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Mean Skin Temperature Weighted by Skin Area, Heat Transfer Coefficients and Thermal Sensitivity

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Abstract

Many formulas for calculating the mean skin temperature have been proposed hitherto. All the formulas can be described by a general form——the sum total of the product of both the regional skin temperature and the weighting factor concerned with the region. The weighting factor in these formulas was classified into five groups from the point of the content and the concrete values were compared.

Based on the heat equilibrium between man and his environment, the author newly derived a mean skin temperature formula weighted by skin areas and the heat transfer coefficients.

With reference to the thermal sensitivity coefficients given by Nadel et al, a new formula, which is weighted by three important factors——the skin area, the heat transfer coefficicients and the thermal sensitivity, was proposed.

As the result of a comparison run against formulas reported previously, the weighting factors of the skin area-heat transfer coefficient formula are similar to those of the Hardy -DuBois formula, and the weighting factors of the formula by the skin area, the heat transfer coefficients and the thermal sensitivity are similar to those of the formula by Nadel et al.

1. Introduction

The skin temperature, which is closely related to the thermal sensation, is a physiological value regulated by both the conditions of man and his surrounding environment. The temperature of the skin surface is generally different for each region of the human body, for instance, the skin temperature of the forehead is comparatively high and the limbs have lower temperatures under usual circumstances. Physiologists and biological engineers have proposed formulas for calculating the mean skin temperature and these weighting factors have a wide variety. Although all of the formulas proposed can be written by a general equation, i. e., the sum total of the product of the skin temperature at each part of the skin surface and the weighting factor related to the part, they can be classified into the following five groups from a viewpoint of the contents.

1. one representative skin temperature.
2. arithmetic mean of skin temperatures.
3. area weighted mean skin temperature.
4. mean skin temperature weighted by the area and the thermal sensitivity.
5. mean skin temperature weighted by area and the heat transfer coefficients.

In the present study, based on the skin area-heat transfer coefficient weighting

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formula, a new formula for calculating the mean skin temperature, which is weighted by three important factors——the skin area, the thermal sensitivity and the heat transfer coefficients, is proposed.

2. Nomenclature

F_i : weighting factor, N. D.
C_F : relative area of face observed, N. D.
C_T : relative area of trunk observed, N. D.
C_{UA} : relative area of upper arms observed, N. D.
C_{LA} : relative area of lower arms observed, N. D.
C_{UL} : relative area of upper legs observed, N. D.
C_{LL} : relative area of lower legs observed, N. D.
C_{FO} : relative area of feet observed, N. D.
C_H : relative area of hands observed, N. D.
n : number of skin temperature measurement, N. D.
T_s : mean skin temperature, °C
T_{si} : skin temperature at a specific site i of the body, °C
T_a : air temperature, °C
T_r : mean radiant temperature, °C
P_s : mean skin vapor pressure, mmHg
P_{si} : skin vapor pressure at a specific site i of the body, mmHg
P_a : ambient vapor pressure, mmHg
A : total body surface area (assumed to be equal to the areas of convection, radiation and evaporation heat transfer respectively), m^2
A_i : skin segment area at a specific site i of the body, m^2
h_c : mean convective heat transfer coefficient of the human body, $kcal/m^2h°C$
h_{ci} : local convective heat transfer coefficient at the site i of the body, $kcal/m^2h°C$
v : air movement, m/s
$\varkappa$: modified Lewis relation, °C/mmHg
h_r : mean radiative heat transfer coefficient of the body, $kcal/m^2h°C$

Table 1. Kinds of weighting factors

content of weighting factor	form of weighting factor
weighting factor with unity	$F_i=1$
equal weighting factor	$F_i=\frac{1}{n}$
weighting factor by skin area only	$F_i=\frac{A_i}{A}$
skin area-thermal sensitivity weighting factor	$F_i=\frac{A_i}{A}\cdot S^*$
skin area-heat transfer coefficient weighting factor	$F_i=\frac{A_i}{A}\cdot\frac{h_{ci}+h_{ri}}{h_c+h_r}$
skin area-heat transfer coefficient-thermal sensitivity weighting factor	$F_i=\frac{A_i}{A}\cdot\frac{h_{ci}+h_{ri}}{h_c+h_r}\cdot S^*$

Table 2. Values of weighting factors.

