NASA TECHNICAL MEMORANDUM NASA TM X-62,172

NASA TM X-62,172

(NASA-TM-X-62172) MATHEMATICAL MODELS OF THERMOREGULATION AND HEAT TRANSFER IN MAMMALS. A COMPENDIUM OF RESEARCH A. Shitzer (NASA) Jul. 1972 75 p CSCL 06C

N72-28043
Unclas
G3/04 35540

MATHEMATICAL MODELS OF THERMOREGULATION AND HEAT TRANSFER IN MAMMALS

A Compendium of Research

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July 1972

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INTRODUCTION

Since the days of the Italian physician Santorio[1] and the French chemist Lavoisier[2] who, respectively, established the facts that the human body exchanges water vapor with the environment and generates heat, men have been intrigued and fascinated by the human thermoregulatory system. The ability of this system to maintain a fairly constant "deep body" temperature and to dissipate or preserve heat under widely varying environmental conditions are only examples of the complexity of this system.

First attempts to better understand the thermoregulatory system had been aimed at observing the thermal behavior of homeotherms under natural and laboratory controlled conditions. Soon this approach reached a point of diminishing return and in order to advance the understanding of various phenomena and mechanisms involved in thermoregulation, scientists had to resort to more sophisticated methods in the study of this system, e.g., mathematical modeling. The earlier works were relatively simple; there principles of conservation of thermal energy and conservation of mass, expressed mathematically, were applied to various thermal conditions. Among these pioneer investigators it appears that Burton[3] in 1934 was the first to apply heat transfer equations to the human body.

A number of years later there emerged the concept of "core and shell"[4] as applied to a human body. According to this concept two temperatures are assigned to the body: deep body (rectal) and skin temperatures. This approach to the problem has been popular with physiologists. The insufficiency of this method to account for, among other things, various control mechanisms brought about a more detailed analysis of the thermoregulatory system. The advent of computer sciences, digital and analog, enhanced the effort. Today the overall thermoregulatory system and the various sensing and control mechanisms involved are better understood although there still are many questions

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1. Best, C. H. and Taylor, N. B., "The Living Body," Holt Rinehart and Winston, 4th ed., 1958, pp. 11-12, 377.
2. Lavoisier, A. L., "Experiences sur la Respiration des Animaux," *Memoire de l'Academie des Sciences*, 1777.
3. Burton, A. C., "The Application of the Theory of Heat Flow to the Study of Energy Metabolism," *Journal of Nutrition*, vol. 7, 1934, pp. 497-533.
4. Eichna, L. W. *et al.*, "The Upper Limits of Environmental Heat and Humidity Tolerated by Acclimatized Men Working in Hot Environments," *Journal of Industrial Hygiene and Toxicology*, vol. 27, 1945, pp. 59-84.

yet to be answered.

Many problems in thermal physiology and bioengineering lend themselves to mathematical formulation and modeling. Among these the following demonstrate the diversity of topics already covered by scientists in these areas:

1. The study of the behavior of the mammalian thermoregulatory system as a control system.
2. The study of the physiological meaning of thermal comfort under varying environmental conditions.
3. The study of the interaction between the human body and an external cooling device, e.g., liquid cooled garments used in space exploration.
4. The study of skin burns.
5. Heat transfer associated with medical treatment, e.g., dental.
6. The measurement of various thermal and physiological properties of live tissues.
7. The study of thermoregulation in hibernation.

Methods of approach to modeling and solving the problem under consideration are diverse, too. They depend, in most cases, on the background of the investigator and the degree of approximation desired. Generally, analytical, numerical and analog methods have been employed. The use of computers, digital and analog, is quite extensive, in common with other areas of science.

A number of reviews on the subject of mathematical models of the thermoregulatory system have been published[5, 6, 7]. An attempt is made here to fill a gap and collate a more comprehensive, though possibly not exhaustive, list of works done on the subject to date. The compendium includes part or parts of a work cited (abstract, summary, etc.) with little or no modification. The part which best summarizes and represents a particular publication is included in the compendium. In a few cases similar publications by the same author(s) were cited to make the work more easily accessible. Also included is a separate list of theses' abstracts on subjects related to modeling of the thermoregulatory system.

In addition to the representative paragraphs and the exact citation, a table is included which describes, in some detail and on a comparative basis, a number of the more often used aspects of mathematical modeling, as applied here. These are as follows:

1. Geometry of the model (cylindrical, rectangular and spherical).
2. Thermal energy mechanisms considered (conduction, metabolic heat generation, transport of heat by blood perfusion and thermal inertia).
3. Method of solution (analytical, numerical or analog).
4. Boundary condition satisfied at the skin surface.
5. Thermoregulation mechanisms considered.

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5. Chato, J. C. and Hertig, B. A., "Thermal Behavior of Biological Media," *AIAA Paper* 70-813, 1970.
6. Shitzer, A., Chato, J. C. and Hertig, B. A., "A Study of the Thermal Behavior of Biological Tissue with Application to Thermal Control of Protective Suits," NASA-CR-116873, 1971.
7. Fan, L. T., Hsu, F. T. and Hwang, C. L., "A Review on Mathematical Models of the Human Thermal System," *IEEE Trans. on Bio-Medical Eng.*, vol. BME-18, 1971, pp. 218-234.

6. Classification of the work into one or more of the following categories:
   a. Entire body
   b. Single element of body
   c. Localized temperature field in the tissue
   d. Body heat exchange with an external artificial device.

This table utilizes the original terminology used by each of the various investigators.

This compendium is hoped to serve the purpose of providing a quick reference to the many works done in the area of mathematical modeling of heat transfer and thermoregulation in mammals.

ANNOTATED REFERENCES

Articles and Reports

1. Atkins, A. R.
An Electrical Analogue of Heat Flow in the Human Body.
The South African Mechanical Engineer, vol. 13, 1963, pp. 40-46.

Author's Summary

The application of an analogue to the study of complex problems is becoming increasingly popular and appears to be reaching into all fields of science. An analogue may be defined as a model of the defining equations whose mode of behavior or response are identical with the system it is intended to be analogous to. The variables in each equation might belong to two completely different physical categories. The electrical analogue is the most widely used as its function may be represented by an electrical circuit diagram which assists in understanding the problem. Such a circuit is simple to construct if actual experimental data is required.

