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The Human Thermoregulation Range within the Neutral Zone

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Summary

A mathematical and physical model of thermoregulatory mechanisms has been derived and experimental data are presented for the elements of the model. The thermoregulatory range within the neutral zone has been analyzed by regression analysis of the experimental data. The optimal globe temperature and the adaptational shifts in temperature for winter and summer are also given.

Key words

Thermal comfort – Thermal physiology – Human thermoregulation – Radiant asymmetry – Cold draft

Introduction

The first formulations of the thermoregulatory process in the human body/environment coupling were made by Burton (1934), Wyndham *et al.* (1952), and Hardy and Hammel (1963), and later by Werner (1977) and many others. Then a first approach was introduced to take into account the distributed parameter properties of a biological control system, which has been further elaborated by Werner (1975, 1977, 1981, 1984, 1987). The conclusions of Hensel (1973) concerning setpoint models are also important. Discussions continued in the works of Cabanac (1975), Bligh (1978) and others. We consider the article by Buse and Werner (1985), dealing with internal thermal resistance and its minimal and maximal values in the range of thermoregulation, to be of special significance. Their results correspond to our experimentally obtained data.

The total heat rate production and its distribution into individual components during heat exchange between the human body and the environment are shown in Fig. 1, where $\dot{q}_m$ = M - W = metabolic heat (see Jokl 1989). $\dot{q}_{res}$ and $\dot{q}_{ev,d}$ are the components of the heat rate from the organism by respiration and by skin moistening (evaporation), with the human body being in the thermal neutral zone. The heat flow q_{dry} represents the component transferred from the organism through the clothing layer with a total thermal resistance $R_{t,wa}(\dot{q}_{dry} = \dot{q}_c + \dot{q}_r)$. The regulatory process within the neutral zone is achieved mainly by vasodilation and vasoconstriction changing the body's internal resistance into the thermoregulatory and adaptational heat flux $\dot{q}_{tr} + \dot{q}_a$ to the skin surface. $\dot{q}_{tr} + \dot{q}_a$ is the heat flux regulating the instantaneous value of the skin temperature during the subject's interaction with the environment, q_{tr} is the organism's immediate response to changes of the microclimate or metabolic heat changes; q_a is the reaction shift due to adaptation to heat in summer and cold in winter. q_{tr} + q_a may be negative (heat loss) or positive (heat gain). It is the transient heat flow – even in the thermal neutral zone – that is called "quasi-stationary", to be differentiated from the hypothermia and hyperthermia zone.

$\dot{q}_{tr} + \dot{q}_a$ represents the rates of heat storage or heat debt accumulation. When the body is in a steady-state thermal balance with the environment, these therms are equal to zero. But it is possible to consider the state of the subject in the neutral zone by non-steady-state conditions due to periodical changes of metabolic heat rate, q_m, or short thermal excitations in time followed by changes of internal thermal resistance of the body within the neutral zone.

The temporary characteristics of each non-steady process are determined, in addition to the thermal resistances $R_{t,i}$ and $R_{t,wa}$ by the human body heat capacity, C_t. The values characterizing the heat exchange are: T_{sk}, T_{core}, and T_g. The internal thermal resistance, $R_{t,i}$ also determines the changes in thermoregulation and the adaptational heat, $\dot{q}_{tr} + \dot{q}_a$, which is necessary for maintaining the skin temperature within physiological values if the core

