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APPLICATION OF A PREDICTIVE CORE TEMPERATURE MODEL TO HEAT STRESS EXPERIMENTATION

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ABSTRACT

An interactive procedure for evaluating and maintaining an individual's core temperature at a predetermined level was developed and tested. The procedure involved the use of previously developed models for predicting core temperature changes during work and rest. Various levels of metabolic activity were used for rapid core temperature elevation and adjustments in dry-bulb temperature and relative humidity maintained the desired core temperature level. Evaluation of the procedure was made using five female subjects at four different levels of elevation. Results are presented which show the accuracy of the control.

INTRODUCTION

For years, work physiologists have sought to condense the important factors of a hot environment into a single index which could accurately represent the effects on humans. In this search, the concept of an environmental stressor resulting in physiological strain has been used to relate "heat stress" to "heat strain." According to Henschel (1963), heat stress is the total load on an individual from both environmental and metabolic sources. Heat strain is the resulting biochemical, physiological and psychological adjustments made by the individual. The heat stress index forms the connecting link between the two.

When evaluating human performance, safety and health in a hot environment, the usual approach has been to measure the responses of subjects exposed to various levels of a selected heat stress index. Although the use of a heat stress index, especially in field studies, facilitates the experimental procedure, performance comparisons based on an appropriate heat strain parameter would provide information applicable to a greater number of situations. Particularly for laboratory evaluations of performance, the use of a heat stress index is an unnecessary middle step which affects the accuracy of the results. A better approach is to measure performance as a direct function of a heat strain parameter. The major task from the experimenter's viewpoint is to accurately control the parameter. If this can be accomplished, measurements of strength, endurance or psychomotor performance are usually straightforward.

One of the best indicators of physiological strain in a hot environment is body core temperature. It shows the status of the thermoregulatory system and warns of potential heat disorders. Although the level of core temperature depends on the environmental and metabolic conditions, it may be controlled during a two to three hour experimental session by proper manipulation of the environment and work load. The required inputs to accomplish this task are (1) an accurate model which predicts core temperature for a given set of conditions and (2) an interactive procedure for monitoring the temperature and changing the conditions.

PREDICTIVE CORE TEMPERATURE MODELS

Various approaches have been used in an attempt to model the thermoregulatory system of the body. One category of models predicts the internal temperatures of specific regions of the body using heat transfer equations (Wissler, 1963; Crosbie, Hardy and Fessenden, 1963). Other models use significant environmental and individual factors to predict physiological responses such as core temperature and heart rate. Although there are several models which estimate an equilibrium core temperature based on metabolic rate and certain environmental parameters, few models include all relevant variables. Even fewer predict the time pattern of the change.

Givoni and Goldman (1972, 1973) developed two biophysical models which predict the time pattern of rectal temperature and heart rate responses of heat acclimatized individuals exposed to various combinations of work, environmental conditions and clothing properties. Other variables were added to their models by Dayal (1974, 1976). The factors included in Dayal's models are:

(1) air temperature
(2) radiant heat load
(3) environmental vapor pressure
(4) ambient air velocity
(5) metabolic energy expenditure
(6) aerobic capacity of the individual
(7) permeability properties of clothing
(8) thermal resistance of clothing
(9) different modes of heat transfer

The index used for the core temperature model is rectal temperature which lags changes in the temperature of the hypothalmus by approximately 30 minutes. First, an equilibrium temperature is predicted for the given set of conditions. Then one of three formulas is used to determine the time course of the change: one for rest in the heat, one for the rising stage during work and a third for the recovery stage. All three equations have an exponential form which depends on the difference between the initial and final rectal temperatures.

The input variables for the model are easily determined and calculation of the predicted values is straightforward. Dayal found good agreement between predictions from the model and data from several studies at various work loads and environmental conditions. Givoni and Goldman also provided nomograms to aid in computing the various components of the prediction equations.

