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THE SIMULATION OF HUMAN CORE TEMPERATURE

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Two fit subjects performed two cycle-ergometer exercise bouts, one of 200 W for 48 min with a following 12-min recovery phase and one of 250 W for 30 min with a subsequent 15-min monitored recovery period. Experiments were performed in ambient conditions of 18 ± 1°C, 52% relative humidity ± 5% and 0.5 $m \cdot s^{-1}$ + 0.5 air velocity (mean ± range). Experimental values obtained from rectal and tympanic temperature sites were compared with simulation figures produced from a *FORTRAN* model of human thermoregulation. Data obtained provide qualified experimental support for the concept of a simple feedback model to simulate human core temperature during exercise in ambient temperatures below 20°C.

Introduction

Models of thermoregulation have been proposed in many forms and among the earliest is Bernard's (1850) observation on animal heat. He stated that when an animal is heated or cooled it returns to its initial temperature by exceeding it and then returning, exactly like a pendulum which oscillates as it returns to rest. Subsequently, a verbal model, Richet (1885) included the role of the hypothalamus in controlling human body temperature and Rubner (1902) presented work on the concepts of 'physical' and 'chemical' regulation which still remain pertinent to present discussion of temperature control. In 1934, Burton introduced mathematical notation into thermoregulatory modelling and since then many mathematical models of the human system have been proposed such as those of Wyndham *et al.* (1960), Crosbie *et al.* (1963) and Wissler (1964).

In 1966, Stolwijk and Hardy observed that the study of thermoregulation was reaching a point where descriptive investigation was yielding progressively less in terms of insight into conceptual problems. They advocated more quantitative and analytical approaches to the problem and themselves constructed the first feedback model for operation in conjunction with an analog computer. Later Stolwijk (1971) proposed a more detailed extention of this model in *FORTRAN* notation for use in digital computers. This model has been independently validated by Konz *et al.* (1977) for a single subject in a high environmental temperature condition and for three subjects performing incremented work phases in varying ambient conditions by Hancock (1980).

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In the optimal computer model of thermoregulation subject variables (e.g., height, weight, age, sex, and clothing insulation values) and environmental variables (e.g., air temperature, relative humidity, radiant heat, air velocity and type and amount of work) are used as computer inputs and the model produces simulation data for physiological reactions (e.g., body core and extremity temperatures, sweat rate and cardiac output). Stolwijk's model, within limitations imposed by lack of anthropometric data for sex and somatotype, deals with most of these demands. However, there remains a paucity of literature concerning either validation of or challenge to the model proposed.

Models of thermoregulation serve to fulfil two functions. From the conceptual approach they advance discussion and research on the human thermal system. From an applied perspective a validated model of temperature regulation may provide simulation data in advance of the human operator being exposed to potentially dangerous situations. This prediction aspect is particularly important in environments where man is liable to experience considerable physiological stress, in deep mining, deep-sea diving and deep space extra-vehicular activity. On such occasions a subject may be required to perform heavy work for a protracted period. One limiting factor in such a situation is body core temperature increase toward unsupportable physiological levels. This paper examines the reaction of a variation of Stolwijk's model to protracted heavy work and subsequent monitored recovery phases and compares such data with equivalent reported experimental results.

The computer model

In Stolwijk's model the controlled system, the body, is subjected to thermal disturbance from body metabolism and the external environment. These disturbances in body temperature are monitored and fed back by thermal receptors into an integration or controlling system. Discrepancy between reference and feedback information is used to calculate the amount of regulatory control action required. Such action, to oppose disturbance, is effected through muscular heat production, sweat activation and vasomotor activity.

Specifically, the passive system is composed of 25 compartments. Six segments representing feet, legs, arms, hands, trunk and head are each composed of four tissue layers; core, muscle, fat, and skin. The final compartment, which is constituted of the larger arterial and venous passages, exchanges heat with the other 24 compartments using the convective heat transfer associated with blood flow. Heat balance equations are calculated dependent upon convection, conduction and metabolic heat production within each compartment. In addition, skin layers use heat loss through evaporation as an additional avenue of thermal control.