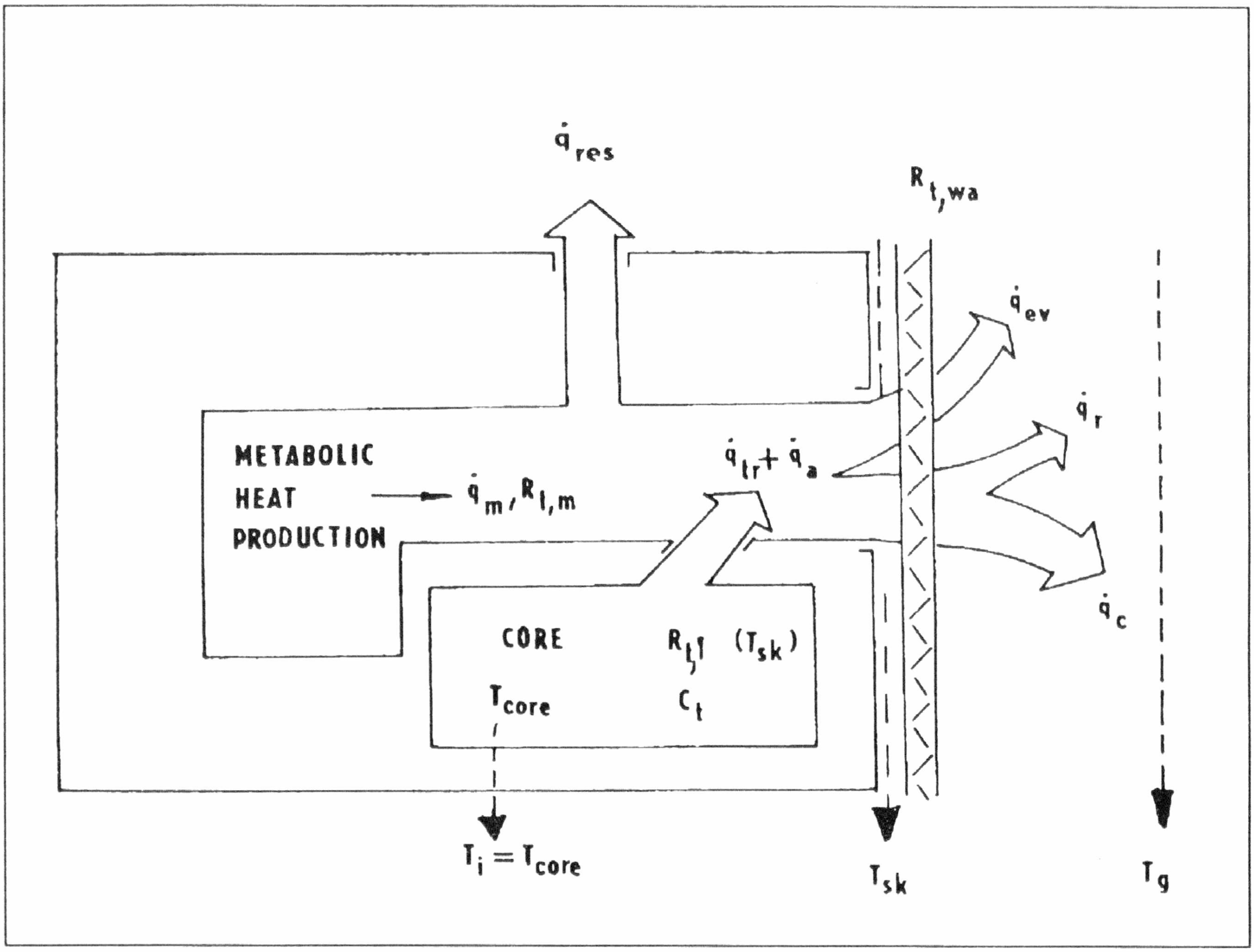

Fig. 1
Total heat rate production and its distribution in individual components during heat exchange between the human body and the environment.

temperature should remain constant (T_{core} = 36.7 ± 0.4 °C).

Mathematical model

The heat flow balance, as presented in the model shown in Fig. 1, can be expressed by a thermal flux equation at the boundary: subject-environment. Thus (if heat conduction is neglected):

$$\dot{q}_{sk} = -(\dot{q}_m + \dot{q}_{res} + \dot{q}_{tr} + \dot{q}_a) = (T_g - T_{sk})/R_{t,wa} + \dot{q}_{ev,d} \quad [W.m^{-2}] \qquad (1)$$

Let us introduce $\Sigma\dot{q}_i = \dot{q}_m + \dot{q}_{res} + \dot{q}_{ev,d}$

Heat flux within the human body can be represented as (see model in Fig. 1):

$$\dot{q}_m + \dot{q}_{res} + \dot{q}_{tr} + \dot{q}_a = G_{t,ti}\,(T_i - T_{sk}) = (1/R_{t,ti})(T_i - T_{sk}) \quad [W.m^{-2}] \qquad (2)$$

where $G_{t,ti}$ is the total body thermal conductance, which could be expressed by Equation 3:

$$G_{t,ti} = (\dot{q}_m + \dot{q}_{res})/(T_i - T_{sk}) + (\dot{q}_{tr} + \dot{q}_a)/(T_i - T_{sk}) = G_{t,m} + G_{t,i} \quad [W.m^{-2}.K^{-1}] \qquad (3)$$

where $G_{t,i}$ is the internal thermal conductance and $G_{t,m}$ is the metabolic thermal conductance.

