with two sets of weighting factors (0.67, 0.33; 0.8, 0.2 or 0.9, 0.1) may yet provide a reasonable index of heat storage under such circumstances. If the exposure time is > 90 min, the progressive convergence of T_{re} and $\bar{T}_{sk}$ minimizes the impact of the choice of final weighting factors, particularly when the subject is wearing full protective clothing.

Influence of other sources of error

Vallerand et al. (1992) pointed out that differences in thermometric and calorimetric estimates of heat storage could also arise from inappropriate assumptions regarding the average specific heat of body tissues. There is a potential range of 2.93–3.77 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ about the mean value of 3.47 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ (Burton 1935; Hardy and DuBois 1938b). If the lower or upper extreme value were to be used in the thermometric calculations, our estimates of heat storage (Table 6) would be underestimated by 16% or overestimated by 9%, respectively. The potential range of variation is from -38 to $+21\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}}$ when wearing normal clothing and from -87 to $+48\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}}$ when wearing protective clothing. Further research is thus required to obtain more precise data on the average specific heat of the body, and factors affecting it, such as obesity (cf. Frim et al. 1990; Kakitsuba and Mekjavic 1987).

The value of $2.43\ \mathrm{kJ \cdot g^{-1}}$ has been widely used for the heat of evaporation of sweat. However, this is the latent heat of vaporization of water at 30°C. Therefore, changes in the solute (electrolyte) content of sweat (Taylor 1986; Wenger 1988) and the water vapor pressure (temperature and relative humidity) of the microenvironment (Aoyagi et al. 1994, 1995) as a result of physical training or heat acclimation might modify the latent heat of evaporation of sweat. The heat of evaporation of sweat appears to be independent of the prevailing air temperature or humidity (Snellen et al. 1970; Wenger 1972). Likewise, Wenger (1972) has estimated that solutes would change the latent heat by at most 0.01% relative to pure water at any given temperature and humidity. Various values above $2.50\ \mathrm{kJ \cdot g^{-1}}$ have been reported: $2.60\ \mathrm{kJ \cdot g^{-1}}$ (Snellen et al. 1970), $2.61\ \mathrm{kJ \cdot g^{-1}}$ (Mitchell et al. 1968), $2.70\ \mathrm{kJ \cdot g^{-1}}$ (Hardy 1949), $2.89\ \mathrm{kJ \cdot g^{-1}}$ (Nielsen 1966), 2.81 and $2.91\ \mathrm{kJ \cdot g^{-1}}$ (Snellen 1966), although Wenger (1972) has argued that none of these estimates differ significantly from $2.43\ \mathrm{kJ \cdot g^{-1}}$. If an average value of 2.75 rather than $2.43\ \mathrm{kJ \cdot g^{-1}}$ were to be adopted, the underestimation of our heat storage estimates (Tables 5, 6) could amount to $93\text{–}102\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}}$, corresponding to a $\Delta\bar{T}_b \cdot \Delta t^{-1}$ value of $0.6\text{–}0.7^\circ\mathrm{C \cdot h^{-1}}$ [93 or $102\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}} \div (3.47\ \mathrm{kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}} \times 81.8\ \mathrm{kg} \div 1.98\ \mathrm{m^2})$] when wearing normal clothing and $47\text{–}52\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}}$, corresponding to a $\Delta\bar{T}_b \cdot \Delta t^{-1}$ value of $0.3-0.4^\circ\mathrm{C \cdot h^{-1}}$ [47 or $52\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1}} \div (3.47\ \mathrm{kJ \cdot kg^{-1} \cdot {}^\circ C^{-1}} \times 81.8\ \mathrm{kg} \div 1.98\ \mathrm{m^2})$] when wearing protective clothing. This tendency would be remarkable for untrained and unacclimated subjects, but plainly a change in assumptions regarding latent heat has a major influence on the type of calculation made here. It is thus important to initiate larger scale research to reach a consensus on an appropriate figure for the heat of evaporation of sweat.

Conclusions

In the present type of experiment, where clothed subjects move from a thermoneutral to a hot environment and then perform a continuous moderate aerobic form of exercise, a formula using either one or two set(s) of weighting factors for T_{re} and $\bar{T}_{sk}$ apparently provides the best thermometric estimate of changes in $\bar{T}_b$ and heat content, depending on the efficiency of evaporative cooling from wet clothing (particularly when wearing normal clothing) and the duration of heat-exercise exposure (especially when wearing protective clothing).

When wearing normal clothing in a thermoneutral environment, $\bar{T}_b = 0.8 \cdot T_{re} + 0.2 \cdot \bar{T}_{sk}$, and in a hot environment, $\bar{T}_b = 0.8 \cdot T_{re} + 0.2 \cdot \bar{T}_{sk}$. When wearing protective clothing in a thermoneutral environment, $\bar{T}_b = 0.67 \cdot T_{re} + 0.33 \cdot \bar{T}_{sk}$, and in a hot environment, $\bar{T}_b = 0.9 \cdot T_{re} + 0.1 \cdot \bar{T}_{sk}$.

However, better agreement on the average specific heat of the body and the latent heat of evaporation of sweat is needed before a definitive conclusion is possible.

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Appendix

Body surface area

A_D was estimated from Wt and Ht, using the equation of DuBois and DuBois (1916):

$$A_D = 0.202 \cdot \mathrm{W}t^{0.425} \cdot \mathrm{H}t^{0.725}. \tag{A1}$$

Respiratory weight losses

The values for m_e and m_r were estimated using the equations of Mitchell et al. (1972) and Snellen (1966), respectively:

$$m_e = 0.019 \cdot (60 \cdot \dot{V}\mathrm{O_2}) \cdot (49 - P_a) \tag{A2}$$

$$\mathrm{m_r} = (60 \cdot \dot{V}\mathrm{O_2}) \cdot (RQ \cdot \rho\mathrm{CO_2} - \rho\mathrm{O_2}) \tag{A3}$$

where $\rho\mathrm{CO_2}$ and $\rho\mathrm{O_2}$ are the densities of carbon dioxide ($1.977\ \mathrm{g \cdot l^{-1}}$ STPD) and oxygen ($1.429\ \mathrm{g \cdot l^{-1}}$ STPD), respectively.

Dry heat transfer coefficients

The linear values of h_r (Nishi 1981) and h_c (Nishi and Gagge 1970) can be approximated as:

$$h_r = 4 \cdot \sigma \cdot \varepsilon \cdot [(\bar{T}_{sk} + \bar{T}_r) \cdot 2^{-1} + 273.15]^3 \cdot (A_r \cdot A_D^{-1}) \tag{A4}$$

$$h_c = 23.4 \cdot v_{tw}^{0.39} \tag{A5}$$

where σ is the Stefan-Boltzmann constant ($20.4 \cdot 10^{-8}\ \mathrm{kJ \cdot m^{-2} \cdot h^{-1} \cdot {}^\circ K^{-4}}$); ε is the emissivity of the body (1); $\bar{T}_{sk}$ is averaged over 1-min intervals; $\bar{T}_r$ is the mean radiant temperature (40°C; $\bar{T}_r$ is approximately equal to T_a, given an approximate matching of chamber wall and ambient temperatures); and $A_r \cdot A_D^{-1}$ is the ratio of the effective radiating area to the DuBois total surface area (a value of 0.72 for a standing person; Gonzalez 1988).

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