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1)	Teichner															
	Lund-Gisoifi						1									
2)	Mitchell-Wyndham	$\frac{1}{15}$				$\frac{1}{15}$	$\frac{1}{15}$			$\frac{1}{15}$		$\frac{1}{15}$				$\frac{1}{15}$
	Stolwijk-Hardy	$\frac{1}{10}$				$\frac{1}{10}$	$\frac{1}{10}$		$\frac{1}{10}$							$\frac{1}{10}$
	Teichner		$\frac{1}{10}$			$\frac{1}{10}$	$\frac{1}{10}$					$\frac{1}{10}$				$\frac{1}{10}$
	Kurata-Funazu															$\frac{1}{2}$
3)	Kisetsu-Seirihan	0.0155	0.0155	0.012	0.041	0.083		0.0405	0.041		0.405		0.0305	0.0405	0.0265	0.086
	Kurata-Funazu	0.031			0.082						0.081	0.061		0.081		0.172
	Hardy-DuBois	0.07				0.0875				0.0875		0.14				0.095
	QREC		0.10			0.125	0.07					0.07				0.125
	Hardy-DuBois	0.07								0.35		0.14				0.19
	Teichner		0.149			0.186	0.107									0.186
	Palmes-Park		0.14			0.19						0.11				0.32
	Miura et al	0.1				0.4						0.05				0.2
	Newburgh-Spealman					0.34						0.15				0.33
	Ramanathan					0.3	0.3									0.2
	Burton					0.50						0.14				
	Winslow et al	$C_F/3$	$C_F/3$			$C_T/4$	$C_{UA}/2$			$C_T/4$		$C_{LA}/2$				$C_{UL}/2$
4)	Nadel et al	0.21				0.21	0.12			0.17		0.06				0.15
5)	Mochida I	0.066				0.153	0.149			0.153		0.151				0.163
6)	Mochida II	0.198				0.179	0.138			0.145		0.076				0.153

		(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)
1)	Teichner		1												
	Lund-Gisoifi														
2)	Mitchell-Wyndham		$\frac{1}{15}$	$\frac{1}{15}$		$\frac{1}{15}$	$\frac{1}{15}$		$\frac{1}{15}$	$\frac{1}{15}$		$\frac{1}{15}$		$\frac{1}{15}$	$\frac{1}{15}$
	Stolwijk-Hardy	$\frac{1}{10}$				$\frac{1}{10}$			$\frac{1}{10}$			$\frac{1}{10}$			$\frac{1}{10}$
	Teichner		$\frac{1}{10}$	$\frac{1}{10}$		$\frac{1}{10}$				$\frac{1}{10}$		$\frac{1}{10}$			
	Kurata-Funazu						$\frac{1}{2}$								
3)	Kisetsu-Seirihan				0.067	0.072	0.043	0.012	0.083	0.0405	0.0305	0.0265		0.086	0.067
	Kurata-Funazu					0.072	0.043		0.166			0.053			0.134
	Hardy-DuBois			0.065		0.07			0.0875	0.0875		0.05		0.095	0.065
	QREC		0.125	0.15		0.05				0.125		0.06			
	Hardy-DuBois			0.13		0.07						0.05			
	Teichner		0.186							0.186					
	Palmes-Park									0.19		0.05			
	Miura et al			0.2								0.05			
	Newburgh-Spealman			0.18											
	Ramanathan			0.2											0.36
	Burton														
	Winslow et al				$C_{LL}/2$	C_{FO}	$C_F/3$		$C_T/4$	$C_T/4$		C_H		$C_{UL}/2$	$C_{LL}/2$
4)	Nadel et al				0.08										
5)	Mochida I				0.183										
6)	Mochida II				0.092										

