招待講演 1

Computer Simulation of Physiological Responses to Heat and Exercise

Professor Stephan Konz and C. L. Hwang

Department of Industrial Engineering, Kansas State University
Manhattan, Kansas 66506 USA

An extensive modification has been made of the Stolwijk (1970) computer model of human thermoregulation. The modifications and their validation are described in more detail in Konz et al (1977). For a literature survey on mathematical models of thermoregulation, see Hwang and Konz (1977).

Model description--overview The body is divided into 6 segments (head, trunk, arms, hands, legs and feet) each of which is subdivided into core, muscle, fat and skin for a total of 24 elements. Blood flow between the cores of the 6 segments is through a hypothetical "central blood compartment" so there are 24 + 1 = 25 elements in all. Periodically the computer program computes a heat balance for each of the 25 elements.

The heat balance at each element is composed of heat generation (metabolism), heat input, and heat output.

Metabolism is composed of basal metabolism, activity metabolism, and the Q10 effect. For the three interior layers (core, muscle and fat), heat input and output are through conduction and convection (blood flow). The fourth layer (skin) has, in addition, heat exchange with the environment through evaporation, convection and radiation. In addition the core compartment of the torso has evaporative heat exchange with the environment (respiration).

Required input The program has been "individualized" to predict for individuals of specific characteristics. This permits better comparison with specific experimental data and, hopefully, will lead to better predictions and models. The user enters AGE, WEIGHT, HEIGHT, SEX, and FITNESS; for example, 46 years, 68.2 kg, 175 cm, male, and good fitness. The user also needs to describe the task and environment and enters CLO/SEGMENT, JOB, METABOLISM, AIR TEMPERATURE/SEGMENT, AIR VELOCITY, RADIANT TEMPERATURE, RELATIVE HUMIDITY, and BAROMETRIC PRESSURE. For example, clothing/segment of 0, .3, .05, 0, .3 and .1; walk-run, 400 Watts, 21.1 C, 3.3 m/s, 21.1 C, .7, and 736 mm Hg. It is possible to vary JOB, METABOLISM, AIR TEMPERATURE, AIR VELOCITY, RADIANT TEMPERATURE and RELATIVE HUMIDITY during the simulation. For example, a man might walk at a metabolic rate of 250 W in a 25 C environment for 30 minutes and then sit at 100 W in a 20 C environment for 40 minutes.

<u>Output</u> The program "tells all". Some of the summary outputs are the subject's comfort vote, the cardiac output, skin blood flow, stroke volume, heart rate, perceived exertion, metabolic heat production, mean body temperature, rectal temperature, mean skin temperature, oral temperature, evaporative water loss and salt loss.

<u>Example equations</u> Periodically the computer calculates the error (or difference) between temperature, T(N), and set temperature, TSET(N), for each of the 25 compartments:

ERROR (N) = T(N) - TSET(N) + RATE (N) * F(N)

The RATE(N)*F(N) term is available for those who believe there is a multiplicative effect. In our simulations, RATE (N) = 0.

Second, the computer checks the sign of the error. If ERROR (N) is positive, it is redefined as WARM(N); if negative, it is redefined as COLD(N).

Third, the computer calls forth one or more of the four controller actions: sweat on the skin layer (SWEAT), modify skin blood flow (DILAT or STRIC), or shiver in the muscle layer (CHILL).

SWEAT = CSW * ERROR(1) + SSW* (WARMS-COLDS) + PSW * ERROR(1)* (WARMS-COLDS)
DILAT = CDIL * ERROR(1) + SDIL * (WARMS-COLDS) + PDIL * WARMS(1)* WARMS
STRIC = -CCON * ERROR(1) - SCON * (WARMS-COLDS) + PCON* COLD(1) * COLDS
CHILL = -CCHIL *ERROR(1) - SCHIL * (WARMS-COLDS) + PCHIL* ERROR(1) * (WARMS-COLDS).

Each of the four commands is considered to be the sum of a signal from the hypothalamus, ERROR(1), and the skin (WARMS - COLDS). If you believe the two signals add, then set PSW, PDIL, PCON and PCHIL = 0 as we did. If you believe the two signals multiply, then set SSW, SDIL, SCON AND SCHIL = 0 and CSW, CDIL, CCON, and CCHIL = 0.

