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# Predictive validity of a computer model of body temperature during exercise

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**ABSTRACT**

HANCOCK, PETER A. Predictive validity of a computer model of body temperature during exercise. *Med. Sci. Sports Exercise*, Vol. 13, No. 1, pp. 31-33, 1981. The predictive validity of a computer model of human temperature regulation is tested by comparison with experimental data. Three male subjects were exercised at five different rates (B.M.R., 100 W, 150 W, 200 W, and 250 W) on a cycle ergometer in a controlled-environmental facility. Thermal conditions ranged from 13° to 29°C on the Effective Temperature (E.T.) scale. Two core (rectal and tympanic) and four skin temperature sites (2 torso, 1 leg, and 1 arm) were monitored. Experimental figures for core temperature ($T_C$) and mean body temperature (MBT), evolved from the six monitored sites, were compared with matched simulation data from the computer model. A high negative correlation ($r = -0.87$) was found for increasing "effective temperature" and mean absolute difference ($\bar{d}$) between experimental and simulation data for mean body temperatures. The model has increasing predictive validity as higher heat stress is encountered (E.T. > 25°C, $\bar{d}$ MBT < 0.3°C), which decreases (E.T. < 16°C, $\bar{d}$ MBT > 0.8°C) in reduced environmental temperatures.

SIMULATION, HUMAN TEMPERATURE RESPONSE, MATHEMATICAL MODEL

Considerable research has been directed to the understanding of processes concerning mammalian thermoregulation (1). Specifically, much work has addressed the problem of temperature control in the quiescent, fevered, and working human being (4). For the most part, human thermal equilibrium is maintained by individual behavioral regulation and mitigating thermal support provided by environmental heating and air conditioning.

There are many spheres of human activity in which this behavioral thermoregulation fails to achieve the desired thermal balance in the working man. On these occasions the physiological effector systems of sweating and shivering are enabled to maintain human body core temperatures within desired limits. One such situation commonly experienced by many individuals is the physical exertion associated with both formal and informal athletic activity.

To understand the operation of the human thermal system as it acts during physiological compensation, many explicative models have been proposed. These range from the simple verbal expressions of the early researchers in the late nineteenth century (7,8), to the present day complex mathematical expressions giving rise to computer simulations. The present paper examines the predictive validity of one of the most important of these latter models (9) by comparing derived simulation data with human experimental figures collected over a range of work conditions and environmental temperatures.

## THE COMPUTER MODEL

A full description of the original FORTRAN version of the model has recently been reported (9) and validated for a single subject in a high environmental temperature (6). Some amendments to the model have been proposed as a result of a further validation using three subjects operating in incremented work phases in varying environments (3).

The feedback model of temperature control artificially divides the body into two systems. In the first, a controlled system represents the human body. Six body segments, i.e., head, trunk, arms, hands, legs, and feet are each divided into four elements, i.e., core, muscle, fat, and skin. The major blood passages of the body compose the final or 25th element. Heat flow within each element depends upon heat produced through metabolic action, heat input, and heat output. All elements may gain or lose heat through conduction and convection, while skin layers also utilize evaporation as a mode of thermal control. Heat exchange with the environment through respiration is assigned to the core elements of the trunk and head.

Different subjects may be simulated by use of individual anthropometric data input for height, weight, age, sex, basal metabolic rate, and clothing insulation values. Different environmental situations require inputs for work (rate and type), air temperature, relative humidity, radiant temperature, and air velocity.

In the second system, the controlling system evaluates temperature balance in each compartment with reference to an input-set temperature. Dependent on body conditions, one or more of four effector systems are activated. Shivering initiates heat production in the muscle layers of the different segments; vasodilation and vasoconstric-

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tion act to modify skin blood flow, while sweating induces evaporative heat loss from the skin layers and is dependent on body and environmental conditions. In the current work, environmental conditions, individual subject anthropometric data, clothing insulation values, and amount and regimen of work were used as inputs to the computer model. Matched outputs for each of the experimentally monitored temperature sites were derived from the model simulation and used to compare with recorded human data. Simulated and experimental mean body temperatures were calculated from these figures. The following describes the experimental data collection.