The thermoregulation and adaptational heat flux first affects the skin temperature, T_{sk}. The internal thermal resistance value, $R_{t,i} = 1/G_{t,i}$, characterizing the vasodilation and vasoconstriction process, can be calculated from the equation:

$$R_{t,i} = (T_i - T_{sk})/(\dot{q}_{tr} + \dot{q}_a) \; [W^{-1}.m^2.K] \qquad (4)$$

The thermoregulation and adaptational heat at the start of the transient effect can be expressed as:

$$\dot{q}_{tr} + \dot{q}_a \doteq \Delta T_{sk}/R_o \doteq (T_{sk} - T_{sk,opt})\ 1/R_o\ [W.m^{-2}] \quad (5a)$$

where $R_o = R_{t,i} + R_{t,wa}$

or also for $\Sigma q_i = 0$:

$$\dot{q}_{tr,o} + \dot{q}_{a,o} = (T_g - T_{sk})(1/-R_{t,wo})\ [W.m^{-2}] \quad (5b)$$

The symbol Δ is the temperature difference relative to the steady state while the human body is exposed to changes in environmental conditions within the thermal neutral zone.

Equation 1 can be expressed as:

$$T_g - T_{sk} = -R_{t,wo}\,\Sigma q_i - R_{t,wa}\,(\dot{q}_{tr} + \dot{q}_a)\ [K] \quad (6)$$

or, if Equation 4 is applied:

$$T_g - T_{sk} = -R_{t,wa}\,\Sigma \dot{q}_i - (R_{t,wa}/R_{t,i})(T_i - T_{sk})\ [K] \quad (7)$$

Equations 6 and 7 represent a family of lines with the slope $-R_{t,wa}$; the vertical shift of the lines is proportional to the thermoregulatory and adaptational heat.

Experimental estimation of mathematical model parameters

An experiment lasting several years was undertaken in the climatic chamber from which the parameters in Equations 6 and 7 could be identified.

The experimental subjects were male university students each of them underwent six experiments lasting about three hours at four levels of activity: (1) sitting in a chair, (2) sitting on a bike-ergometer without pedaling, (3) pedaling on a bike-ergometer with a 40 W load and (4) pedaling on a bike-ergometer with a load of 1 W per kg body mass (as long as he was able to do it). Metabolic heat production during each activity was measured by the indirect calorimetric method. Mean skin temperature, heart rate and body water loss were estimated continuously during each experiment.

Two sets of clothing were used by the subjects: lightweight (pajamas) and a heavier one (anti-g suit for fighter pilots).

Thermal insulating properties of both types were also estimated during the experiment.

There were no differences between air temperature and surface wall temperatures. Six temperatures were chosen (29 ± 3 °C and 14 ± 3 °C, which determine temperature ranges where some of the subjects started to leave the neutral zone and appeared to begin sweating or shivering. In the experiment described in this section, subjects were only sitting to avoid the transiet effect caused by changes in metabolic heat. The values of Tsk and Σq_i were measured only if subjects were evidently in the neutral zone. The relative humidity was maintained within the comfort range corresponding to a partial water vapour pressure from 700 to 1850 Pa. The beginning of sweating and shivering was always assessed by the same person. Experiments were carried out during all seasons, thus reflecting the seasonal adaptation effect on maximal and minimal thermoregulatory heat, i.e. it was possible to determine adaptational heat. The results were only accepted from subjects within the thermal neutral zone with the thermoregulatory heat constant.

The experimental results were arranged into three seasonal groups: summer, winter, spring plus autumn.

At the higher temperatures, the temperature range at which sweating started was determined first and then, a regression line was plotted for the measured points within the range where the onset of sweating had not yet appeared. The upper limit of the thermoregulatory range was determined in this way (and, analogously, the lower limit on the basis of the onset of shivering). The upper limit of the onset of sweating could also be found as a regression line through the points representing the onset of sweating: this would be located above the upper limit of the thermoregulatory range. Analogously, the lower limit of the onset of shivering must be lower than the lower limit of the thermoregulatory range.