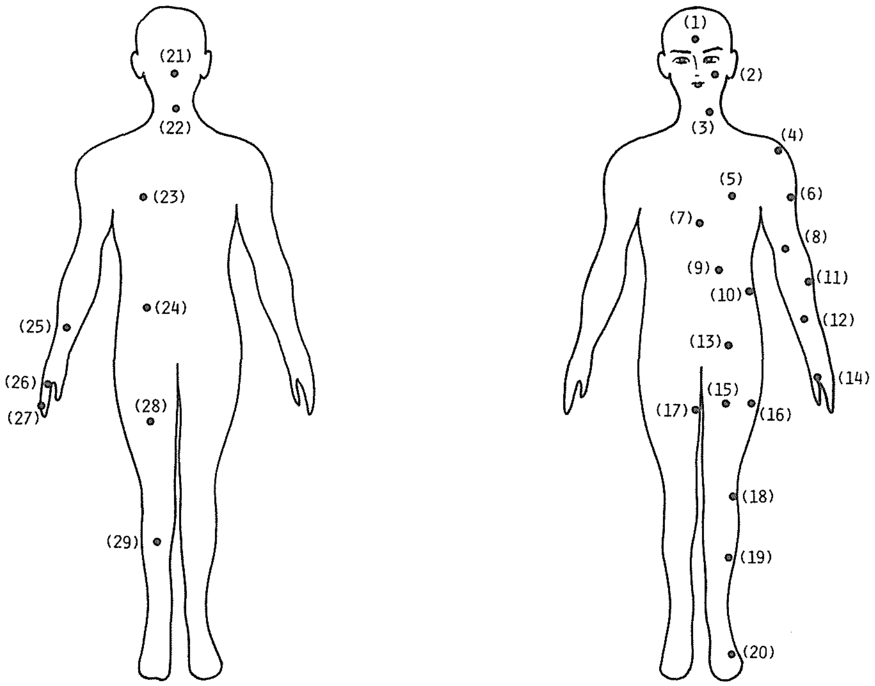

Fig. 1 Sites of skin temperature measurement

h_{ri} : local radiative heat transfer coefficient at the site i of the body, kcal/m²h°C

ε_s : emissivity of the human body, N. D.

σ : Stefan-Boltzmann Constant, kcal/m²hk⁴

k : temperature factor on radiation exchange ($= [(273+T_s)^2+(273+T_r)^2]\ [(273+T_s)+(273+T_r)]$, K^3

Q : net rate of metabolic heat, kcal/h

Q_c : convection heat loss, kcal/h

Q_{ci} : local convection heat loss, kcal/h

Q_r : radiation heat loss, kcal/h

Q_{ri} : local radiation heat loss, kcal/h

Q_e : evaporation heat loss from the skin surface, kcal/h

Q_{ei} : local evaporation heat loss, kcal/h

Q_n : respiration heat loss, kcal/h

Q_v : heat loss by clothing ventilation, kcal/h

Q_w : rate of accomplished work, kcal/h

Q_t : rate of storage of body heat, kcal/h

P_r : Prandtl number, N. D.

R_e : Reynolds number, N. D.

G_r : Grashof number, N. D.

N_u : Nusselt number (mixed=natural and forced convection), N. D.

$N_{u.for}$: Nusselt number (forced), N. D.

S^* : thermal sensitivity coefficient, N. D.

3. Form and concrete figures of the formulas proposed up to the present

Many proposals have been made as the calculating formula of the mean skin temperature and all the formulas can be described by the following general form.

$$T_s = \sum_{i=1}^{n} F_i T_{si} \tag{1}$$

Tables 1 and 2 show the formal classification of the weighting factor in Eq(1)and the concrete values of some formulas proposed up to the present [1] . The subscript numbers of the skin temperature in Table 2 are corresponding to each region shown in Fig. 1. The weighting factors derived in Chapters 4 and 5 are also tabled.