## METHOD

Informed consent for the following procedures was obtained from all the subjects. Thermal conditions, as assessed on the Effective Temperature Scale (5), were set inside the controlled environmental facility prior to subject entry. During experimentation, continuous monitoring of air temperature, relative humidity, and air velocity was concurrently undertaken inside the chamber on a WBGT Index Meter Min 3 MK 5 (Minilab), and monitored externally on the facility control panel. Three male subjects wearing shorts and training shoes (clothing insulation value = 0.1 clo) had temperature thermistors attached in the chamber ante-room. Skin thermistors were positioned at four sites. On the torso one thermistor was attached to the sternum opposite the fourth inter-costal space and one on the inferior angle at the base of the right scapula. The two skin thermistors on the extremities were attached at the mid-point of the right biceps brachii (arm) and right rectus femoris (leg). Core thermistors were inserted to a depth of 10 cm at the rectal site and to a position adjacent to the tensor tympani in the right external auditory meatus.

On entry to the environmental chamber subjects adjusted the saddle height to comfort on the Muller cycle-ergometer, and additional seat padding was provided. At the work rate of 250 W, temperatures were monitored every 3 min for the 30-min duration of the work phase. At 200 W subjects were required to complete a 48-min work phase, temperatures were monitored every 3 min on a Light Laboratories six-point thermometer. In all other conditions in which work was incremented, a 12-min phase at Basal Metabolic Rate (B.M.R.) *in situ* in which temperatures were monitored every 2 min was followed by two 18-min work phases at 100 W and 150 W, respectively. Temperatures were recorded every 3 min in the latter phases. All conditions were completed with the exception of one subject at 250 W who was febrile on the final day of experimentation.

## RESULTS

Core temperature ($T_C$) figures were derived from weighted values of rectal ($T_R$) and tympanic ($T_T$) data reported from both experimentation and computer simulation, through the expression:

$$T_C = (4\ T_R + T_T) / 5\ . \qquad [1]$$

Similarly, mean body temperature (MBT) figures were calculated from weighted values of core and mean skin ($\bar{T}_S$) temperature data from the equation:

$$MBT = 0.64\ T_C + 0.36\ \bar{T}_S\ . \qquad [2]$$

MBT figures were calculated according to the periodic observation regime as outlined for each experiment in the previous section.