INTERACTIVE PROCEDURE

To utilize the predictive model to control an individual's core temperature, certain simplifications must be made. Because of the large number of factors included in the model, it is first necessary to fix certain of the factors at initial values. Some of these may be determined by the requirements of the investigation. For many situations, it it desirable to fix all factors, with the exception of air temperature, vapor pressure and metabolic load, at levels which will provide an appropriate range of variation. Air temperature and vapor pressure may then be adjusted to provide control within this range. To accelerate the core temperature rise, the metabolic level may be initially increased to produce the desired rate of change.

The first step in the procedure is to determine the environmental, metabolic and clothing properties which will yield the desired equilibrium rectal temperatures. This may be done using an iterative computer program to find the proper levels of the variables. Next, the length of time to reach equilibrium must be calculated and compared to the available time in the experimental session. If the time is too long, the temperature rise is accelerated by the introduction of a higher work load. As the desired temperature is approached, the work load is reduced to that required to maintain the temperature. Dynamic adjustment can then be made using slight changes in the environmental conditions.

Although the predictive model provides good estimates of the equilibrium temperature, there are larger variations in individual time patterns. Thus, it is desirable to have some initial information on the particular response pattern of each subject. Continuous monitoring of rectal temperature is necessary to make the proper changes in work load and environment. Three major factors must also be considered:
(1) Core temperature continues to drift upward after reduction of the work load.
(2) Certain types of activity may cause a significant drop in core temperature which is not accounted for by the model.
(3) There exists a certain time lag between any change in the external conditions and any observed change in core temperature.

APPLICATION OF PROCEDURE

<u>Experiment</u>

This procedure was used in a study which evaluated changes in static work capabilities which occur in hot environments (Schlegel, 1980). Changes in static muscular strength and continuous hold endurance were measured at specific core temperature increments above each subject's resting level. The increments selected were 0.0, 0.3, 0.6, 0.9 and 1.2 ^{o}C. These values represent a range from the "normal" core temperature to a temperature which indicates considerable heat strain but which is still within a critical safety limit of 39 ^{o}C.

To minimize changes in blood flow caused by high energy expenditure levels, it was decided that the measurements would be made with the subject resting in the hot environment. With a zero work load in the initial stages, the time to reach equilibrium for the higher temperature increments would normally be four hours. By initially using an additional work load, this time was reduced to one hour, with 30 minutes required for the increase and 30 minutes allowed for the stabilization of core temperature and recovery of blood flow. The criterion for core temperature equilibrium was a change of $\pm$ 0.03 ^{o}C or less in a 15 minute period. Strength and endurance tests were performed during the second hour of the session while core temperature was continually controlled.

Variables and Equipment

Five female subjects in above average physical condition were selected for the study. Each subject performed at each of the core temperature levels. The specific levels for each subject are given in Table 1. Rectal temperature was monitored using a thermistor probe inserted to a depth of 10 cm beyond the anal sphincter, thermistor interface circuitry and a DECLAB 11/03 minicomputer system. The temperature readings had an accuracy of ± 0.05 °C and a reproducibility of ± 0.01 °C. Environmental temperatures, skin temperatures and heart rate were also monitored by the computer system.

All trials were conducted in a controlled environmental chamber (Sherer-Dual CER 1216) with metabolic work performed on a motorized treadmill (Quinton 14-44-A). Values for each of the variables were as follows:

(1) air temperature - 25 to 40 °C
(2) radiant heat load - 0
(globe temp = dry-bulb temp)
(3) relative humidity - 40 to 50 %
(4) ambient air velocity - < 1 m/sec
(5) metabolic work (treadmill)
(a) speed - 0.5, 0.9 and 1.3 m/sec
(b) elevation - 0, 2.5, 5 and 10 %
(6) aerobic capacity - above average
(7) clothing - cotton shorts, halter top, jogging shoes and sockettes (long hair pulled back)

Procedure

Five days of preliminary testing were performed in order to acclimatize and train the subjects. During this time, each subject's core temperature pattern was determined. The various time lags between onset or removal of work load and an observable change in rectal temperature were calculated. This data was then used for the actual experimental sessions conducted during the second five day period. All trials for a particular subject were conducted at the same time of day with only one trial per subject per day.

