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SIMULATED AND EXPERIMENTAL TEMPERATURE RESPONSES IN MAN DURING EXERCISE IN VARYING ENVIRONMENTS

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Abstract – Stolwijk's mathematical model of thermoregulation is validated against reported human experience.

Computed temperatures from the model were compared against experimental data obtained, using various matched environmental conditions. Three fit male subjects 168.5 ± 1.8 cm, 64.2 ± 1.9 kg, 24.5 ± 2.6 yr. (mean ± range) underwent pre-work and incremented work phases in the various conditions. Measurements of rectal temperature (T_R), tympanic temperature (T_T), and four skin sites ($\bar{T}_S$) were taken. Air temperature (T_{AIR}), air velocity (V), relative humidity (RH) and work (W), were manipulated.

Good simulations were achieved at 30°C air temperature, rectal temperature deviation $\bar{d} < 0.10$°C. As lower ambient temperatures were encountered initial transient drop of simulated core temperature was emphasized, and this was not reflected in experimental data. It is proposed that the process of thermoregulation during exercise in the cold requires further conceptual refinement in the model. By subdivision of active muscular layers in the passive system of the model superior simulations at low air temperatures, may be achieved.

Human temperature response   Dynamic model   Computer simulation   Experimental comparison

INTRODUCTION

The ability to predict human response to thermal stress has been considerably facilitated by the advent of closed loop analog and digital simulations. The first of these models was developed by Stolwijk and Hardy [1] in 1966. Later a refined presentation for use with a digital computer was given by Stolwijk [2]. Konz and co-workers [3] independently validated this model for a single subject over a 2 hr exposure and encouraged others to refine and challenge the model for future use.

In pursuits such as deep sea diving and extra-vehicular space activity it is essential that simulation information be available in advance of the event to improve efficiency and safety. It is the purpose of this paper to examine the validity of an amended version of Stolwijk's model to protracted work and increasing work phases on a cycle ergometer in varying environmental conditions.

MODEL DESCRIPTION

In Stolwijk's model the thermal properties of the body are represented in a passive system of 25 compartments. Each segment, i.e. head, trunk, arms, hands, legs and feet contains four compartments – core, muscle, fat and skin. The large veins and arteries, comprising a central blood compartment, complete the model. Values for metabolic heat production and conductive and convective heat exchange between compartments are assigned. Heat exchange with the environment, through skin compartments, is modelled by radiation, convection and evaporation. Temperature signals from each compartment are integrated and processed by a controlling system which modifies blood flow, metabolic heat

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Table 1. List of symbols used in the controlled or passive system with definition and dimension

Symbol	Vector length	Definition	Dimension
C(*N*)	25	Heat capacitance of compartment *N*	W-H/°C
T(*N*)	25	Temperature of *N*	°C
F(*N*)	25	Rate of change of temperature in *N*	°C/h
HF(*N*)	25	Rate of heat flow into or from *N*	W
TC(*N*)	24	Thermal conductance between *N* and *N*+1	W/°C
TD(*N*)	24	Conductive heat transfer between *N* and *N*+1	W
QB(*N*)	24	Basal metabolic heat production in *N*	W
Q(*N*)	24	Total metabolic heat production in *N*	W
EB(*N*)	24	Basal evaporative heat loss from *N*	W
E(*N*)	24	Total evaporative heat loss from *N*	W
BFB(*N*)	24	Basal effective blood flow to *N*	1/h
BF(*N*)	24	Total effective blood flow to *N*	1/h
BC(*N*)	24	Convective heat transfer between central blood and *N*	W
HC(*I*)	6	Convective and conductive heat transfer coefficient for Segment *I*	W/sq m-°C
S(*I*)	6	Surface Area Segment *I*	m^2
HR(*I*)	6	Radiant heat transfer coefficient for Segment *I*	W/sq m-°C
H(*I*)	6	Total environmental heat transfer coefficient for Segment *I*	W/sq m-°C
V		Air velocity	m/sec
TAIR		Effective environmental temperature	°C
RH		Relative humidity in environment	Point percentage
ITIME		Elapsed time	min
INT		Interval between outputs	min
DT		Integration step	h
P(*I*)	10	Vapour pressure table from 5–50°C	mm Hg
EMAX(*I*)	6	Cal. Ma. rate of evaporative heat loss from Segment *I*	W
WORK		Total metabolic rate required by exercise	W
P. SKIN		Saturated water vapour pressure at skin temperature	mm Hg
PAIR		Vapour pressure in environment	mm Hg
TIME		Elapsed time	h

production, and the sweat response to thermal stress. A full listing of the symbols used in the controlled and controlling systems is given in Tables 1 and 2.