The study of man's thermal response is a subject of great importance today. The physiologist wishes to know how long a man might endure in some extreme climate such as outer space, the Antarctic or in a refinery. The problem is of particular interest to the mining industry where the ventilation engineer wishes to know how a man's work output is influenced by his climatic environment. The most economic form of ventilation may then be practiced.

The factors influencing the thermal response of a man are:

1. The type of work
2. The humidity
3. The wind velocity
4. The air temperature
5. The radiant wall temperature
6. The body size and weight
7. The amount and type of clothing

Insufficient knowledge is available of the physiological processes of heat flow and regulation in man for the physiologist to predict his response to changes in climatic conditions or of work rate. The body has an active control mechanism which helps to maintain regions within certain limits of temperature. There is still controversey on how the control system works. Until more is known, any predictions of thermal response will be limited.

The use of an electrical network as a physical model to aid the mathematical analysis was first suggested by MacDonald and Wyndham. The authors suggested that a simple thermal model should first be derived then this simulated with an electrical analogue or analogue computer. Similar work is being done

in the USA by both analogue and digital computers.

One must simulate the average transient and steady-state conditions with a working model. The control characteristics of the model must be capable of adjustment so that it can eventually be made to behave in a similar manner to the average thermal conditions of the body.

2. Atkins, A. R. and Wyndham, C. H.
A Study of Temperature in the Human Body with the Aid of an Analogue Computer.
Pflügers Arch., vol. 307, 1969, pp. 104-119.

Shortened Authors' Summary

To be able to predict man's thermal response to any given environment it is essential to have a thorough understanding of man's thermoregulatory mechanism. The mechanism is dependent on a number of highly non-linear variable. An analogue computer can be of great value with such a problem as non-linear control characteristics are easily incorporated into its behavior. This paper describes the application of such a computer. A number of tests were made to study some thermal control characteristics and the results are compared with those of a series of experiments performed on two resting subjects who were exposed to various environmental conditions in a climatic chamber.

Shortened Authors' Discussion

The experimental results were used as a guide for testing the various control characteristics and the experience gained may be summarized as follows:

a. The control of sweat rate by an internal temperature is the most important and powerful mechanism for stabilizing the internal body temperature in warm environments.

b. The location of the control reference source is not critical for resting conditions though the arterial temperature produced the most favorable results.

c. Skin temperature does not play an important part in controlling sweat rate in warm resting conditions. The influence of skin temperature in the case of a working subject obtaining a high core temperature in a cold environment has not been considered and must not be overlooked.

d. Surface blood flow control, which saturates at a moderate ambient temperature, does not change the core temperature of a resting subject significantly. Its main function is to increase the skin temperature and, therefore, reduce the heat load on the body.

e. Blood flow control is initiated mainly by the core temperature.

f. In a mild cold environment, blood flow is the only form of control. Skin temperature initiates an immediate change in blood flow thus stabilizing the core temperature for the first hour. The internal temperature control predominates at a later stage and has a lasting effect on control. Steady state is reached only after about five hours.

3. Beckman, W. A., Mitchell, J. W. and Porter, W. P.
Thermal Model for Prediction of a Desert Iguana's Daily and Seasonal Behavior.
ASME PAPER #71-WA/HT-35, 1971.

Authors' Abstract

A mathematical description of the transient thermal response of the desert iguana, *Dipsosaurus dorsalis*, to environmental changes is developed. A lizard model was combined with a desert micrometeorological model, and the combination was used to predict the lizard's diurnal and seasonal thermoregulatory behavior. The model analysis is sufficiently general so that it can be used to predict the thermoregulatory behavior of other species of lizards.

4. Barker, R. S.
Status Report Biothermal Man Fortran Program
Douglas Missile and Space Systems Div., 1966.

Shortened Author's Introduction

This document presents an informal discussion of the status of the Douglas Aircraft Company's Biothermal Man Fortran Program. This program is being developed in order to achieve an analytical tool capable of predicting steady state and transient thermal conditions for people. The computation of these conditions for astronauts is emphasized. To accomplish this task the thermal characteristics of space suits have been included, as a option, in the mathematical model. At the present time, gaseous cooling only is involved in the mathematical relationships used for the suit coolant. Two different coolant distribution systems, representative of present space suit design configurations, are provided as options in the program.

The mathematical model for the man consists of individual "zones" which are sub-divided into discrete lumped thermal capacitance "nodes." For example, the torso zone consists of skin, subcutaneous, muscle, and core nodes. These nodes are currently geometrically represented as rectangular layers. Within an individual zone heat is considered to flow radially outward from the core node through the muscle and subcutaneous nodes to the skin node. In addition heat flows between core nodes from adjacent zones. Variations in these internal heat flow rates due to variations in blood flow rates (vasomotor effects) are approximated by assigning appropriate temperature and metabolic rate dependencies for the intra-nodal thermal conductances.

It is anticipated that future development of the program will include incorporating additional conductance connections between various nodes. These connections will be used to represent thermal characteristics of the circulatory system other than those presently accounted for.

The total metabolic heat rate is distributed among appropriate nodes. Respiratory heat losses due to sensible heat transferred and water transferred are assigned to the torso core node. Sweat rates are normally considered to be dependent upon skin temperatures and core or intracranial temperatures. Simultaneous heat and water vapor transfer rates at the skin are computed.

5. Brown, A. C.
Analog Computer Simulation of Temperature Regulation in Man.
Report No. AMRL-TDR-63-116, 1963.

Author's Abstract

The objectives of this study were (1) to derive the mathematical equations describing heat distribution and temperature regulation in man; (2) to solve these equations by the use of an electronic analog computer; (3) to use the computer to predict the response of a human to cold water immersion and to check the predictions against experimental data.