The values of parameters T_i, $\dot{q}_{res}$ and $\dot{q}_{ev,d}$ were evaluated from the measured data as was the heat flux $\dot{q}_i = \dot{q}_m + \dot{q}_{ev} + \dot{q}_{res}$. The result of measurements obtained in this way and plotted with the y-coordinates (T_g - T_{sk}) and the x-coordinates ($q_m + \dot{q}_{res} + \dot{q}_{ev,d}$) in Fig. 2 and 3 can be represented by regression lines that determine the total thermal resistance of clothing used, which is equal to the slope of the regression line (0.1 $W^{-1}.m^2K$ for pajamas, i.e. 0.6 clo). The vertical shift of the lines in the direction of the axis (T_g-T_{sk}) depends on the transient value of the thermoregulatory and adaptational heat ($\dot{q}_{tr}+\dot{q}_a$). See Equation 6 for the internal thermal resistance $R_{t,i} = 1/G_{t,i}$ of the human body, and for the temperature difference (T_i-T_{sk}) see Equation 7.

The thermoregulatory and adaptational heat (for the time exposure determined by the length of this experiment) for the upper and lower limits of the thermal neutral range can be derived from Equations 6 and 7:

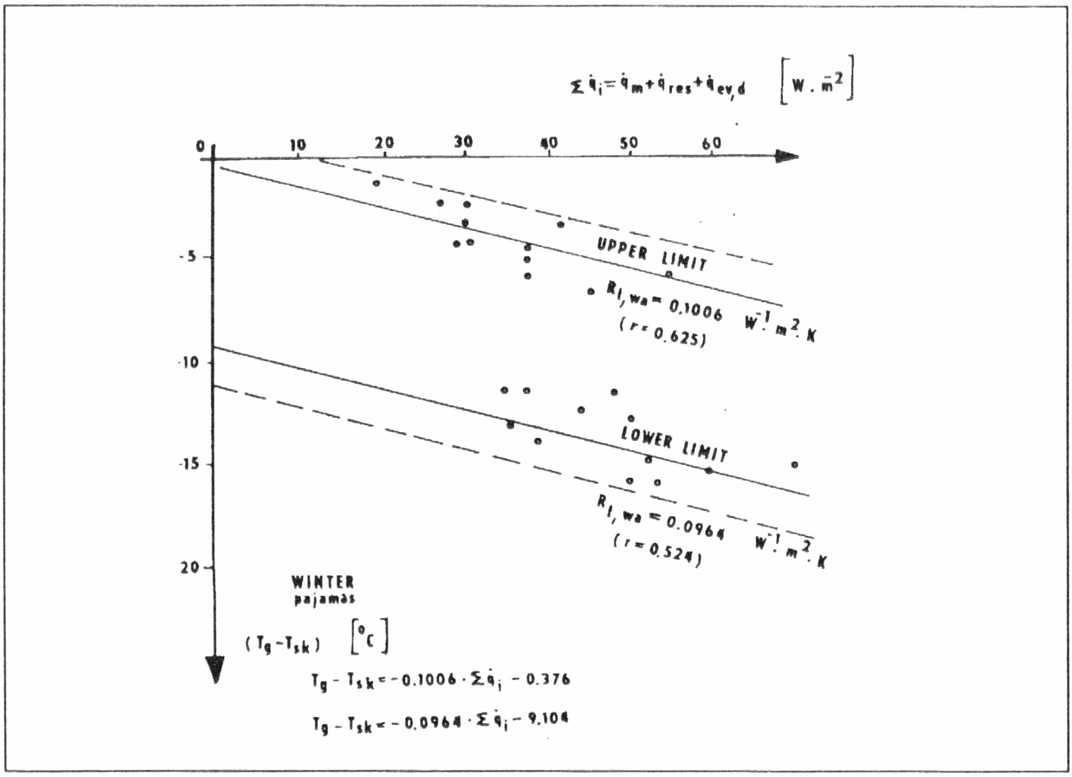

Fig. 2
Experimental estimation of human thermoregulatory range. Clothing: pajamas. Activity: sitting. Season: winter. Number of measurements: 24.

$$(\dot{q}_{tr} + \dot{q}_a)_{upper} = (-B/R_{t,wa}) \qquad [W.m^{-2}] \qquad (8a)$$

$$(\dot{q}_{tr} + \dot{q}_a)_{lower} = (-A/R_{t,wa}) \qquad [W.m^{-2}] \qquad (8b)$$

where A and B are points on the vertical axis (T_g-T_{sk}) cut by the regression lines (see Figs 2 and 3). The thermoregulatory and adaptation heat corresponding to the upper and lower limits for an exposure of about half an hour is presented in Fig. 4. The presence of the thermoregulatory heat can also be identified from the experimental relationship between q_{sk} (heat flow from the skin) and q_{core} (internal heat flow).