The controlling system derives an error signal from the 25 compartments of the controlled system through the expression:

$$\mathrm{ERROR}(N) = \mathrm{T}(N) - \mathrm{TSET}(N) + \mathrm{RATE}(N) * \mathrm{F}(N).$$

The error calculated in the initial case is simply the difference between the instantaneous temperature, T(*N*) and the initial set temperatures, TSET(*N*). In compartments where a dynamic thermosensitivity of the thermoreceptors has been reported, values can be assigned to RATE(*N*). F(*N*), the rate of change of temperature, and T(*N*) are computed from the controlled system whereas TSET(*N*) and RATE(*N*) are fed in as initial values, RATE(*N*) = 0 in this simulation. Where ERROR(*N*) is positive it becomes WARM(*N*) and negative COLD(*N*).

From this data, controller commands are evolved which cause the body to shiver (CHILL), sweat (SWEAT), or to alter vasomotor tone (DILAT/STRIC). These commands comprise temperature signals from the head core, ERROR(1), and the skin (WARMS-COLDS).

Table 2. Definition and dimension of symbols used in the controlling system

Symbol	Definition	
TSET(*N*)	"Set point" or threshold temperatures for receptors in *N*	
ERROR(*N*)	Total output signal from receptors in *N*	
RATE(*N*)	Dynamic sensitivity of receptors in *N*	
COLD(*N*)	Output from cold receptors in *N*	
WARM(*N*)	Output from warm receptors in *N*	
COLDS	Total integrated output from skin cold receptors	
WARMS	Total integrated output from skin warm receptors	
SWEAT	Total efferent sweating command	
CHILL	Total efferent shivering command	
DILAT	Total efferent vasodilation command	
STRIC	Total efferent vasoconstriction command	
SKINR(*I*)	Relative weight of skin of each segment in determining total skin output	Table 7
SKINS(*I*)	Fraction of sweating command to Segment *I*	Table 7
SKINV(*I*)	Fraction of vasodilation command to *I*	Table 7
SKINC(*I*)	Fraction of vasoconstriction command to *I*	Table 7
WORKM(*I*)	Fraction of total exercise occurring in *I*	Table 7
CHILM(*I*)	Fraction of total shivering command to *I*	Table 7
CSW	Coefficient for sweating command from head core	372
SSW	Coefficient for sweating command from skin	33.7
PSW	Coefficient for sweating command from product of head core and skin	0
CDIL	Coefficient for vasodilation command from head core	136
SDIL	Coefficient for vasodilation command from skin	8.9
PDIL	Coefficient for vasodilation command from product of head core and skin	0
CCON	Coefficient for vasoconstriction command from head core	10.8
SCON	Coefficient for vasoconstriction command from skin	10.8
PCON	Coefficient for vasoconstriction command from product of head core and skin	0
CCHIL	Coefficient for shivering command from head core	13.0
SCHIL	Coefficient for shivering command from skin	0.4
PCHIL	Coefficient for shivering command from product of head core and skin	0
BULL	Factor determining temperature sensitivity of sweat gland response	10.0

$$\text{CHILL} = -\text{CCHIL} * \text{ERROR}(1) - \text{SCHIL} * (\text{WARMS-COLDS}) + \text{PCHILL} * \text{COLD}(1) * \text{COLDS},$$

$$\text{SWEAT} = \text{CSW} * \text{ERROR}(1) + \text{SSW} * (\text{WARMS-COLDS}) + \text{PSW} * \text{WARM}(1) * \text{WARMS},$$

$$\text{DILAT} = \text{CDIL} * \text{ERROR}(1) + \text{SDIL} * (\text{WARMS-COLDS}) + \text{PDIL} * \text{WARM}(1) * \text{WARMS},$$

$$\text{STRIC} = -\text{CCON} * \text{ERROR}(1) - \text{SCON} * (\text{WARMS-COLDS}) + \text{PCON} * \text{COLD}(1) * \text{COLDS}.$$