4. Mean skin temperature formula weighted by the skin area and the heat transfer coefficients

In this chapter, a concrete formula is derived according to the relative areas of the seven regions of the Hardy-DuBois formula and the cylindrical diameters by Parker's model.

4-1. General form of the mean skin temperature weighted by the skin area and the heat transfer coefficients

The relation between the metalolic energy produced in the body and the released heat to the environment is given by the following equation.

$$Q = Q_c + Q_r + Q_e + Q_n + Q_v + Q_w + Q_t \tag{2}$$

Eq (2) is transformed to Eq (3) when man is unclothed in a uniform temperature field where the air temperature is equal to the radiant temperature, if the heat losses by respiration, clothing ventilation and the rate of external mechnical work are regarded as negligible in comparison with the heat quantities of convection, radiation and evaporation from the skin surface in a steady state.

$$\begin{aligned} Q &\fallingdotseq (Q_c + Q_r) + Q_e \\ &= (h_c + h_r)(T_s - T_a) A + \kappa h_c (P_s - P_a) \end{aligned} \tag{3}$$

In Eq (3), the skin temperature, the convective heat transfer coefficient, the radiative and the vapor pressure at the boundary layer on the skin surface show" the mean value" respectively.

It is now assumed that the quantity of heat by convection, radiation and evaporation from the body surface is released through the total skin surface.

Let us divide the whole body into several parts and express the heat balance equation between the divided parts and the environment.

$$Q \fallingdotseq (\Sigma Q_{ci} + \Sigma Q_{ri}) + \Sigma Q_{ei}$$
$$= \Sigma (h_{ci} + h_{ri}) (T_{si} - T_a) A_i + \Sigma \kappa h_{ci} (P_{si} - P_a) A_i \quad (4)$$

From Eqs (3) and (4),

$$(h_c + h_r) (T_s - T_a) A + \kappa h_c (P_s - P_a) A$$
$$= \Sigma (h_{ci} + h_{ri}) (T_{si} - T_a) A_i + \Sigma \kappa h_{ci} (P_{si} - P_a) A_i \quad (5)$$

The mean skin temperature T_s, the mean convective heat transfer coefficient h_c, the mean radiative h_r and the mean skin vapor pressure P_s are obtained as follows by solving the identical equation (5).

$$T_s = \Sigma \left(\frac{h_{ci} + h_{ri}}{h_c + h_r} \right) \left(\frac{A_i}{A} \right) T_{si} \quad (6)$$

$$h_c = \Sigma h_{ci} \left(\frac{A_i}{A} \right) \quad (7)$$

$$h_r = \Sigma h_{ri} \left(\frac{A_i}{A} \right) \quad (8)$$

$$P_s = \Sigma \left(\frac{h_{ci}}{h_c} \right) \left(\frac{A_i}{A} \right) P_{si} \quad (9)$$

The mean skin temperature T_s shown as Eq (6) is weighted by the relative skin area and the relative heat transfer coefficients [2]

4-2. Concrete formula of the mean skin temperature weighted by the skin area and the heat transfer coefficients

The actual figures of the mean convection coefficient h_c and the local h_{ci}, of the mean radiative h_r and the local h_{ri} must be decided for the practical use of Eq (6) except for the relative skin areas by the Hardy-DuBois formula.