Discussion

The neutral zone is the result of thermoregulation of the human body provided by the internal thermal resistance or thermal conductance changes whose values can be estimated from the total internal thermal conductance (see Fig. 5), (Itoh *et al.* 1972) by subtracting the metabolic thermal ductance., i.e. Equation 3:

$$G_{t,i} = G_{t,ti} - G_{t.m} \qquad [W.m^{-2}.K^{-1}] \qquad (9)$$

a) For the lower limit, the following values were measured throughout the experiment: mean skin temperature, T_{sk} = 28.55 °C; body temperature, T_i = 37.00 °C; A = -10.274 K, i.e. for $R_{t,wa}$ = 0.1 $W^{-1}.m^2.K$.

$R_{t,i,lower,exper}$ = (T_i - T_{sk}) $R_{t,wa}/(-A)'$ = 0.083 $W^{-1}.m^2.K$.
From the chart in Fig. 5 for T_{sk} = 28.55 °C $G_{t,ti,lower}$ = 9.605 $W.m^{-2}.K^{-1}$ and thus
$G_{t,m}$ = (q_m + q_{res})/(T_i-T_{sk}) = 40/(37-28.55) = 4.734 $W.m^{-2}.k^{-1}$
i.e. $G_{t,i,lower}$ = 9.605-4.734 = 4.871 $W.m^{-2}.K^{-1}$ and $R_{t,i,lower}$ = 0.205 $W^{-1}m^2.K$

But value $G_{t,ti}$ has not been estimated too precisely by the authors: it should be the derivative of the function q_{sk} = f(T_{sk}), i.e. the slope at a given point of the curve q_{sk}.

After such a correction, the value $G_{t,ti}$ changes into $DG_{t,ti}$ = 13.553 $W.m^{-2}.K^{-1}$. Let us call it "differential", so $DG_{t,i}$ = 8.819 $W.m^{-2}.K^{-1}$ and $DR_{t,i}$ = 0.113 $W^{-1}.m^2.K$, which is comparable with the experimentally achieved value: 0.113 $W^{-1}.m^2.K \geq$ 0.083 $W^{-1}.m^2.K$.

b) For the upper limit, the following values were measured during the experiment: mean skin temperature, T_{sk} = 33.81 °C; body temperature, T_i = 37.04 °C; B = -1,138 K, i.e. for $R_{t,wa}$ = 0.1 $W^{-1}.m^2.K$.

$R =_{t,i\ upper,exper}(T_i - T_{sk})(R_{t,wa}/(-B))$ = 0.284 $W^{-1}.ms^2.K$.