The controlling system first monitors conditions in each of the compartments. This information is integrated and used to derive effector commands which are sent to the appropriate system. These commands, modified by peripheral conditions, then induce either sweating, shivering in the muscle layers, or alteration of vasomotor tone.

The present simulation was run on an ICL 1900 series digital computer. The model can be simply incorporated to produce simulation data on a wide variety of extant digital computers.

Method

Two male subjects were chosen on the basis of athletic activity, each having a high degree of event related cardiovascular fitness. Both were additionally selected with body size approximating Dubois and Dubois's 'standard man' where anthropometric data necessary for model input is available in the literature. Emergency facilities and medical personnel were available throughout all experimental sessions.

Two experiments were performed. In the first a 48-min cycle-ergometer work period at 200 W was followed by a 12-min monitored recovery phase. In the second a 30-min work period at 250 W was followed by a 15-min recovery phase. Temperatures were monitored on a Light Laboratories thermometer every 3 min during both work and recovery phases. Conditions inside the artificial environmental facility were set within the following ranges for all experimental sessions, air temperature 17–19°C, relative humidity 47–57% and air velocity $0.1–1.0\ \text{m} \cdot \text{s}^{-1}$.

Core temperature was monitored at rectal and tympanic sites. At the rectal site the indwelling thermistor probe was inserted to a depth of 10 cm and subsequently taped to the lumbar region of the spine to inhibit movement during work phases. Subjects were additionally allowed padding on the cycle ergometer seat to promote comfort and further reduce the possibility of movement artifact. The tympanic temperature probe was inserted in the right external auditory meatus to a site adjacent to the tympanic membrane. It was not attached to the membrane because of subject discomfort and the possibility of tissue damage during heavy exercise. This necessarily introduced some measuring lag at the tympanic site.

Discussion of results

Simulation predictions from the model for trunk core, T(5), and head core, T(1), were compared against experimental data reported. For the rectal site, results for both subjects in each condition are presented in Fig. 1. Intra-subject comparison of patterns shows a similarity of temperature response for both experimental and simulation data. This is reasonable as the difference between the two conditions is only in terms of time and work level. However, when comparing across subjects the similarity of pattern is less well defined. This is due to anthropometric differences between the two subjects which being fed in as computer inputs also affect the simulation pattern.

Across all rectal data the most obvious pattern is the initial temporary drop of simulation data at the onset of work. The observed drop is due in main part to the configuration of the model passive system. This particular simulation is constructed