The author previously derived the new radiative heat transfer coefficient for the human body [3], [4] extending Gebhart's absorption factor method to the radiation heat exchange and applying it to the space between the body and the surrounding walls and linearizing by raising the raidation to the fourth power of the absolute temperature.

$$h_r = \varepsilon_s \sigma k \quad (10)$$

The linear radiation exchange coefficient h_r as shown in Eq (10) is defined by the emissivity of the human surface ε_s, Stefan-Boltzmann Constant σ and the temperature factor k, and does not contain the emissivity of the surrounding walls. Since the change of the temperature factor k is gradual [3], if the temperature range is limited, it becomes possible to regard it as constant. Further, when the radiation heat exchange in an ordinary room is considered, since the long waves are mainly involved, the objects generally seen in a room may be considered as gray bodies and in addition the human skin and clothing surface would have an emissivity close to that of a black body. Therefore, when the temperature range is assumed and if the term $\varepsilon_s \sigma k$ is collectivelly treated as a constant, an actual figure of the radiation coefficient $h_r = 5$ kcal/m^{2}h°C can be obtained, if the emissivity of the body $\varepsilon_s = 0.95$, the temperature factor $k = 1.1 \times 10^8$ K^3 and Stefan-Boltzmann Constant $\sigma = 4.88 \times 10^{-8}$ kcal/m^{2}hk^4 are substituted into Eq (10). Further, from the characteristics of the radiation heat transfer, 5 kcal/m^{2}h°C is also used as the local heat transfer coefficient h_{ri}.

On the other hand, although values and equations for the mean convective heat transfer coefficient of the human body have been proposed by physiologists and biological engineers, in the present study, the values derived from a cylinder model are used as the mean convection coefficient h_c and the local h_{ci}. Since the form of a human body is so complicated that it is difficult to determine the exact value of the convective heat transfer coefficient, a cylinder model dividing the entime body into seven parts will be taken as one of the models for determination. The human body will be considered to be an assembly of several cylinder segments. The cylinder model of a human body by Parker et al [5] is consulted in the present paper and the whole body is divided into seven parts corresponding to the Hardy-DuBois formula [6]. The figures of the cylindrical diameter and the relative skin area used are listed in Table 3. Applying the cylinder model to the convective heat transfer and using the Hilpert's dimensionless equation [7] for the forced convective heat transfer and Oosthuizen-Madan's dimensionless equation [8] for the mixed convection, the mean convective heat transfer coefficient from Eq (7) and the local coefficients can be calculated [3]. Fig. 2 shows the values of the weighting factor in Eq (6). As is evident

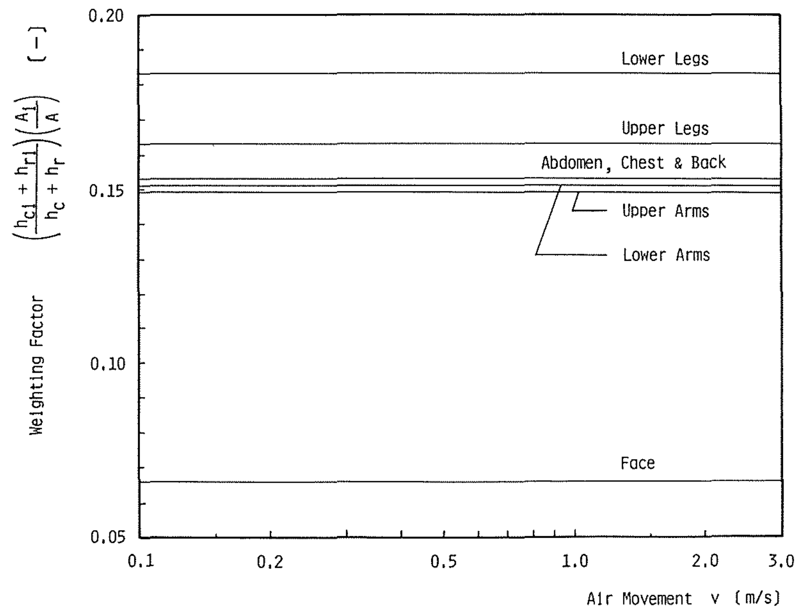

Fig. 2 Relation between the weighting factor by relative skin area and heat transfer coefficients and air movement

from Fig. 2, each weighting factor is almost constant and a concrete formula of the mean skin temperature weighted by the skin area and the heat transfer coefficients is expressed as follows. In addition the sum total of the weighting factors in this case is 1.018 close to unity.