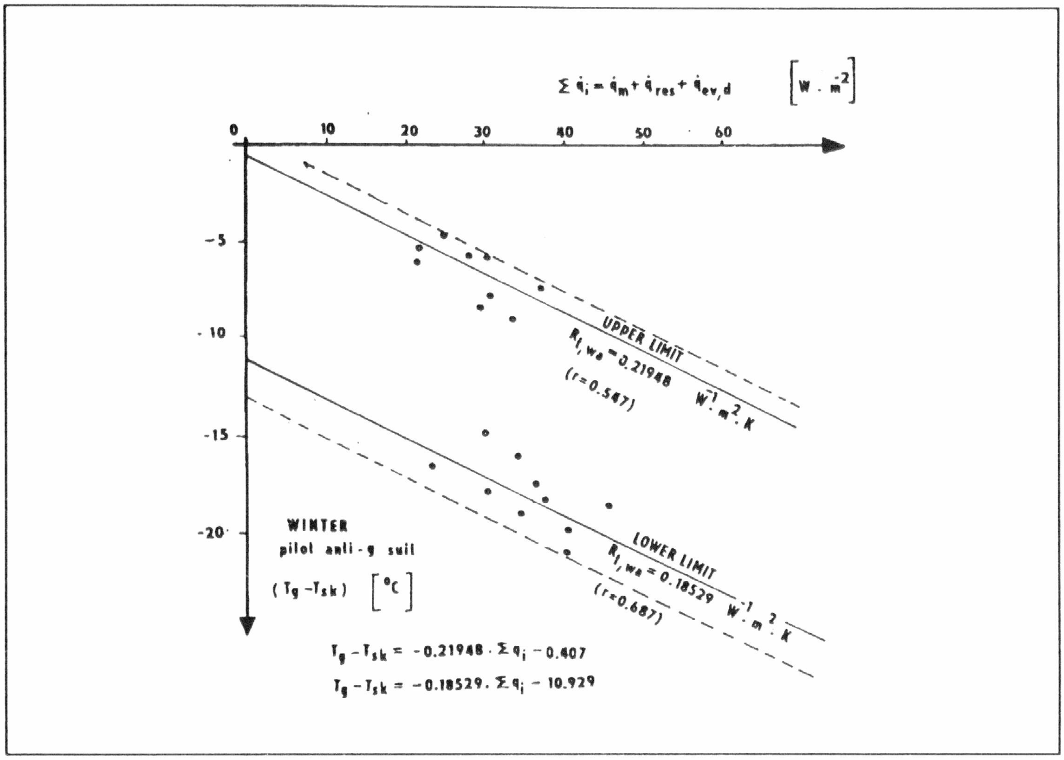

Fig. 3

Experimental estimation of human thermo-regulatory range. Clothing: anti-g suit. Activity: sitting. Season: winter. Number of measurements: 19

Table 1

Globe temperature for the upper and lower limit of the thermoregulatory range

	$R_{t,wa}=0.05W^{-2}.m^2.K$		$R_{t,wa}=0.10W^{-2}.m^2.K$		$R_{t,wa}=0.15W^{-2}.m^2.K$		$R_{t,wa}=0.20W^{-2}.m^2.K$	
Σq_i	$T_{g,upper}$	$T_{g,lower}$	$T_{g,upper}$	$T_{g,lower}$	$T_{g,upper}$	$T_{g,lower}$	$T_{g,upper}$	$T_{g,lower}$
°C	°C	°C	°C	°C	°C	°C	°C	°C
20	33.128	26.480	32.177	24.504	31.206	22.957	30.227	21.374
40	32.411	25.764	30.484	22.811	28.522	20.273	26.548	17.932
60	31.694	25.047	28.792	21.118	25.838	17.589	22.869	14.253
80	30.978	24.330	27.099	19.425	23.154	14.905	19.190	10.575
100	30.261	23.614	25.406	17.732	20.470	12.221	15.511	6.896

From the chart in Fig. 5 for T_{sk} = 33.81 °C we can derive the value $DR_{t,i}$ = 0.246 $W^{-1}.m^2.K$, which is comparable with the result: 0.246 $W^{-1}.m^2.K \leq$ 0.284 $W^{-1}.m^2.K$.

The thermoregulatory and adaptational heat for transients after a short time exposure can be estimated from Equation 8; for transient but long-term exposure, the analysis must be started from the non-steady-state laws.
Concerning internal thermal resistances, for comparison, the values of $R_{t,i}$ presented by Buse and Werner (1985) vary in the range 0.082 – 0.163 $W^{-1}.m^2.K$.

The thermoregulatory range, optimal values and adaptational shift are expressed by means of globe temperature.

In practice it is necessary to transform the exact thermoregulatory and other heats into globe temperature values because (1) there is no simple method for heat rate measurements between the human body and its environment, and (2) it is unusual to use heat rates in standards and regulations.

If Equation 15 is applied to Equation 6, we have for t < τ:

$$T_g - T_{sk} = -R_{t,we}\, \Sigma \dot{q}_i - (R_{t,wa}/R_o)\Delta T_{sk}, \quad [K] \qquad (9)$$

where

$$\Delta T_{sk} = T_{sk} - T_{sk,opt}, \quad [K] \qquad (10)$$

T_{sk} = skin temperature on the upper or lower thermoregulatory limit, e.g. for summer
$T_{sk,opt}$ = optimal skin temperature, i.e. skin temperature without thermoregulatory load on the organism, e.g. for summer

Optimal skin temperature can be estimated in two ways: as a mean value between the upper and lower thermoregulatory limits (i.e. there is the same thermoregulatory reserve towards both limits), or just to insert the optimal value, e.g. according to Fanger (1970).

Substituting the values of the lower limit parameters into Equation 18 we will obtain the value $T_{g,lower}$ (see Tab. 1) and, substituting the values for the upper limits into Equation 18 we will obtain values for $T_{g,upper}$ (see Tab. 1). The optimal globe temperature can be estimated according to the Equation:

$$T_{g,opt} = (T_{g,upper} + T_{g,lower}) \, . \, 0.5 \qquad (11)$$

The graphical expression is shown in Fig. 6. The globe temperature changes corresponding to the human thermoregulatory range plus adaptational shift are shown in Fig. 7.