The mathematical equations for temperature distribution were derived from the physical principles describing heat flux; first in the form of integral equations and the corresponding vector differential equations appropriate for electronic simulation. From these equations, a model of the body was constructed involving four concentric thermal elements. The equations describing the behavior of the thermal elements were simulated electronically. Feedback loops representing the analog of control of metabolism and vasomotor state were introduced into the model, simulating the human temperature regulation system. Solutions were generated by the computer under the specific condition of cold-water immersion, for varying clothing insulation and environmental (water) temperature. The computer predictions were found to be in relatively good agreement with preliminary experimental work.

6. Brown, A. C.
Equations of Heat Distribution Within the Body.
Bull. of Math. Biophys., vol. 27, 1965, pp. 67-78

Author's Abstract

A vector integral equation describing heat distribution within the body has been derived. The factors considered are heat conduction, forced convection via the circulatory system, environmental exchange, metabolic heat production, and change in heat content. The vector partial differential equation and alternative forms incorporating boundary conditions were also developed. A different equation based on a first-order approximation to the fundamental equations was derived to form the basis of a model for heat distribution within the body. It has been shown that factors involving conduction and convection must be considered independently unless the temperature of the blood flowing from a region of the body is equal to the average temperature of the tissue in that region. If this relation between tissue and blood temperature does exist, only a single temperature from each element is needed to describe the heat distribution. In this latter case, models which ascribe all heat transfer to "equivalent" conduction or to convection can give valid predictions.

7. Brown, A.C.
Further Development of the Biothermal Analog Computer.
Aero. Med. Res. Lab. Univ. of Washington, 1966, AMRL-TR-66-197.

Author's Abstract

An electronic analog computer, designed to enable calculation of the response of man to thermal stress, was developed. In accordance with equations previously developed (c.f. Technical Documentary Report AMRL-TDR-63-116), the computer circuits were used to simulate the physical distribution of heat within the body, the thermal stress imposed by the environment, and the physiological mechanisms of homeostatic feedback. Computer predictions were compared with experimental results from cyclic thermal stresses furnished by Lieutenant Colonel W. C. Kaufman, AMRL, and agreement was found to be good. The computer was used to calculate human response to wearing of an unventilated anti-exposure suit. The technical aspects of the computer circuits are presented in detail.

8. Buchberg, H. and Harrah, C. B.
Conduction Cooling of the Human Body - a Biothermal Analysis.
Thermal Problems in Biotechnology, ASME Symposium Series, 1968, pp. 82-95.

Authors' Abstract

Conduction cooling of the human body may be considered as a substitutive thermoregulatory technique. A significant improvement has been made in the analytical bases for predicting coolant system-operating requirements to satisfy body thermoneutrality, taking account of the two-dimensional heat transfer effects propagated in both the coolant tube and body from the line of contact. The conduction equations, representing the biothermal system as a multilayered slab, were solved by the finite difference method of successive point over-relaxation. A conductive liquid analog was constructed to determine the shape factor for conduction from a limited skin contact area through the coolant tube wall. Inlet coolant temperature requirements satisfying both the bio-thermal and coolant tube analyses were determined, and its sensitivity to coolant heat capacity rate and contact area was tested. The analytical results compared well with human calorimetric data making possible improved parametric design studies and optimization.

9. Buettner, K.
Effects of Extreme Heat on Man. II. Analysis of Temperature Changes Caused by Different Kinds of Heat Application to the Skin.
USAF School of Aviation Medicine, 1951, Project No. 21-26-002.

Author's Summary

The temperature change of skin, suddenly heated or cooled, is subject to the

physical laws of heat conduction and heat transfer. Calculations reveal the temperature increase upon application of nonpenetrating constant heat, penetrating radiant heat, Newtonian and contact heat and heating through a protective layer. The temperature fall after heat application can also be predicted. Causation of burns is subject to the law of rate processes and can be predicted from the temperature curves.

10. Buettner, K.
Effects of Extreme Heat and Cold on Human Skin. I. Analysis of Temperature Changes Caused by Different Kinds of Heat Application.
J. Appl. Physiol., vol. 3, 1951, pp. 691-702.

Author's Abstract

Even though we have an excellent knowledge of skin temperature during its steady or semi-steady rate, very little data can be found in the literature on fast-changing skin temperatures as they occur while heat or cold of extreme degree is applied. These fast changes, however, could be exploited as research tools in physiology and in pathology (burns). In the following discussion, let us define extreme heat as an influx of heat into man with such an intensity that temperatures of the skin never reach a steady state until all safety limits are exceeded. In ordinary language, extreme heat results from the effects of flames, glowing materials, atom bombs etc.; and, as an example of the opposite, a wind of 20 miles an hour and of -40°C, hitting the bare face, results in extreme cold.

In 1944, experiments on nonpenetrating radiant heat were begun, since severe injuries were frequently caused by this type of heat. After large air raids many adjacent city blocks were afire simultaneously. This required residents, as well as fire fighters, to expose themselves to radiant heat whose magnitudes reached 0.1 cal. per cm^2 sec. for prolonged periods of time. This kind of injury was far more frequent than that caused by the hot air of the flame.

Under certain specified conditions of heat exposure, the increase in skin temperature can be expressed mathematically as a function of depth, incoming heat and time.

The aim of these calculations is threefold: 1) to establish standard dose data relative to how the production of traumata depends upon the various conditions of exposure to heat; 2) to utilize this knowledge to predict the effectiveness of protective devices; and 3) to use the radiation-temperature-time relationship for the determination of the heat conductivity of the upper skin.

Most of the following mathematical deductions are scattered through nonmedical literature, but some of them are original. To those readers who are not familiar with the mathematical language it may be sufficient to know that fast-changing skin temperatures can be precalculated. The tendency to treat these quick responses as a kind of semi-steady state, constitutes an oversimplification of the problem.

11. Buriss, W. L., Lin, S. H. and Berenson, P. J.
Study of the Thermal Process for Man-in-Space.
NASA-CR-216, 1965.

Authors' Abstract

Thermal control of the human body is analyzed for the environments obtained in spacecraft shirtsleeve cabins and extravehicular pressure suits to provide environmental design criteria applicable to extraterrestrial missions. Basic heat and mass transfer correlations are used to extablish dependence of the thermal processes and comfort criteria on atmospheric pressure and composition, gravity, ventilating velocity, gas temperature, humidity, and mean radiant temperature. The thermal and comfort criteria are analyzed for the lunar and zero-gravity shirtsleeve cabins. Extravehicular suit thermal control methods employing ventilation cooling, liquid-loop cooling, and radiation cooling are analyzed to determine the relative performance, limitations, and problems associated with various methods of extravehicular suit thermal control. Extravehicular suit heat balances are performed for earth orbital, lunar orbital, Mars orbital, lunar plane, and lunar crater environments.