Konz *et al.* [3] indicate options are available dependent on whether skin and head core temperature signals are additive, where PSW, PDIL, PCON and PCHIL are set to zero or multiplicative where SSW, DSIL, SCON, SCHIL, CSW, CDIL, CCON and CCHIL are set to zero. In this simulation the former assumption is adopted.

The CHILL Command initiates shivering in the muscle layer where metabolic rate, Q($N+1$) is calculated by the addition of basal metabolism, work and shivering i.e.

$$Q(N+1) = QB(N+1) + \text{WORKM}(I) * \text{WORK} + \text{CHILM}(I) * \text{CHILL}.$$

Skin evaporation is derived from a basal rate and an added factor derived from the sweat response i.e.

$$E(N+3) = [EB(N+3) + \text{SKINS}(I) * \text{SWEAT}] * 2.0 ** [\text{ERROR}(N+3)/10].$$

where SKINS(I) represents the distribution of total sweat glands over the 6 segments and $2**[\mathrm{ERROR}(N+3)/10]$ allows skin temperature from each segment to contribute to the final sweat command.

The DILAT and STRIC commands alter basal skin blood flow BF($N+3$) in the following expression:

$$\mathrm{BF}(N+3) = \{[\mathrm{BFB}(N+3) + \mathrm{SKINV}(I) * \mathrm{DILAT}]/[1.0 + \mathrm{SKIN}(I) * \mathrm{STRIC}]\} * 2.0 ** [\mathrm{ERROR}(N+3)/10.0],$$

where SKINV and SKINC are the coefficient for skin dilation and constriction in the 6 segment; these values appear in Table 7. On the basis of subject and environmental data, received as inputs, the model calculates the temperature of the 25 compartments, cardiac output, skin blood flow, heat production, evaporative heat loss, mean skin temperature and mean body temperature. In this simulation matched outputs for monitored body temperature sites were required every 2 min during pre-work phases and every 3 min during working phases. The original description of the model is given in Stolwijk [2] and amended versions by other authors have appeared Konz *et al.* [3]; Dhiman [4]. A fuller account of the model and an operationalized computer listing for use in conjunction with an ICL 1900 series computer is presented in Hancock [5]. The slight refinements to the model in this paper are presented below. Values for basal evaporative heat loss from the 24 compartments, EB(N), were assigned as in Table 3.

Weighting of the 9 W basal evaporative heat loss by the respiratory tract was apportioned in consideration of the work of Miller and Seagrave [6] on a 2:1 ratio of head core to trunk core.

Values for surface area, S(I) Table 4, heat capacitance, C(N) Table 5, and basal heat production, QB(N) Table 6, were calculated for each subject on the basis of anthropometric data collected. Radiant heat transfer coefficients, HR(I), convective heat transfer coefficients, HC(I) and combined heat transfer coefficients, H(I), are presented in Table 7. H(I) was calculated for each subject from the equation:

$$\mathrm{H}(I) + (\mathrm{HR}(I) + \mathrm{HC}(I) * [\mathrm{V}/0.1) ** 0.5] * \mathrm{S}(I).$$

Values for set point temperature, TSET(N), basal effective blood flow, BFB(N) and thermal conductance between compartments, TC(N) were as given in Stolwijk's report [2]. Values for SKINR(I), SKINS(I), SKINV(I), SKINC(I), CHILM(I) and WORKM(I) are presented in Table 7. WORKM(I) estimates are similar to those used by both Stolwijk [2] and Konz *et al.* [3] although weighting apportioned to the arm segment is greater in consideration of their support role in cycle ergometer work.