Fourth, the computer translates the command into "action". Respiratory loss is a function of metabolic rate and environmental vapor pressure so it will not change unless metabolism and vapor pressure change during the simulation. Evaporation from the third layer (skin), E (N + 3), is the sum of basal (diffusion) EB (N + 3), and sweat for cooling:

E(N + 3) = EB (N + 3) + SKINS(I)*2**((T(N + 3) - TSET (N + 3))/4.)

The SKINS(I) term considers the varying amount of sweat glands on the six body elements. The 2-raised-to-a-power term attempts to let the local skin temperature modify the "brain's" sweat command.

Fifth, the computer model compares the desired sweat rate to the limits imposed by the environment, EMAX, and by the sweating ability of the body, MAXSBY.

EMAX(I) = (PSKIN - PAIR) * LR * (HC(I)) * S(I))

where PSKIN is the water vapor pressure on the skin, PAIR is the air water vapor pressure, LR is the Lewis ratio, HC(I) is the convection heat transfer coefficient and S(I) is the surface area of the six segments.

MAXSBY = SWGPSM * SA * SWFACC * SWFSEX

where SWGPSM is the maximum sweat in grams/m^2, SA is body surface area, SWFACC is the acclimitization factor, and SWFSEX is the proportion of female sweat to male (SWFSEX = 1.0 for males and .67 for females in our simulations).

Sixth, if E (N+3) is greater than EMAX, the sweat heat removal is limited to the heat equivalent of EMAX but the water loss is limited to the value MAXSBY. The water loss that is not evaporated is considered either to form a film on the skin, FILM(N+3), to be adsorbed into the clothing on that segment, CLOWAT(N), or to drip on the ground, DRIP(N). The total water loss is cumulated as is the total sodium and potassium loss.

At this point, each of the six skin compartments has had its heat content and thus temperature changed due to evaporation. Other calculations take place for convection, conduction and radiation to yield a new heat balance for each of the 25 compartments.

Periodically during the simulation the computer calculates a new heat balance. The program has a limit that no compartment can change more than .1 C/iteration so if there are major changes in heat flow (and thus compartment temperatures), the iterations occur more often.

Validation Konz et al (1977) give more details on experimental validation. The situation simulated was a sitting (130 W) male (21 yr, 177 cm tall, 76.5 kg) with .1 clo (shorts) on the torso, with an environmental air temperature of 43.3 C, velocity of .1 m/s, 45% relative humidity and radiant temperature of 42.8 C. This situation was simulated since we had experimental data on this subject for three different days for about 120 minutes each day. The deviation between the mean of the three experimental values at each 10 minute interval and the predicted value was calculated; then the mean of the absolute values of the deviations over the time, $\bar{d}$, was calculated for different outputs.

Rectal temperature had a mean deviation, $\bar{d}$, of .1 C. Head skin temperature had a mean of .4 C. Trunk skin had a mean of .6 C. Arm skin had a mean of .9 C. Leg skin had a mean of .4 C. Mean skin temperature had a mean of .4 C as the deviations in various body segments tended to cancel each other. Mean body temperature had a deviation of .2 C.

Evaporative loss was predicted with a mean deviation of 31 Watts.

Since this data has been reported we have validated our model on males exercising in a variety of comfortable and warm environments. The temperature deviations above are typical and heart rate usually is predicted within 5 to 10 beats/min.

Acknowledgement: This research was supported in part by NSF Grant No. ENG-7303676.

References

Hwang, C. and Konz, S. Engineering models of the human thermoregulatory system--a review. IEEE Transactions on Bio-Medical Engineering, July 1977.

Konz, S., Hwang, C. Dhiman, B., Duncan, J. and Masud, A. An experimental validatio of mathematical simulation of human thermoregulation. Computers in Biology and Medicine, Vol. 7, 71-82, 1977.

Stolwijk, J. Mathematical models of thermoregulation (Chapter 48) in Physiological and Behavioral Temperature Regulation, C. Thomas: Springfield, Illinois, 1970.