12. Burton, A. C.
The Application of the Theory of Heat Flow to the Study of Energy Metabolism.
Jour. of Nutrition, vol. 7, 1934, pp. 497-533.

Author's Summary

The fundamental law of heat flow demands that there be an internal "physiological" gradient of temperature from the interior of the body to an area of surface as well as an external physical gradient from that surface to the surroundings. The laws governing flow of heat down these gradients are considered. Newton's law applies to the loss of heat from the skin by convection, radiation and conduction, the loss by evaporation being considered separately. The application of the laws of conduction to the transport of heat through the underlying tissues to the skin is shown and the conclusion is reached that the distribution of temperature with depth will be in general, as it has been found, parabolic. A "thermal circulation index" is defined by which from measurements of skin temperature, changes in the properties of heat transfer of the tissues may be studied. Examples of such changes are given. The dependence of the skin temperature upon internal temperature, upon environmental temperature, and upon the circulation is deduced.

On the assumption that there is thermal "similarity," i.e., that the factor of absolute size is the only variable in growth, a relation is deduced for the variation of metabolism per unit area with increasing weight. Comparison with the "age curves" of metabolism in humans shows that the eventual decrease from an early maximum to the adult level is consistent with an increase in absolute amount of the thermal insulation, its relative amount remaining constant. From birth to the maximum at 1 1/2 years, however, there

must be a progressive decrease in the relative amount or in the effectiveness of the insulation.

The trends of metabolism per unit area in other species are discussed and conclusions are drawn as to the interpretation of the surface area law in view of the fact that the body temperature, the thermal properties of the tissues, and the thermal activity of the body are interdependent.

13. Chan, A., Sigelmann, R. A., Guy A. W. and Lehman, J. F.
Calculation of Temperature Distribution in Layered Tissues due to Distributed Thermal Sources by Finite Difference Method.
Proc. 22nd. Conf. on Eng. in Medicine & Biology, 1969, pp. 27.3.

Shortened Authors' Abstract

In this paper, the problem of obtaining the temperature distribution is mathematically formulated and solved numerically by the method of finite differences. The diffusion equation with a distributed source, satisfied by the temperature function T(x,t) is

$$\frac{\partial^2 T_i}{\partial x^2} - \frac{1}{\kappa_i}\frac{\partial T_i}{\partial t} = -\frac{H_i(x)}{\kappa_i}\ ; \qquad i = 1,2,3 \qquad (1)$$

where κ = diffusion constant = $k/c\rho$
k = thermal conductivity
c = specific heat
ρ = density

The subscript i indicates the i^{th} layer of the media. In this case, the media are assumed to be infinite along the y and z axes in a rectangular coordinate system and the boundaries separating the two media are assumed to be plane interfaces perpendicular to the x axis. The temperature must be continuous across the boundaries in order to properly satisfy the boundary conditions.

14. Chato, J. C.
A Method for the Measurement of the Thermal Properties of Biological Materials.
Thermal Problems in Biotechnology, ASME Symposium Series, 1968, pp. 16-25.

Author's Abstract

A transient method was developed for the measurement of thermal properties

biological materials. The materials suitable for this technique must be silient enough to close tightly around the measuring probe after it has been serted with the aid of a hypodermic needle. The system requires only a single, all probe and, consequently, the tissue is only minimally disturbed. Once the obe is in place, the duration of a test can be less than two minutes.

The theoretical analysis indicated the possibility of measuring the thermal nductivity, k, the thermal inertia, $k\rho c_p$, and the blood flow rate, w. The perimental study, however, was restricted to the measurement of the thermal nductivity alone within an estimated 20 percent error. It is expected that e measurements can be improved and extended by the use of calibrating materials th more accurately known properties than those available for this study.

. Chato, J. C.
Heat Transfer in Bioengineering.
Advanced Heat Transfer, B.T. Chao ed., Univ. of Ill. Press, 1969, pp. 395-414.

Author's Abstract

veral aspects of heat transfer problems related to biology are explored imarily from the engineering viewpoint. The discussion is divided into four ctions: (1) instrumentation and equipment, (2) internal heat transfer,) external heat transfer, and (4) miscellaneous heat transfer problems. A sting of thermal conductivity and diffusivity data on biological materials given in the Appendix.

. Chato, J. C. and Hertig, B. A.
Thermal Behavior of Biological Media.
AIAA Paper No. 70-813, 1970.

Authors' Abstract

is paper deals with some of the thermal problems related to living stems, particularly man, wherein maintenance of nearly constant internal mperature under widely varying conditions is essential.

First, the physiology of temperature regulation is reviewed to present ckground for "engineering models."

Second, steady state, distributed-parameter models are developed to scribe energy transport phenomena occurring within the tissue and also tween the skin surface and the immediate environment, such as cooling bes in space suits.

Third, models of transient behavior of the entire body are described. ese are basically of the lumped-element type, with each element representing me arbitrary portion of the body.

17. Chato, J. C. and Shitzer, A.
On the Dimensionless Parameters Associated with Heat Transport within Living Tissue.
Aerospace Medicine, 1970, pp. 390-393.

Authors' Abstract

A biothermal model of living tissue has been studied. This model included both internal heat generation and blood flow effects. Based on analytical considerations, three dimensionless groups which have significant effects on the steady state heat transfer in the living human body emerged. From the scant experimental data available, one of the groups, $\{[(Q_o Ab)/(Q_m)][w_b C_b)/k]^{-1/2}/b\}$, appeared to be constant at 0.2. The results indicated also that at high metabolic heat production rates the maximum temperature within the body would occur in the skeletal muscle at a depth which depended on the blood perfusion rate but was independent of deep body temperature.