Table 3. EB(N) Basal evaporative heat loss from N, (Watts)

Segment	Core	Muscle	Fat	Skin
Head	6.00	0.00	0.00	0.63
Trunk	3.00	0.00	0.00	3.25
Arms	0.00	0.00	0.00	1.20
Hands	0.00	0.00	0.00	0.45
Legs	0.00	0.00	0.00	2.85
Feet	0.00	0.00	0.00	0.62

Table 4. S(I), Segmental surface area for the three subjects (m^2)

Subject	Head	Trunk	Arms	Hands	Legs	Feet
B.H.	0.1290	0.4358	0.2880	0.0564	0.5943	0.1425
S.T.	0.1170	0.4533	0.2957	0.0676	0.5694	0.1690
I.M.	0.1190	0.5024	0.2750	0.0594	0.5805	0.1620

Subject details used as computer inputs are given in Table 8 and environmental and work variables are indicated on the figures presented, air velocity <0.1 m/sec for all experimental sessions. Initial temperature estimates for the 25 compartments, T(*N*), were based on the subject's six monitored temperatures while awaiting entry to the environmental facility.

Table 5. C(*N*), heat capacitance for the *N* compartments – three subjects, (c/kcal/°C)

Segment	Core			Muscle			Fat			Skin		
	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.
Head	1.76	1.84	1.68	0.29	0.29	0.29	0.19	0.19	0.20	0.21	0.20	0.22
Trunk	11.36	11.07	9.77	13.89	13.53	14.33	3.65	3.56	3.77	1.04	1.02	1.08
Arms	1.12	1.13	1.16	2.61	2.55	2.70	0.50	0.49	0.52	0.38	0.37	0.39
Hands	0.13	0.12	0.12	0.05	0.05	0.06	0.08	0.08	0.08	0.14	0.14	0.15
Legs	3.46	3.37	3.57	7.88	7.69	8.14	1.23	1.20	1.27	0.93	0.90	0.95
Feet	0.21	0.23	0.22	0.05	0.05	0.06	0.11	0.11	0.12	0.20	0.18	0.19
Central blood	2.50	2.50	2.50									

Table 6. QB(*N*), basal heat production for each compartment *N* – three subjects, (Kcal/hr)

Segment	Core			Muscle			Fat			Skin		
	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.	B.H.	S.T.	I.M.
Head	10.36	11.09	12.45	0.08	0.09	0.10	0.10	0.09	0.10	0.07	0.07	0.07
Trunk	37.8	39.62	44.70	3.95	4.41	5.19	1.84	1.78	1.89	0.34	0.34	0.36
Arms	0.49	0.53	0.60	0.74	0.83	0.98	0.25	0.24	0.26	0.13	0.12	0.13
Hands	0.05	0.06	0.07	0.02	0.02	0.02	0.04	0.04	0.04	0.05	0.05	0.05
Legs	1.55	1.62	1.83	2.24	2.51	2.94	0.62	0.60	0.64	0.31	0.30	0.32
Feet	0.10	0.11	0.11	0.02	0.02	0.02	0.06	0.06	0.06	0.07	0.06	0.06

Table 7. Values SKIN, CHILM, WORKM, HC, HR and H symbols by segment

Symbol	Head	Trunk	Arms	Hands	Legs	Feet
SKINR(*I*)	0.250	0.400	0.100	0.015	0.200	0.035
SKINS(*I*)	0.070	0.360	0.134	0.050	0.317	0.069
SKINV(*I*)	0.132	0.322	0.095	0.121	0.230	0.100
SKINC(*I*)	0.030	0.100	0.150	0.250	0.170	0.300
CHILM(*I*)	0.030	0.850	0.050	0.000	0.070	0.000
WORKM(*I*)	0.000	0.280	0.110	0.010	0.590	0.010
HC(*I*)	0.66	1.86	3.95	6.04	3.60	5.92
HR(*I*)	6.38	5.22	5.22	3.48	5.22	4.64
H(*I*)*	0.93	4.82	2.33	0.90	5.26	1.37

* Presented for figures based on the segmental surface area of standard man [9].

