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A THERMAL MODEL OF THE HUMAN BODY EXPOSED TO AN ELECTROMAGNETIC FIELD

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The human body was modeled by numerical procedures to determine the thermal response under varied electromagnetic exposures. The basic approach taken was to modify the governing heat transfer equations for man in air to account for thermal loading due to the energy absorbed from the electromagnetic field. The human body was represented in an electromagnetic model by a large number of small cubical cells of varying tissue properties, and the energy density was determined for each cell. This information was used as input to a thermal response model. The thermal response model consisted of solving a series of two-dimensional transient conduction equations with internal heat generation due to metabolism and shivering, internal convection heat transfer due to blood flow, external interaction by convection and radiation, and cooling of the skin by sweating and evaporation. This model represented the human body by a series of cylindrical segments in which each radius and length was determined independently by comparing the height and weight of the subject to the statistical 2.5%, 50%, and 97.5% man.

These two codes were combined in a number of different ways, and the results are shown to indicate the effect of different methods for distributing the electromagnetic heat deposition. The output of the combined code gives the local temperature of 61 discrete locations as well as the thermoregulatory responses of vasoconstriction, vasodilation, shivering, and sweating. This code was then used to determine local "hot spots" and overall thermoregulatory response to a number of electromagnetic field intensities and frequencies both at resonant and nonresonant conditions.

The numerical model presented in this paper is a combination of an electromagnetic coupling model and a thermal response model. The human body is represented in the electromagnetic model by a large number of small cubical cells of varying tissue properties, and the energy density is determined for each cell. This information is used as input to the thermal response model. The thermal response model consists of solving a series of two-dimensional transient conduction equations with internal heat generation due to metabolism and shivering, internal convection heat transfer due to blood flow, external interaction by convection and radiation, and cooling of the skin by sweating and evaporation. This model represents the human body by a series of cylindrical segments in which each radius and length is determined independently by comparing the height and weight of the subject to the statistical 2.5%, 50%, and 97.5% man.

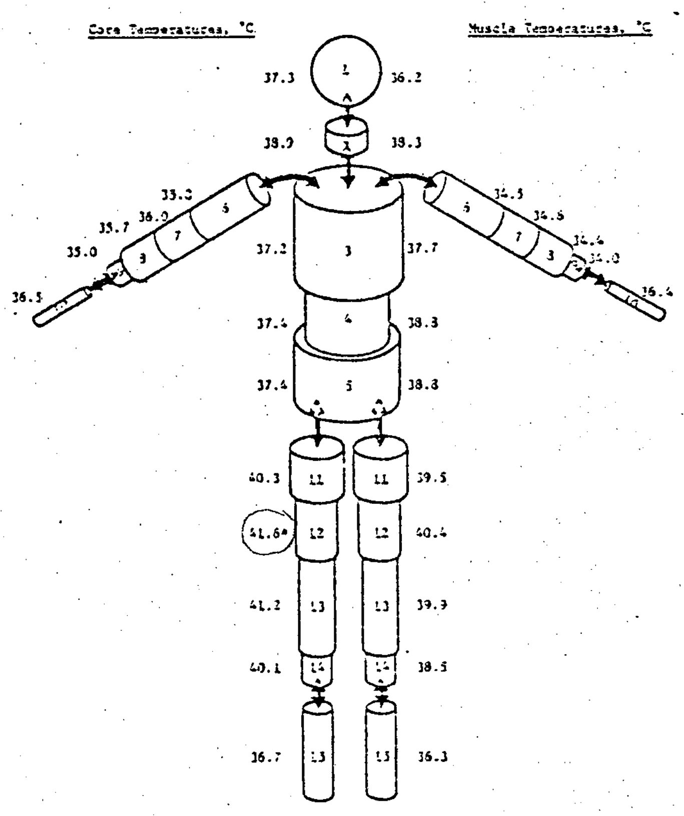
The fundamental concept of this technique is that the continuous temperature distribution in the body can be approximated by a discrete model composed of a set of piecewise continuous functions defined over a finite number of elements or nodes. The discrete model used here is a forward-difference approximation of the defining differential equation for transient heat conduction. To accomplish this approximation, the thermal response model divides the body into 61 nodes. An average temperature is calculated for each node at discrete points in time. Since the thermoregulatory mechanisms of vasoconstriction, vasodilation, shivering, and sweating are all functions of the difference between the current node temperature and a thermally neutral set temperature, each of these mechanisms is also a function of time. Prior to each time step, the net heat generation for each node must be calculated and superimposed on the solution to the differential equation.

Due to the mathematics involved, the electromagnetic coupling model divides the model into cubical cells and the thermal response model divides the body into cylindrical segments. These two different finite element approaches complicate the combination of the two models. The cubical cells used in the electromagnetic coupling model allow the body to be represented as a three-dimensional simulation. The thermal model uses cylindrical segments, each with four concentric layers, to accurately depict the thermal response in two dimensions. Since each segment is symmetrical in the angular direction, and the thermal gradient in this direction is extremely small compared to the gradients in the other predominant direction, the two-dimensional simulation will provide an accurate representation.

The approach taken for combining these two models is as follows. The absorbed power densities calculated in each cubical cell of the electromagnetic model are combined to form cross-sectional elements, and then the total power per element is determined by summing the products of the individual power densities and individual cell volumes. These elements are then combined to form a composite element with a thickness equal to the length of the cylindrical segment of the heat transfer model which represents the same portion of the object. Once the total electromagnetic power deposition has been determined for each cylindrical segment of the heat transfer model, the power deposited in each annular layer of the segment is calculated by multiplying the total power by the ratio of the thermal conductances of each layer to the total conductance for each segment. This information is then combined with all of the other energies added to and subtracted from each layer in the form of conduction, thermoregulation, or environmental interaction. The governing heat transfer equations for each layer are then solved and the temperature response calculated.

To illustrate a typical response, the following conditions were used as input to the combined electromagnetic coupling and thermal response model: incident power = 10 mW/cm^2; frequency = 80 MHz; ambient temperature = 30°C; relative humidity = 30%; subject height = 175 cm; and subject weight = 78 kg. The incident field was a plane wave propagating from the front to the back of the object with its electric field vector oriented parallel to the major length of the body. For this polarization and frequency of the incident field, the body size of the object easily approximates resonant conditions.

The steady-state thermal condition of the object is shown in the following figure where the core and muscle temperatures of each segment are listed. The numbers on the left side of the object refer to the core temperatures, while those on the right side designate muscle temperatures. Due to the external field conditions, symmetry conditions exist; i.e., the temperature distributions for each leg and arm are equal. Note that the core temperature in the lower thigh is high enough to indicate that a localized "hot spot" exists.



* "Hot Spot."

A series of these types of exposures at different incident power densities were run at two different frequencies, and temperature profiles are shown below for the average muscle temperature (TM), mean body temperature (TB), hypothalamic temperature (TH), rectal temperature (TR), esophaylal temperature (TO), and skin temperature (TS). For the 80 MHz case, the uncontrolled rise in inner core temperatures for incident power levels greater than about 20 mW/cm^2 strongly indicates that the protective mechanisms for heat control have broken down.