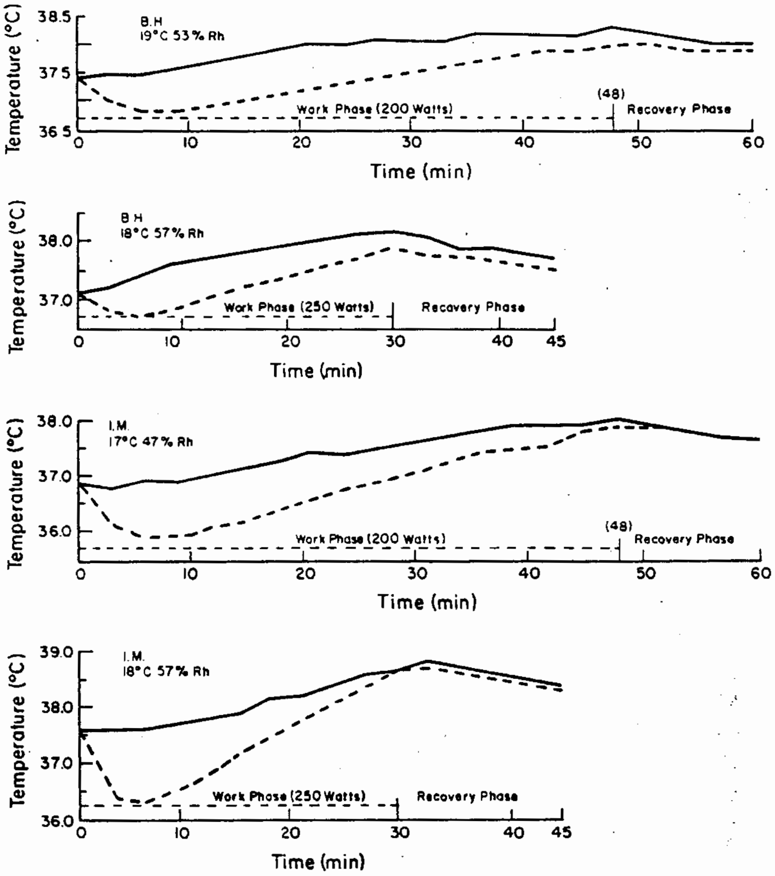

Fig. 1. Computed vs. experimental rectal temperature comparisons (- - - -, comp.; ——, exp.)

to reflect cycle ergometer exercise. Work imposed is apportioned in a 60%, 30%, 10% ratio for leg, trunk and arm muscle segments respectively. The leg muscle segment, T(18), is relatively cold in comparison with the trunk core, T(5), at the onset of work. Blood flow is directed in relation to oxygen demand from working segments, in this simulation mainly the leg muscle segment. Cooled blood returning from this segment at the onset of work reduces core temperature, producing the simulation data reported. Continuing muscular work and relatively high circulating blood temperature both serve to heat active muscle layers. Blood then returning from these layers no longer depresses trunk core temperature and discrepancy gradually decreases (Fig. 1). Subsequent recovery phases are impressively simulated, mean data deviation B.H. $(T_R)\bar{d} < 0.2°C$, I.M. $(T_R)\bar{d} < 0.05°C$.

Experimental data presented is consistent with previous thermophysiological findings. Nielsen (1938) has indicated that when continuous work is undertaken for a period of 40–60 min, heat generation and dissipation are nearly equal causing a thermal equilibrium. At this point core temperature plateaus to remain stable while work continues. There is some evidence for such a phenomenon in the longer work phase of Experiment 1. Further, Neilsen (1976) has stated that core temperature increase over resting levels is proportional to both work rate and oxygen consumption during work. In comparing two subjects of the same approximate size (height, weight and surface area), but with different V_{O_2} max who exercise in the same environmental conditions at the same work rate, the 'low V_{O_2} max man' will reach a higher core temperature than the other, the 'high V_{O_2} max man'. Experimental data in this study support these conclusions, where the 'high V_{O_2} max man' B.H. attained a lower core temperature maximum, 38.2°C, and increase over resting level, 1.1°C, than the 'low V_{O_2} max man' I.M. 38.8°C, and range 1.2°C. These comparisons are only for Experiment II where environmental conditions were coincident at 18°C, 57% relative humidity 0.1 $m \cdot s^{-1}$ air velocity (Fig. 1).

The original discrepancy between experimental and simulation data is where experimental data does not exhibit a drop at the onset of work. Man with his necessity to maintain core temperature within narrow limits could not support such a sudden fluctuation. At exercise onset man recruits selected muscles to deal with imposed work. Initial simulation, especially during exercise in lower air temperatures, may be improved by passive system muscle layer fractionation to reflect the system as it operates in man. Konz *et al.* (1977) have reported that simulation data consistently matches experimental data after a period of +40 min, for rectal measurements. With the elimination of initial discrepancy the model provides a valuable simulation for this important core temperature site.

Comparisons for the tympanic temperature site are presented for both subjects in both conditions in Fig. 2. In a similar manner to the rectal site, the tympanic site exhibits a consistent intra-subject pattern. Inter-subject pattern variability is again due to anthropometric differences between the two subjects.

Across all experiments the simulated temperatures from the head core T(1) are at the least equal and generally higher than comparable experimental data. This incompatibility is attributed to the inability to directly measure the head core temperature. In addition to the lag introduced by thermistor site away from the tympanic membrane in the auditory meatus, there is also a considerably larger lag due to the distance and tissue separating the tympanum from the head core.