Table 8. Details of subjects

	Subject		
	B.H.	S.T.	I.M.
Height (cm)	170.0	169.0	166.7
Weight (kg)	64.05	62.45	66.10
Age (yr)	27.1	24.2	22.4
Sex (M or F)	M	M	M
Clothing (clo) Insulation	0.1	0.1	0.1

EXPERIMENTAL DATA

Three fit male subjects, Table 8, were studied under the following environmental conditions: Air temperature 23°–35°C and relative humidity 40–50% (range). Work varied from basal metabolic rate *in situ* to a maximum of 150 W work performed.

Hardy *et al.* [7] indicate that during heavy work exposures in high air temperatures and relative humidity ratings, subjects are liable to encounter considerable physiological stress. It is recommended that selection of subjects, for such conditions, be restricted to those with a high degree of cardio-vascular fitness.

RESULTS

Computer predictions were compared against the six monitored sites; rectal, tympanic, trunk skin (2 sites), leg skin (1 site) and arm skin (1 site). Experimental temperatures were monitored every 2 min during pre-work phases and every 3 min during work phases. All temperature measures of the six body sites, were taken on a Light Laboratories (5°–40°C) six point thermometer.

Simulated rectal temperatures in 25°C air temperature exhibited a marked transient drop at the onset of the work phase, 12 min experimental time. In man counter-current heat exchange protects trunk core temperatures from such a sudden fluctuation. The model was unable to match this and cooled blood returning from relatively cold muscle layers caused the effect reported, Fig. 1.

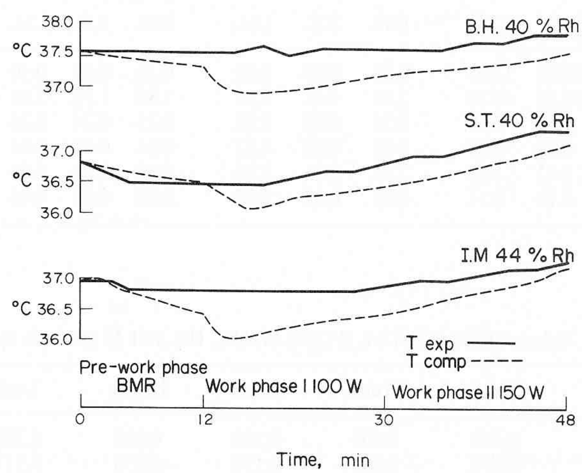

Fig. 1. Rectal temperature, experimental vs computed. Environmental conditions 25°C 40%/RH.

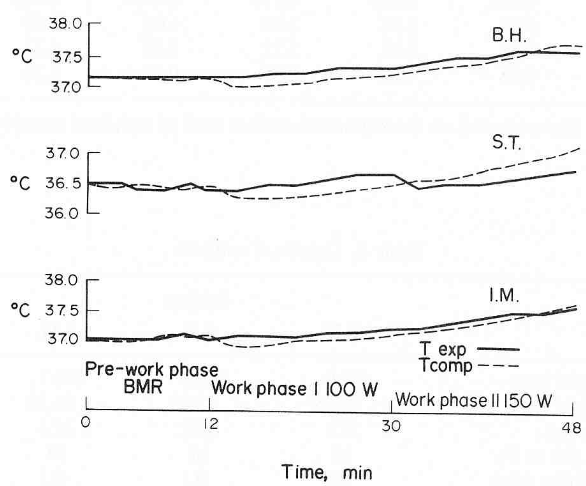

Fig. 2. Rectal temperatures, experimental vs computed. Environmental conditions 30°C 50%/RH.

This phenomenon may be observed at higher air temperatures, 30°C, Fig. 2, although at such ambient temperature the effect is far less marked. Figure 3 indicates rectal temperature comparisons for the three subjects in different air temperatures. The drop of core temperatures at the onset of work disappears as hotter environments are encountered. These data suggest that the model is better conceptually constructed to simulate dynamic thermophysiological reaction to higher rather than lower ambient temperatures.

For subject S.T., Fig. 2, it is interesting to note the drop of rectal temperature at the onset of work phase II, 30 min experimental time. This is very probably due to a movement artifact of the rectal temperature probe as increased work effort was required. It is important to recognize that error occurs both in experimental and simulation data, although this variation does not always indicate problems in the construction of the model tested. A further example of computed and experimental data incompatibility is presented in Fig. 4.