Conclusions

A new way of using experimental data, starting from a quasi-steady-state description introduced by Jokl (1989) enables the estimation of a) the total resistance of clothing (see the slope of lines in Fig. 4a and b) the thermoregulatory range of the human body, c) the adaptations for winter and summer, and d) optimal values of T_g as a mean of upper and lower

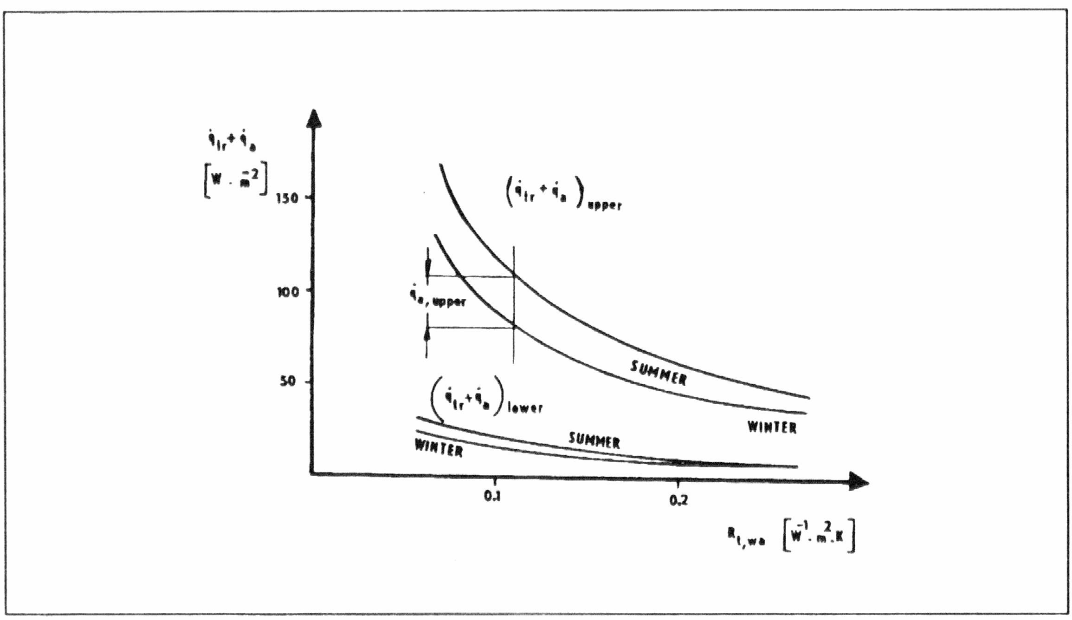

Fig. 4
Thermoregulation heat q_{tr} + q_a in relationship to the total thermal resistance of clothing

limit values. The results can be proved by (1) comparing internal thermal resistances with other authors (Itoh *et al.* 1972) or (2) comparing optimal globe temperatures with other authors' data (e,g, Fanger 1970). The study will be continued by further experimental verifications and by characterizing nonlinear thermoregulation.

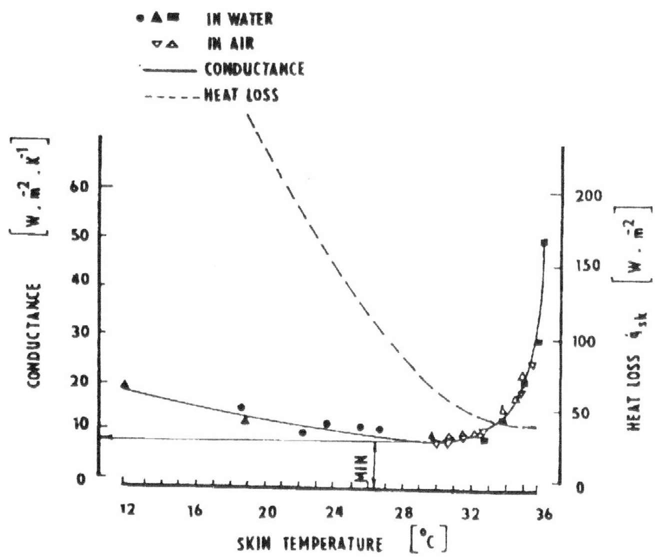

Fig. 5
Total internal thermal conductance of human body, $G_{t,ti}$ and skin heat loss in relation to skin temperature, T_{sk} (black squares from Burton and Bazett 1936, black triangles from Dubois and Lefevre 1898, black circles from Liebermeister 1869, Itoh *et al.* 1972)