$$\begin{aligned} T_s = {} & 0.066\,T_{\text{face}} + 0.153\,T_{\text{chest \& back}} + 0.153\,T_{\text{abdomen}} \\ & + 0.163\,T_{\text{upper legs}} + 0.183\,T_{\text{lower legs}} + 0.149\,T_{\text{upper arms}} \\ & + 0.151\,T_{\text{lower arms}} \end{aligned} \tag{12}$$

5. Mean skin temperature formula weighted by the skin area, the heat transfer coefficients and the thermal sensitivity

5-1. Mean skin temperature formula weighted by the relative skin area and the thermal sensitivity

Nadel et al [6] performed the experiment on the thermal sensitivity of the skin surface and the results are shown in Fig. 3. From the experimental results, they proposed the following formula (14) weighted by the skin area and the thermal sensitivity in comparison to the modified Hardy-Dubois formula (13).

$$\begin{aligned} T_s = {} & 0.07\,T_{\text{face}} + 0.18\,T_{\text{chest \& back}} + 0.18\,T_{\text{abdomen}} \\ & + 0.16\,T_{\text{upper legs}} + 0.16\,T_{\text{lower legs}} + 0.13\,T_{\text{upper arms}} \\ & + 0.12\,T_{\text{lower legs}} \end{aligned} \tag{13}$$

$$\begin{aligned} T_s = {} & 0.21\,T_{\text{face}} + 0.21\,T_{\text{chest \& back}} + 0.17\,T_{\text{abdomen}} \\ & + 0.15\,T_{\text{upper legs}} + 0.08\,T_{\text{lower legs}} + 0.12\,T_{\text{upper arms}} \\ & + 0.06\,T_{\text{lower arms}} \end{aligned} \tag{14}$$

5-2. Mean skin temperature formula weighted by the skin area, the heat transfer coefficients and the thermal sensitivity

Based no the author's formula (12), if we use the thermal sensitivity coefficients given by Nadel et al, and derive a mean skin temperature formula [9] , then Eq (15) [10] , which contains the skin area, the heat transfer coefficients and the thermal sensitivity, should hold. In this case, the sum total of the weighting factors is 0.981 and the value is also close to unity.

$$\begin{aligned} T_s = {} & 0.198\,T_{\text{face}} + 0.179\,T_{\text{chest \& back}} + 0.145\,T_{\text{abdomen}} \\ & + 0.153\,T_{\text{upper legs}} + 0.092\,T_{\text{lower legs}} + 0.138\,T_{\text{upper arms}} \\ & + 0.076\,T_{\text{lower arms}} \end{aligned} \tag{15}$$

5-3. Comparison of the formulas for the mean skin temperature

Table 4 shows a comparison of the weighting factor in the Hardy-BuBois formula (13), Eq (14) by Nadel et al, Eqs (12) and (15) by the author.

The weighting factors of the Hardy-DuBois formula and the author's formula (12) are almost similar notwithstanding the difference of the content of the weighting factors in the two formulas. The conclusion of great interest will depend on the offset effect in which the

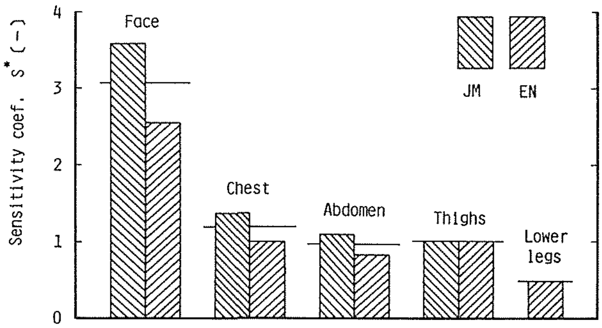

Fig. 3 Mean thermal sensitivity coefficients for a variety of skin regions normalized to the thigh sensitivity coefficient (Nadel et al[6])