18. Chato, J. C. and Shitzer, A.
Thermal Modeling of the Human Body--Further Solutions of the Steady-State Heat Equation.
AIAA Journal, vol. 9, 1971, pp. 865-869.

Authors' Abstract

The thermal behavior of the human body has been modeled with particular emphasis on direct cooling of the skin by cooling tubes used in current extravehicular activity (EVA) space suits. Steady-state analytical solutions have been obtained for several boundary conditions and for various values of the parameters involved. Although the results provide insight into the problem and even compare acceptably with some of the scant previous investigations, much more work is needed both analytically and, especially, experimentally before the numerical results can be considered reliable for biological purposes. The analysis presented herein is, nevertheless, applicable to any steady-state heat conduction problem in rectangular bodies with internal heat generation.

19. Collins, J. C., Pilkington, T. C. and Schmidt-Nielsen, K.
A Model of Respiratory Heat Transfer in a Small Mammal.
Biophysical Journal, vol. 11, 1971, pp. 886-914.

Authors' Abstract

A steady-state model of the heat and water transfer occurring in the upper respiratory tract of the kangaroo rat, *Dipodomys Spectabilis*, is developed and tested. The model is described by a steady-state energy balance equation in which the rate of energy transfer from a liquid stream (representing the flow of heat and blood from the body core to the nasal region) is equated with the rate of energy transfer by thermal conduction from the nose tip to the environment. All of the variables in the equation except the flow rate of the liquid stream can be either measured directly or estimated from physiological measurements, permitting the solution of the equation for the liquid stream flow rate. After solving for the liquid stream flow rate by using data from three animals, the energy balance equation is used to compute values of energy transfer, expired air temperature, rates of water loss, and efficiency of vapor recovery for a variety of ambient conditions. These computed values are compared with values measured or estimated from physiological measurements on the same three animals, and the equation is thus shown to be internally consistent. To evaluate the model's predictive value, calculated expired air temperatures are compared with measured expired air temperatures of eight additional animals. Finally, the model is used to examine the general dependence of expired air temperature, of rates of water loss, and of efficiency of vapor recovery on ambient conditions.

20. Cooper, T. E. and Trezek, G. J.
A Probe Technique for Determining the Thermal Conductivity of Tissue.
ASME Paper No. 70-WA/HT-18, 1970.

Authors' Abstract

A small "needle" like probe has been developed for determination of the thermal conductivity of either *in vitro* or *in vivo* tissue. The distinguishing characteristic of this probe is that, when it is suddenly embedded into a medium at a different temperature, the duration of its temperature time response is such that it can be related to the thermal properties of the medium. This is accomplished by a match with an analytically determined response curve which accounts for metabolic heat generation, blood flow, and conductive effects. Initially, the probe technique was used to determine the thermal conductivity of a 1 percent agar-water mixture and the results were within 5 percent of water. Subsequently, experimental thermal conductivity data were obtained on the following *in vitro* human organs: liver, kidney, heart, spleen, whole brain, brain gray matter, and brain white matter. *In vivo* conductivity data have been obtained recently for canine liver with and without blood flow. These data indicate that the *in vivo* value without blood flow is approximately the same as the *in vitro* value after the organ had been removed and refrigerated for 24 hours. Blood flow, if not considered, resulted in apparent conductivities which were 15 to 25 percent higher than that of the tissue.

21. Crosbie, R. J., Hardy, J. D. and Fessenden, E.
Electrical Analog Simulation of Temperature Regulation in Man.
Temp., Its Measurement and Control in Science and Industry, J.D. Hardy ed., vol. 3, 1963, pp. 627-636.

Authors' Summary

Using the basic equations for heat balance which have been developed to take into account heat losses by radiation, convection, and evaporation, an electrical analog has been constructed to simulate the physiological responses to heat and cold in the nude man. As has been previously shown, physiologic temperature regulation involves three of the basic types of control modes, namely, proportional control, rate control, and some of the characteristics of on-off control. The rate and proportionality constants have been determined experimentally on the assumption that the regulated temperature is the average body temperature. Time constants for the various thermal changes can be determined from the thermal constants of tissue and the response times of the physiological variables of sweating, vasomotor activity, and change in metabolic rate. The simulator predicts steady-state situations of rectal temperature, skin temperature, metabolic rate, vasomotor state, and evaporative heat loss under both resting conditions and exercise. Dynamic responses to sudden shifts in environmental temperature, air velocity, relative humidity, and metabolic rate can be simulated to a considerable extent using equations based on the controls outlined in the foregoing.

22. Dussan, B. I. and Weiner, R. I.
Study of Burn Hazard in Human Tissue and its Implication on Consumer Product Design.
ASME Paper 72-WA/HT-39, 1971.

Authors' Abstract

This paper recalls the medical definitions of first, second, and third degree burns of human tissue and presents an analytical solution to the burn hazard problem inherent in the event of tissue contact with a relatively hot solid. The results are given in terms of tissue depth, biophysical properties, and initial conditions, all of which are expressed in parametric form. The rate of damage (dependent on tissue temperature and its biophysical properties) relates tissue damage to temperature. The importance of this work is evident in its application to sophisticated design problems involving potential burn hazards of various consumer products. It allows accurate assessment of the magnitude of the hazard and its abatement as a function of modification in geometry and materials.

23. Eberhart, R. C., Jackson, M. and Trezek, G. J.
Application of Bio-Heat-Transfer Model to Determine Regional Blood Flow Rate.
ASME Paper 71-WA-HT-38, 1971.

Authors' Abstract

The temporal patterns of central and skin temperature may provide important predictive and diagnostic information during the recovery period from major surgery. Experimentally it is found that large changes in toe temperature occur at a predictable time, early in the postoperative period. These changes reflect cardiovascular dynamics and are related to modern concepts of thermoregulation. In order to explore the contribution of time-varying blood flow to heat transfer a bio-heat-transfer model was applied to the great toe. This model allowed prediction of toe blood flow rate from measurements of the central and skin temperatures. Experimental verification of the analytically determined blood flow rates was made using a modified technique of venous occlusion plethysmography.