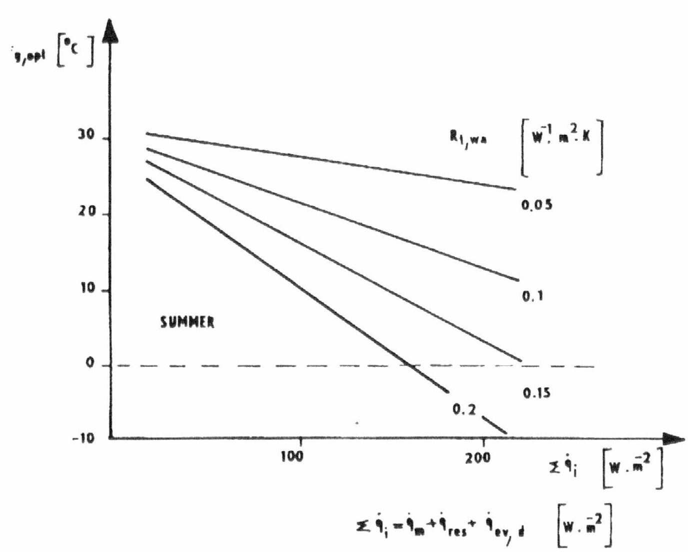

Fig. 6
Optimal globe temperature as a mean value of upper and lower thermoregulatory limit

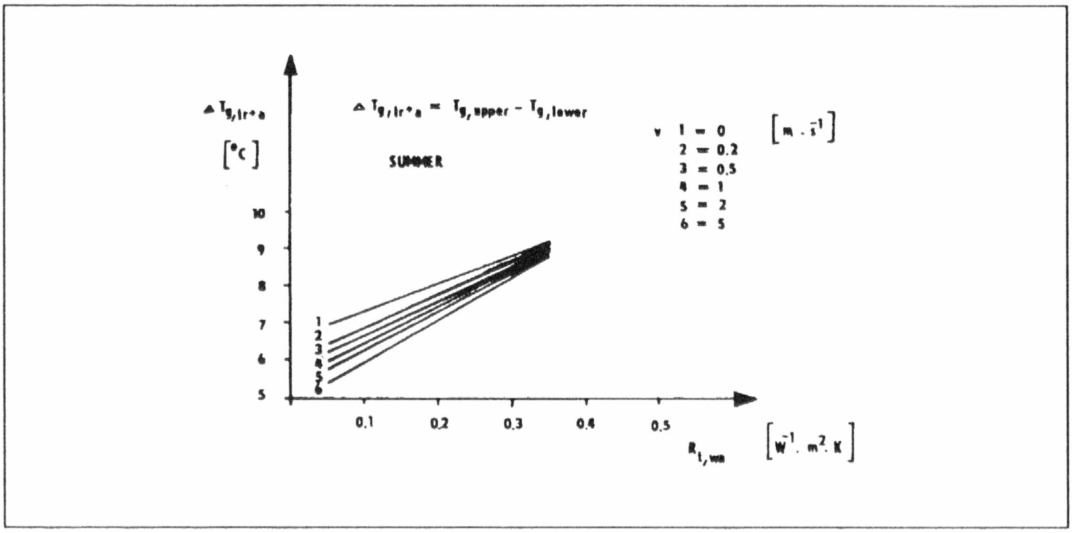

Fig. 7

Globe temperature changes corresponding to the human thermoregulatory range plus adaptation shift

Explanation of abbreviations

C_t = thermal capacitance of human body
$C_{t,i}$ = internal thermoregulatory conductance
$G_{t,m}$ = metabolic thermal conductance
$G_{t,ti}$ = total internal thermal conductance
m = subject's mass
q_a = adaptation heat flux
q_c = convective heat flux
q_{dry} = heat flow through the clothing layer
q_{ev} = evaporative heat
q_m = metabolic heat
q_{res} = respiratory heat
q_{tr} = thermoregulatory heat flux
R_o = total insulating thermal resistance
$R_{t,i}$ = thermoregulatory internal thermal resistance
$R_{t,m}$ = metabolic thermal resitance
$R_{t,ti}$ = total internal thermal resistance
$R_{t,wa}$ = total thermal resistance of clothing
T_{core} = body core temperature
$T_{g,opt}$ = optimal globe temperature, body within the zone of thermal comfort
T_g = globe temperature
T_i = T_{core} - see T_{core}
T_{sk} = skin temperature
t_e = setting time for the body in the transient state
τ = system time constant
v = air velocity

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