The simulated temperature from leg skin is compared against experimental data obtained from one leg skin thermistor. The model calculates an average temperature for the skin of each segment. However, the leg thermistor was placed over the medial point of the right rectus femoris, a muscle integrally concerned in cycle ergometer work. In man, especially during exercise, a differential heat distribution pattern is experienced over each segment in relation to active and less active muscles. Over this exercising muscle a poor simulation is achieved when comparing experimental data against T (20), the computed temperatures of

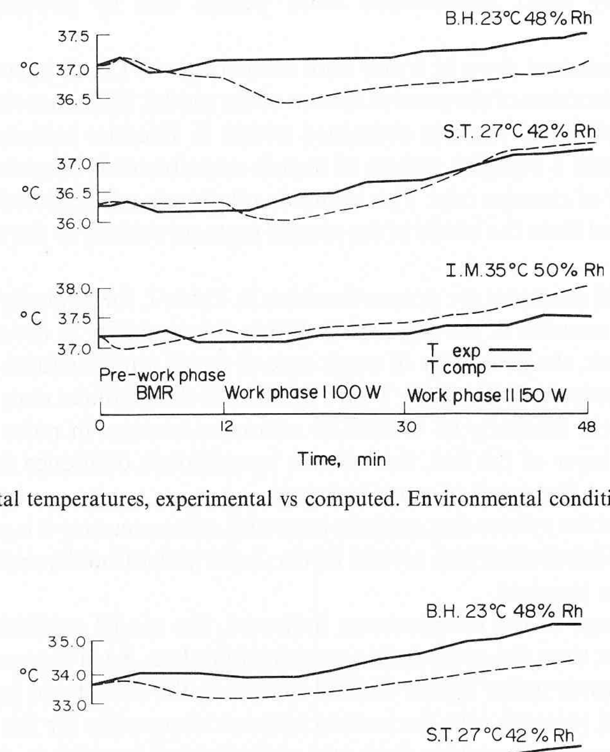

Fig. 3. Rectal temperatures, experimental vs computed. Environmental conditions as shown.

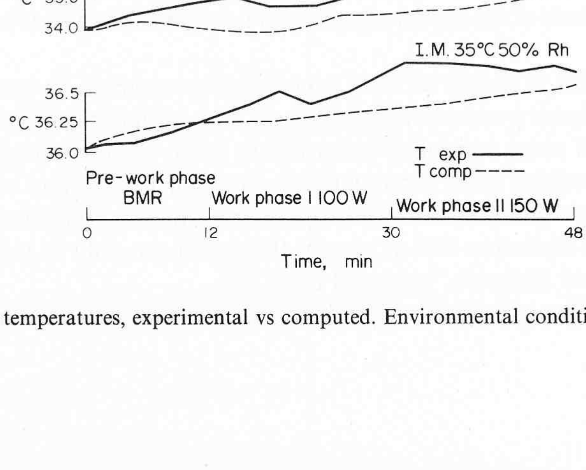

Fig. 4. Leg temperatures, experimental vs computed. Environmental conditions as shown.

the leg skin. However, a far superior simulation is obtained when such experimental data is matched against T (18), the modelled temperature of the muscle layer of the leg. When only limited temperature sites can be monitored, care must be exercised in the placement of thermistors. Ideally, with several thermistor locations on each segment such an anomaly may be avoided.

The model considers air velocity as constant over each segment. In practice, air velocity over moving segments may be considerably larger than that over less active segments. Such an inconsistency would tend to reduce experimental temperatures in comparison with modelled temperatures

DISCUSSION AND CONCLUSIONS

Stolwijk's model has significantly increased knowledge of man's thermal response to varying environments. The model has received independent validation at air temperatures above 40°C. In air temperatures at and below 25°C simulation problems are encountered, especially during muscular work.

The experimental data collected was for incremented work phases. Neilsen [8] indicates that some considerable period of constant work, +40 min, is required for equilibrium of heat production and dissipation to be achieved. It is doubtful if active man, with varying rest/activity cycles during the day, ever reaches a steady-state situation. The dynamic model reacts to relatively short incremented work phases and so provides useful real-life simulations.