24. Fan, L. T., Hsu, F. T. and Hwang, C. L.
Steady State Simulation of the Human Thermal System.
Proc. of the 23rd Conf. on Eng. in Med. & Biol., vol. 12, 1970, p. 79.

Authors' Abstract

Steady-state simulations of the human thermal system with and without an external thermal regulation device are carried out. The mathematical model of the human thermal system without the external thermal regulation device is essentially the model by Wissler. The model with the regulation device is obtained by modifying Wissler's model. The thermal regulation device is controlled in such a way that the requirements of the thermoneutrality of the human body under the specific environmental condition and specific body activity are satisfied. The effects of localized control of the external thermal regulation device on the totality of the human thermal system are examined. The results indicate that the thermoneutrality of the human body can be attained through the partial cooling or warming of the body.

25. Gautherie, M.
Analog Studies on the Mechanisms and Factors of the Phenomenon of Periodic Oscillation of Cutaneous Temperatures of the Fingers' Skin.
Acta Electronica, vol. 12. 1969, pp. 313-338.

Author's Summary (Translated)

In humans, cutaneous temperatures of the fingers vary periodically with

time; the mean values of the period and the amplitude of the oscillations being 1 min. and 1°C, respectively. The author, who reported the observation of this phenomenon in a previous paper, is studying here the mechanism and factors, utilizing infrared thermometry. It seemed at first that the origin of the oscillations was the periodical variations at the frequency of the influx of nerves in the orthosympathetic vasoconstrictors. Later, as a result of diverse physiologic observations and a model consisting of an oscillator and transistors, the effects and mode of action of other factors were analyzed, namely, blood perfusion rate, blood temperature, chemical agents causing vasoconstriction and vasodilatation, age and the ambient temperature. Finally, a cybernetic scheme is proposed which provides evidence on two important factors: on the one hand, the existence of a negative feedback that allows to envisage the spontaneousness of the oscillations; and on the other hand, an action of the ambient termperature on the feedback loop that makes the phenomenon resemble a servomechanism possessing the role of a contributor that regulates the flow of heat in the fingers between 6.5 and 36 deg. C.

26. Gros, C. and Gautherie, M.
Investigation by Infrared Thermometry of the Evolution in the Course of Time of Human Skin Temperature as a Function of Ambient Temperature. Idea of Cutaneous Thermal Adaptance.
Rev. Franc. Etudes Cliniques et Biol., vol. 13, 1968, pp. 697-703.

Authors' Abstract (Translated)

The evolution during time of the temperature of human skin when exposed to cold has been measured by infrared thermometry for different regions of the body surface. By means of a simplified model of the heat exchanges between the organism and the surroundings, a mathematical law has been derived which gives a satisfactory representation of the experimental results and the idea of cutaneous thermal adaptance was formulated. The conclusions are especially important for clinical application of infrared thermography and the study of thermoregulating mechanisms.

27. Harrah, C. B. and Buchberg, H.
Prediction of the Skin Temperature Distribution and Gross Body Conductance for Conduction Cooling of the Human Body.
Proceedings of the Symposium on Individual Cooling, 1969, pp. 92-100.

Authors' Abstract

The prediction of the skin temperature distribution and gross body conductance are compared with calorimetric data for the case of conduction cooling of the human body by means of a network of coolant tubes. Thermoneutrality was assumed and account was taken of the two-dimensional heat transfer effects propagated in both the coolant tube and body from the area of contact. The conduction equations representing the biothermal system as a multilayered slab were solved by the finite difference method of successive point over-relaxation. Conduction in the coolant tube making limited contact with the skin was estimated by determining the appropriate conduction shape factor as a function of an effective contact area factor. An order of magnitude estimate of the net radiation loss from the skin indicated that it was reasonable to neglect radiation exchange in the original model.

28. Henriques, F. C. and Moritz, A. R.
Studies of Thermal Injury.
I. The Conduction of Heat to and Through Skin and the Temperatures Attained therein. A Theoretical and an Experimental Investigation.
Am. J. of Pathology, vol. 23, 1947, pp. 531-549.

Authors' Summary

The various physical factors which determine the transfer of heat energy to and through the skin and the temperatures attained thereby have been defined and discussed. A general theory of heat flow, which enabled the estimation of the time-temperature relationships within the epidermis during exposure to heat, was developed.

The thermal conductivities and heat capacities of epidermis, dermis, and subcutaneous fat and muscle were measured *in vitro*.

Experimental observations pertaining to the rate at which thermal energy is taken up by the skin, during surface exposures of varying intensity, and the sub-surface thermal gradients established therein have been presented.

The time-temperature relationship at the dermal-epidermal junction was computed under two greatly different experimental conditions: (*i*) when the skin surface temperature was immediately brought to, and maintained at, the temperature of the heat source, and (ii) when the entire skin surface was exposed to specified circumambient and circumradiant temperatures. These data indicate the extreme importance of the mode of applying heat to the skin surface in the time-temperature relationships within the epidermis.

29. Herrington, L. P.
The Biotechnical Problem of the Human Body as a Heat Exchanger.
ASME Transactions, vol. 80, 1958, pp. 343-346.

Shortened Author's Summary

Engineering-design problems now frequently involve a man-machine problem in which design is affected by human tolerance to cold or heat stress. Special physical features of these environments frequently render the conventional data of thermal-engineering rules inapplicable. It has been shown in this paper that a large body of calorimetric data on the human heat exchanger can be summarized in statistically derived empirical equations in five variables. Such equations when applied within the ranges indicated greatly reduce the labor of computation, and to a large degree obviate the need for special physiological knowledge required of the engineer who would make such computations from the classical equations of heat loss.

30. Herrington, L. P.
Full-Scale Human Body-Model Thermal Exchange Compared with Equational Condensations of Human Calorimetric Data.
ASME J. of Heat Transfer, vol. 81, 1959, pp. 187-194.

Author's Shortened Introduction

The current report will extend this analysis with respect to four principal topics:

1. The comparisons of data obtained with electrically heated body models as instruments of measurement with the heat exchange indicated by a linear differential equation for human subjects in the calorimeter.
2. The comparison of the original observed calorimeter data on human subjects with the heat exchange indicated by the equational derivation.
3. The presentation of four new equations representing the response of different segments of the human body to internal and ambient factors affecting heat exchange, and an indication of their use in man-machine problems of heat tolerance prediction.
4. A report of the extension of this study to instrumentally recorded data of the human calorimeter in the region above 80 deg. F. in which thermally provoked evaporative regulation results in an empirically derived linear differential expression of distinctly different coefficients.