Table 3. Relative skin areas and diameters of body segments

	Face	Chest&Back	Abdomen	Upper legs	Lower legs	Upper arms	Lower arms
relative skin area[6] [−]	0.07	0.18	0.18	0.16	0.16	0.13	0.12
diameter[5] [m]	0.19	0.31	0.31	0.15	0.10	0.10	0.08

Table 4. Comparison of values of weighting factors

	Hardy-DuBois (modified): Eq(13)	Mochida : Eq(12)	Nadel et al: Eq(14)	Mochida : Eq(15)
	$\frac{A_i}{A}$	$\frac{A_i}{A}\cdot\frac{h_{ci}+h_{ri}}{h_c+h_r}$	$\frac{A_i}{A}\cdot S^*$	$\frac{A_i}{A}\cdot\frac{h_{ci}+h_{ri}}{h_c+h_r}\cdot S^*$
Face	0.07	0.066	0.21	0.198
Chest&Back	0.18	0.153	0.21	0.179
Abdomen	0.18	0.153	0.17	0.145
Upper legs	0.16	0.163	0.15	0.153
Lower legs	0.16	0.183	0.08	0.092
Upper arms	0.13	0.149	0.12	0.138
Lower arms	0.12	0.151	0.06	0.076

skin area of chest and abdomen is larger than that of the limbs, and the convective heat transfer coefficient of chest and abdomen is smaller than that of the limbs on the contrary, since the equivalent diameter of chest and abdomen is larger than that of the limbs. Further, the similar weighting factors of Eq (14) by Nadel et al and Eq (15) by the author are a natural course of events, because Eqs (14) and (15) were derived from the Hardy -DuBois formula and Eq (12) containing the similar weighting factors respectively.

6. Conclusions

All the mean skin temperature formulas proposed hitherto are written by one general form to sum up the product of the reginoal skin temperature and the weighting factor concerned with the region. The content of the weighting factor in these formulas is classified into five groups, namely,

1. the weighting factor with unity.

2. the equal weighting factor.
3. the weighting factor by the skin area only.
4. the weighting factor by the skin area and the thermal sensitivity.
5. the weighting factor by the skin area and the heat transfer coefficients.

The present paper deals with a new mean skin temperature formula weighted by the skin area, the heat transfer coefficients and the thermal sensitivity, on the basis of the formula weighted by the skin area and the heat transfer coefficients, which was previously derived by the author and the thermal sensitivity coefficients given by Nadel et al.

The characteristics of the formula derived in this paper are that the weighting factor in the present formula is close to that of Nadel et al and that the weighting factor of the area-heat transfer coefficient mean skin temperature is similar to the relative skin area by Hardy-DuBois. The conclusion seems to be an offset effect that the skin areas of the chest and abdomen is larger than that of the limbs, on the other hand, the convective heat transfer coefficient of chest and abdomen with larger diameters is smaller than that of limbs with smaller diameters.

The mean skin temperature weighted by the skin area and the heat transfer coefficients:

$$T_s = 0.066\,T_{face} + 0.153\,T_{chest\,\&\,back} + 0.153\,T_{abdomen} + 0.163\,T_{upper\ legs} + 0.183\,T_{lower\ logs} + 0.149\,T_{upper\ arms} + 0.151\,T_{lower\ arms}$$

The mean skin temperature weighted by the skin area, the heat transfer coefficients and the thermal sensitivity:

$$T_s = 0.198\,T_{face} + 0.179\,T_{chest\,\&\,back} + 0.145\,T_{abdomen} + 0.153\,T_{upper\ legs} + 0.092\,T_{lower\ legs} + 0.138\,T_{upper\ arms} + 0.076\,T_{lower\ arms}$$

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