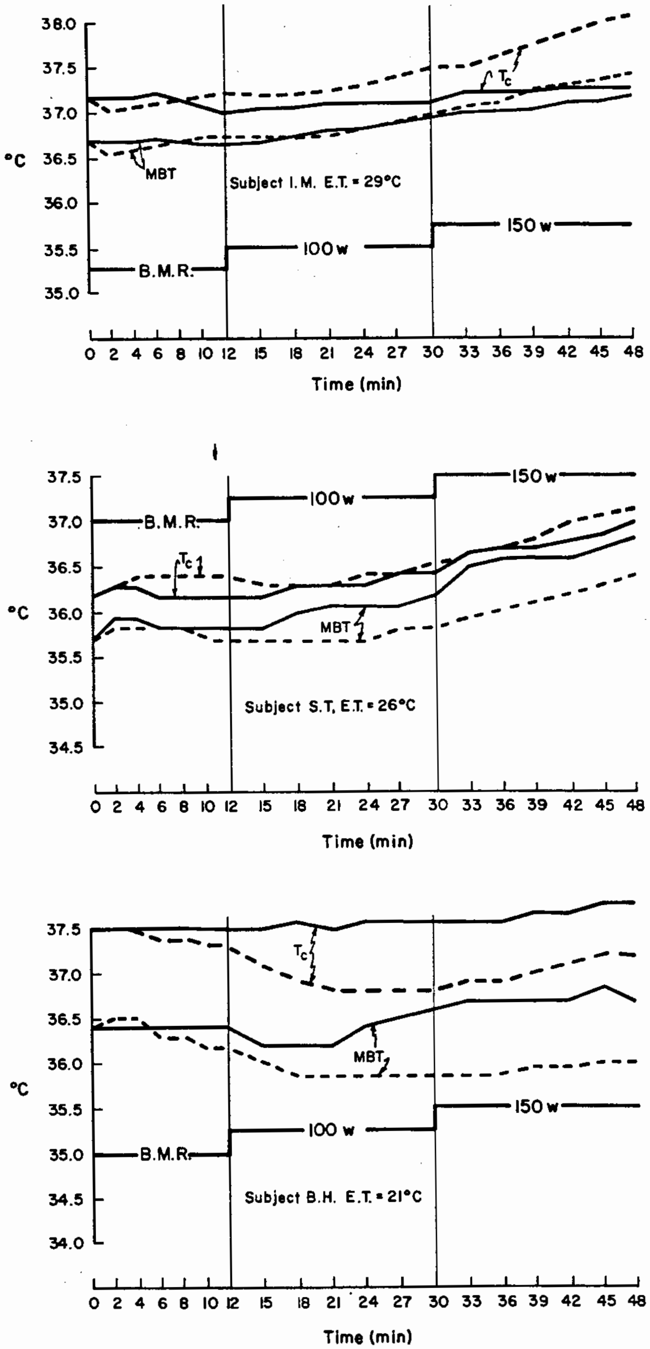

**Figure 1—Experimental vs simulated—core (Tc) and mean body temperature (MBT) for three subjects in descending "effective temperature."**

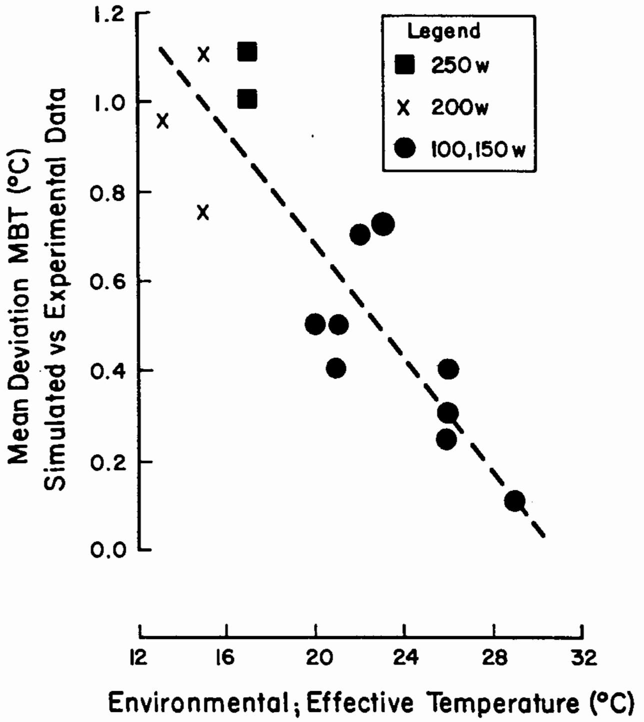

**Figure 2—Mean deviation ($\bar{d}$) between experimental and simulated mean body temperature (MBT) against ascending environmental, "effective temperature."**

Figure 1 illustrates experimental and simulated core and mean body temperatures for three subjects during incremented work phases, in descending "effective temperatures." As environmental heat stress increases (Figure 1, across subjects), simulation of mean body temperature improves. To quantify this improvement, the absolute difference between simulated and experimental MBT figures was summed across all observations within one experiment. This figure was divided by the number of observations within that experiment to provide mean absolute difference, ($\bar{d}$). This mean absolute difference ($\bar{d}$) is plotted against the "effective temperature" of the environment from which it was derived (Figure 2). This is illustrated for all subjects in all conditions.

## DISCUSSION

The high negative correlation ($r = -0.87$) between ascending "effective temperature" and descending mean deviation between experimental and simulated MBT is indicative of the model's increasing predictive validity in the heat. The reasons for the deviation between simulated and experimental ($T_R$) have been previously described (3). Briefly, work induces increased blood flow in active muscle segments. Relatively cold blood flushed from the whole of these segments at work commencement returns to the central blood compartment which artificially depresses the core temperature of the torso ($T_R$) in which it is contained. In man, initial differential muscle recruitment within leg segments allows for gradual heating of circulating blood which protects body core temperature from such a fluctuation. Experimental mean skin temperature exceeds simulated values. The model calculates a mean temperature for the skin of each segment, i.e., arm, leg, and torso. The experimental thermistors, situated over working muscles, are atypical of the whole segment and are appreciably hotter than comparable simulated values.

As "effective temperature" of the environment increases, initial set temperature difference between adjacent segments is compressed. Blood returning from active muscle segments no longer depresses simulated rectal temperature and MBT simulation improves. For practical purposes the model is particularly useful above the upper limit of the thermal comfort zone (2). With the appropriate computer inputs for clothing insulation values, environmental conditions, and individual athlete anthropometric data, the model may be employed to simulate MBT in heat stress. This prediction, useful in assessing physiological tolerance limits, may circumvent the possibility of debilitating or fatal hyperthermia due to environmental and metabolic heat stress generated by violent physical activity on hot days.

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