Author's Shortened Summary

The purpose of this paper may be summarized as follows:

(a) One of these aims has been achieved by condensing calorimetric data on seated, clothed human subjects into linear differential equations which permit the bio-engineer to quickly approximate the effect of complex air and radiant temperatures on the human element of a man-machine design problem.
(b) These aims have been accomplished for a range of thermal loads typical of the region from 40 to 80 F., and separately by reason of different human temperature regulation characteristics, for the range from 80 to 105 F.
(c) Static heat exchangers--an electrically heated model of the human body and a hemispherically capped cylinder--have been used to establish an experimental connection between the heat-exchange properties of these inani-

mate bodies and linear differential equations which generalize the thermal interchange of the human body as observed in a calorimeter environment.

31. Hsu, F. T., Fan, L. T. and Hwang, C. L.
Unsteady-State Simulation of the Human Thermal System.
Proc. of the 23rd Conf. on Eng. in Med. and Biol., vol. 12, 1970, p. 80.

Authors' Abstract

Unsteady-state simulations of the human thermal system with and without an external thermal regulation device are carried out. The mathematical model of the human thermal system without the external thermal regulation device is essentially the model by Wissler. The model with the regulation device is obtained by modifying Wissler's model. The thermal regulation device is controlled in such a way that the requirements of the thermoneutrality of the human body at any moment during the transient period are satisfied. The effects of localized control of the external thermal regulation device on the totality of the human thermal system are examined. The results indicate that the thermoneutrality of the human body can be attained through the partial cooling or warming of the body.

32. Hsu, F. T., Fan, L. T., and Hwang, C. L.
Steady-State Simulations of the Human Thermal System.
Institute for Sys. Design & Optimization, Kansas State Univ., Report No. 23, 1970.

Authors' Abstract

A mathematical model of the human thermal system under steady state conditions is formulated by using six cylindrical elements representing longitudinal segments of the head, torso, arms, and legs to approximate the human body. The model allows the use of different physiological parameters such as local rate of metabolic heat generation and local blood flow rate in various locations of an element. The regional variations of the physiological parameters are also taken into consideration.

A set of ordinary differential equations representing the thermal behavior of all elements are approximated by a set of algebraic equations which resulted from the application of the explicit forward finite difference method. Specifically twenty-eight linear algebraic simultaneous equations are obtained by using five grid points in the special coordinate of each element. The model is then simulated for a number of steady state environmental conditions.

33. Iberall, A. S.
Human Body as an Inconstant Heat Source and its Relations to Clothes Insulation. Part I — Descriptive Models of the Heat Source.
Trans. of the ASME/Journal of Basic Eng., vol. 81, 1960, pp. 96-102.

Author's Abstract

A precise characterization of the thermal resistance of clothes requires an accurate description of the static and dynamic thermal characteristics of the human-heat source. Experimental measurements on the human have revealed a frequency spectrum of sustained thermal power oscillations that mask theoretical long-time equilibrium adjustments. This points to the number of degrees of freedom that must be involved in the thermoregulation of the human, and the specific nonlinear characteristics of the system. Therefore, at best, a resistance model for clothes is possible only as an ohmic relation among time-averaged equilibrium values, and for a specific mode of operation of the system. The validity of this hypothesis, however, has not been proved.

34. Kandror, I. S.
A Possible Approach to Simulation of the Human Organism's Thermoregulatory System.
Izdatel'stvo Nauka, 1969, pp. 35-42.

Author's Abstract (Translated)

Description of a mathematical scheme for modeling the human thermoregulatory system. From the viewpoint of automatic control theory, thermal control is accomplished by a complex multiloop nonlinear system with two negative feedback loops (chemical and physical thermal regulation) and one positive (parametric) feedback loop. The transfer of information throughout the entire network entails both neuroflex and humoral factors.

35. Keller, K. H. and Seiler, L. Jr.
An Analysis of Peripheral Heat Transfer in Man.
J. Appl., Physiol. vol. 30, 1971, pp. 779-786.

Authors' Abstract

A one-dimensional steady-state continuum model for heat transfer through the tissue of peripheral regions is presented combining the effects of tissue conduction, convection by blood flow, vascular heat exchange, and tissue metabolism. The effective conductivity of the nonisothermal region is determined under various flow conditions. The results are presented graphically and compared with existing data. It is shown that the minimum effective conductivity is the thermal conductivity of the tissue and the maximum is the geometric mean of the conductivity and the capillary perfusion rate. A method

for estimating the reduction in effective conductivity due to arterial precooling from anatomical considerations is discussed.

36. Layne, R. S. and Barker, R. S.
Digital Computer Simulation of the Biothermal Man.
Douglas Missile and Space Systems Division, Paper No. 3369, 1965

Authors' Abstract

At the present time an inadequately defined portion of the digital computer simulation of the thermal characteristics of manned space flight is the simulation of man's thermal properties, thermoregulatory mechanisms and thermal interrelations with his environment. This paper describes a flexible one-dimensional biothermal digital computer model that is intended to partially solve this problem. It also describes the theoretical considerations, using the latest theories and experimental data that are needed to construct this model or similar models.

Much of the theoretical discussion concerns man's thermoregulatory mechanisms, that is, the servo-mechanism by which man attempts to maintain constant skin and internal body temperatures. These include perspiration, metabolism, and vasomotor action. These mechanisms are quantitatively described and put into the form of tables or equations to be used in the computer program. Appropriate empirical constants were modified in order to fit the output of the computer program to existing test data.

The model consists of 25 discrete nodes, each with a lumped thermal capacitance. Man himself consists of 4 nodes representing, respectively, skin, subcutaneous tissue, muscles and the so-called thermal core. The equations relating conduction, convection and radiation heat transfer between nodes and heat storage in the nodes are solved by the forward finite difference approximation method.