The observed transient drop in trunk core temperature T (5), as exercise commences is related to the construction of the passive system of the model. Each muscle segment does not differentiate for individual muscles contained within it. Exercise initiates increased blood flow demand; in man a complex system of muscle recruitment is operated to deal with the onset and increase of exercise rate. This complex relation is not reflected in the model and relatively cold blood from the whole of the muscle segment returns to the trunk core, cooling it.

Where WORKM estimates are proportioned as in Table 7, the majority of muscular work is assigned to the muscles of the leg, T (18). When this majority is devoted to the muscle segment of the trunk, the proximity of trunk core to trunk muscle causes a reduced relative difference in temperature, T (5) : T (6), T (5) : T (18), and thus reduces core temperature drop at the onset of work. Similarly as WORKM estimates increase in more distant segments, T (22) the muscle layer of the feet, the relative temperature difference is greater and core temperature drop at the onset of work increases.

In order to reflect the system that exists in man with more accuracy it is proposed that each muscle segment be subdivided into several layers; layer activation depending on type of and demand of exercise required.

At the lower range of the temperatures indicated, the model exhibits larger and more sudden fluctuations than the comparable experimental data. Such suggests that man keeps vital core temperatures under tighter control than does the model and indicates an area of possible conceptual research into the control systems responsible for the integration of the simultaneous demands of muscular work and physiological reaction to cold environments.

This is indicated in Stolwijk's comments on the original model [2], "Both the experimental efforts and the emphasis of the model reported on here were directed at heat elimination" p. 65.

The model is unable to specify air flow over different segments. In cycle ergometer work where the legs experience a considerably higher air flow, with respect to other segments, this may be the cause of some computed temperature error. Differentiated air flow for each segment could be modified as an input variable. To further refine and validate this closed-loop model of thermoregulation more anthropometric data is required for varying groups. It is a serious practical limitation that at present the model can only be tested against groups similar to Dubois and Dubois's "standard man" [9].

Stolwijk's model has provided a simplified yet accurate representation of a complex physiological system and has served to stimulate argument and discussion about human thermal control. The present paper validates an amended version of the model against short incremented work phases and suggests certain refinements to the model for future use. The author agrees with an earlier report [3] in encouraging others to challenge and improve the model thereby obtaining a better understanding of the structure and action of the thermoregulatory process.

SUMMARY

The computer model of human thermoregulation proposed in FORTRAN notation by Stolwijk in 1970 is tested against experimental data derived from subjects exercising on a cycle ergometer in various environmental conditions. Three male subjects 168 ± 1.8 cm, 64.2 ± 1.9 kg, 24.5 ± 2.6 yr (mean ± range), with a high degree of cardiovascular fitness, undertook a 12 min monitored pre-work phase and two 18 min work phases at 100 W and 150 W; work was continuous. Six body temperature sites, rectal (T_R), tympanic (T_T) and four skin sites (T_S) were monitored. Results were compared from matched model outputs, where figures from the literature and anthropometric measures of each subject provided computer input. Air temperature (T_{AIR}), air velocity (V) and relative humidity (RH) were controlled in a climatic chamber.

Results obtained when comparing rectal sites suggest the model produces reasonable simulations at 30°C air temperature, $\bar{d} < 0.1$°C. Where lower ambient temperature is encountered, i.e. 25°C, simulations exhibit a marked transient drop at the onset of the first work phase, 12 min experimental time. This was not reflected in the experimental data for any of the three subjects. This deviation is attributed to the construction of the passive system in the model. Muscular work induces increased blood flow demand in muscle compartments, especially those of the leg in this simulation. Where initial muscle compartment temperature is low, cold blood returns from the whole muscle layer to the core thereby cooling it.

The paper proposes subdivision of muscle layers in the passive system to more accurately reflect the complex method of muscle recruitment as it operates in man at the onset of work. Segmental air velocity is proposed as an input variable and the limitation of the application of the model to that population approximating standard man (Dubois and Dubois) is indicated. The problem of experimental validation is discussed and further refinement and challenge to the simplified yet accurate representation of the human thermal system is encouraged.

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