In an earlier experimental validation, Konz *et al.* (1977) reported comparisons for model versus head skin temperature. They found a mean deviation of model from experimental values of 0.4°C. This difference was attributed to a possible insufficiency of apportioned sweat command to the head. In such a situation not only would head skin simulation by consistently higher than experimental data but also simulated head core temperature would exceed experimental figures. This core temperature site also

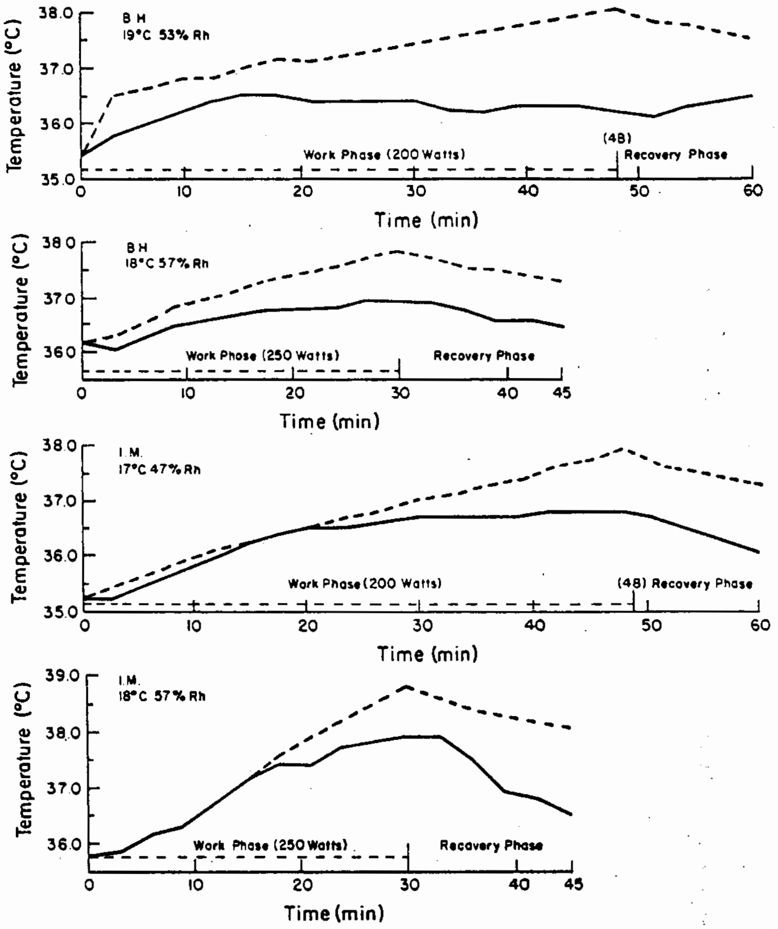

Fig. 2. Computed vs. experimental tympanic temperature comparisons (- - - -, comp.; ——, exp.)

exhibits experimental data consistent with Nielsen's observation where the 'high $\dot{V}_{O_2}$ max man' B.H. shows a lower peak thympanic temperature 36.9 and smaller range 0.8°C than the 'low $\dot{V}_{O_2}$ max man' I.M. 37.9°C and 2.1°C.

Conclusions

In this model, including a segmental passive system, segment temperature is an averaged value for the whole segment. Experimental data conversely is a point measurement. Miller and Seagrave (1974) stated that the difficulty in compromising the two temperatures may be reduced to a problem of finding a single site within a segment which is at the mass average temperature of that segment. In measuring core temperature, thermistor sites are limited and this limitation may be the cause of some disparity.

The two experiments reporting the two experimental sites illustrate an important point in physiological modeling. There may be problems concerned with the conceptual construction within the model as in the case of the simulated rectal temperature. Conversely, experimental data may inaccurately represent a specific segment as is the case of the tympanic site. It is important to combine model development in close connection with a comparable experimental program.

The present paper examines the reaction of an amended version of Stolwijk's model to protracted work periods and subsequent recovery phases. At the rectal site, despite initial transient discrepancy, the model provides useful simulations over a long period. Over a shorter period amendments to the present passive system of the model are necessary to increase experimental/simulation data compatibility. At the tympanic site measurement error and insufficient head skin sweat command are considered mainly responsible for data mismatch reported. Any model of human core temperature regulation by definition is only a simplified representation of a complex system. To refine and develop it for theoretical and practical purposes needs continual challenge and validation using experimental results.

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