After instrumentation of the subject and collection of baseline data, the subject was placed on the treadmill and began walking at a speed of 1.3 m/sec. This was a sufficient work load for the 0.0 and 0.3 °C runs. For the 0.6 °C run, the treadmill was elevated to 5 %, and for the 0.9 and 1.2 °C runs, it was elevated to 10 %. As the core temperature approached the desired value, the treadmill was lowered in stages and the speed reduced to 0.5 m/sec. Simultaneously, the air temperature and relative humidity were raised to the levels required to maintain the core temperature. If the core temperature had stabilized after 30 minutes rest, the strength and endurance testing was begun.

RESULTS

As seen in Table 1, there was a large variation between the five subjects in terms of resting core temperature (37.00 to 37.77 °C). However, the daily variation for each subject was minimal. The target and actual rectal temperatures for each subject and trial are also shown in the table. Of the 25 trials, 12 were conducted with an error of 0.05 °C or less. Five trials had an error exceeding 0.15 °C. The average of the absolute errors for all 25 runs was 0.09 °C.

The largest error occurred for the 0.0 °C control level. This level was conducted at a dry-bulb temperature of 25 °C, which is the temperature for thermal balance. The core temperatures of three of the subjects dropped significantly (0.12 to 0.25 °C) during this run. This meant that the actual spread between the control run and the 0.3 °C run was closer to 0.4 °C. Based on the averages for the actual temperatures during the endurance test, the temperature increments relative to the control run were as follows:

0.37 0.64 1.00 1.37

Although the control of core temperature worked reasonably well, a few runs were conducted which had a large error. This offset the averages as outlined above.

SUMMARY

During the course of the experimental sessions, three different response patterns were observed in the subjects when they were removed from the treadmill:
(1) The core temperature dropped immediately (within 1 minute).
(2) The core temperature climbed for a short time (∿ 5 minutes) but then remained steady.
(3) The core temperature climbed for a long time (∿ 10 minutes) and dropped slowly.
These patterns appeared to depend primarily on the individual regardless of

Table 1

Target and Actual Core Temperatures (°C)

		Core Temperature Increment (°C)				
		0.0	0.3	0.6	0.9	1.2
Subject						
1	T	37.35	37.65	37.95	38.25	38.55
	A	37.10	37.68	37.90	38.22	38.62
	E	-0.25	0.03	-0.05	-0.03	0.07
2	T	37.05	37.35	37.65	37.95	38.25
	A	36.89	37.22	37.56	38.04	38.76
	E	-0.16	-0.13	-0.09	0.09	0.51
3	T	37.50	37.80	38.10	38.40	38.70
	A	37.38	37.68	38.17	38.38	38.70
	E	-0.12	-0.12	0.07	-0.02	0.00
4	T	37.00	37.30	37.60	37.90	38.20
	A	37.00	37.40	37.58	37.85	38.00
	E	0.00	0.10	-0.02	-0.05	-0.20
5	T	37.77	38.07	38.37	38.67	38.97
	A	37.78	38.06	38.18	38.69	38.94
	E	0.01	-0.01	-0.19	0.02	-0.03
Avg. Error		-0.10	-0.03	-0.06	0.00	0.07

T - target core temperature for trial
A - actual core temperature during testing
E - error between actual and target (A - T)

the temperature increment. Accounting for these differences was the major problem in accurately controlling the temperature.

Despite the problems encountered, the procedure provided a means for evaluating strength and endurance changes which yielded significant results. In the current implementation, the experimenter made the decisions concerning the timing and the magnitude of the changes in the work load and the environmental conditions. A more refined procedure using an interactive computer program is currently under investigation. This would provide the fine adjustments necessary to keep core temperature stabilized. However, it has been shown that this methodology is a viable approach for examining physiological and psychomotor changes due to heat stress.

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