37. Lee, W. K.
Distributed-Parameter Model for Passive Thermal Behavior of a Cooling Biological System.
Univ. of Missouri, Columbia, Dept. of Chem. Eng., 1970

Author's Conclusions

A distributed-parameter model for a passive heat exchange mechanisms of the marmot entering hibernation was formulated from the lumped-parameter model. Three nonlinear partial differential equations were solved numerically by employing the Crank-Nicolson implicit method for a finite-difference approximation.

It was suggested that significantly different cooling curves might be obtained if a more accurate representation of the temperature profiles were used. Faster cooling rates were obtained from the distributed model under the assumption such that temperature at the center of the core is a brain temperature. If more physiological data are available, a distributed-parameter model could represent the more accurate temperature profile, and be of further value to studies of thermal regulation during hibernation.

One parameter was changed in order to obtain a good fit to the experimental values.

38. Love, T. J., Haberman, J. D., Francis, J. E.
A Comparison of Predicted Skin Temperatures with Thermographic Measurements.
Tempt. It's Measurement and Control, 1971.

Authors' Abstract

A simple one dimensional model is applied with modified boundary conditions to predict skin temperatures of the thorax. A solution of the modeling differential equation is presented in terms of the dimensionless variables such that the thermographic practitioner may utilize the curves to predict skin temperatures or to utilize skin temperature measurements as a method of estimating physiological variables.

A series of thermograms showing calibrated isotherms on the anterior female thorax is presented along with predicted temperatures based on estimated tissue properties, blood perfusion rates and metabolic heating.

A factor which accounts for reduced radiation and convection is used to modify the Biot number and thus yields elevated skin temperatures observed in the inframammary fold and axillary.

39. Luecke, R. H., Gray, E. W., and South, F. E.
Simulation of Passive Thermal Behavior of a Cooling Biological System: Entry into Hibernation.
Pflügers Archiv. vol. 327, 1971, pp. 37-52.

Authors' Summary

A mathematical model is developed which describes the dynamic generation and transfer of heat in the marmot at normothermic to hibernating body temperatures. Since the animal approximates a ball as it enters hibernation, the form of the model was a sphere divided into three concentric layers - central core, muscle and skin. Each layer was assumed homogeneous in composition but distributed with respect to temperature. Both conductive and convective heat exchange were considered - conductive heat exchange occurring radially through the layers and convective *via* the blood flow. Separate relationships between temperature and metabolism were used for heat generation in the different layers. The non-linear partial differential equations describing heat

exchange between layers were solved numerically on the IBM 360/50 computer. The temperatures computed from the model were compared with experimental temperatures of marmots entering hibernation. Using nominal values of the estimated parameters, the agreement between model and experimental temperatures was fair. To help improve the model, the principal parameters were varied to determine sensitivities. Changes in metabolic rates and blood flow had only small effects, but the model was quite sensitive to changes in the outer surface heat transfer coefficient and shape factor. A small *a posteriori* adjustment was made to the heat transfer coefficient which gave an excellent fit between computed and experimental dynamic temperature behavior.

40. Ma, Y. H., Rust, L. W., Larson, R. E. and Spano, L. A.
Mathematical Simulation of Simultaneous Energy and Mass Transfer Process in a Clothing-Airspace-Skin System.
Proc. Summer Compt. Simul. Conf. N. Y. Assn. for Computing Mach., vol. 2, 1970, pp. 859-867.

Authors' Summary

A mathematical model has been developed to describe the response of a fabric-skin system subjected to various environmental stresses. Computer results based on this model were obtained for an individual exercising at various metabolic rates under different environmental conditions.

It was found, for example, that after initiation of vigorous exercise (metabolic rate of 1500 Btu/hr) in humid conditions (relative humidity of 73.2%) the skin temperature of an individual rises to a maximum. This is followed by a slow decrease due to evaporative cooling and then a subsequent rise because of the excess heat generated by the heavy work. Effects of humidity as well as working load were also investigated.

41. Miles, J. B., Chambers, A. B. and Blackaby, J. R.
Computer Simulation of the Physiological Parameters Utilized in the Automatic Temperature Control of Liquid Cooled Garments.
Proc. Summer Computer Simulation Conference, 1972, p. 1129.

Authors' Abstract

A computer model has been developed for simulating human response to the application of automatically controlled skin cooling. The operation of the model has been compared with data collected in a recently completed experimental program.

During extravehicular activity (EVA) astronauts wear liquid cooled garments (LCGs) for the purpose of removing excess body heat. The garments fit snugly and the net-like fabric contains many small tubes through which is passed chilled water. During periods of high exercise the major portion of excess metabolic heat is removed by direct conduction of this chilled water.

Because of the overwhelming potential of this cooling system, careful control of the inlet water temperature is necessary. Currently this is accomplished by use of a three position manual valve which controls the amount of LCG water that is bypassed to the heat sink (a sublimator located atop the portable life support system). Making the control automatic would relieve the astronaut of this task as well as provide better thermal balance, since the astronaut may not be a good and responsive judge of his own thermal state. Under consideration in this study is an automatic temperature controller that will eliminate the need for manual control of the LCG inlet temperature by the astronauts. The control scheme calls for monitoring the astronaut's water loss (both sensible and insensible) by means of dewpoint sensors located in the outlet air ventilation line to the EVA pressure suit. As water loss rate increases, indicating an increase in exercise rate, the LCG temperature is lowered in order to remove more heat by conduction from the skin. The assumption behind this controller is that with increasing metabolic activity, an increasing water loss rate, within prescribed limits, is acceptable and even preferable for comfort.

This paper describes a computer simulation of the astronaut (a human thermal model), the LCG, the pressure suit, and the LCG automatic controller.

The principal elements in the computer simulation include: 1) a three-compartment (core, muscle, skin) biothermal model of man, featuring thermal control mechanisms of vasodilation, sweating, and shivering which are actuated by a signal derived from core and skin temperatures and metabolic rate as compared to a reference temperature; 2) the heat transfer between the man and both the LCG and the surrounding air contained in the pressure suit; 3) the mass transfer of water vapor to the air by sweating and respiration; 4) the rise in dewpoint of the outgoing ventilation air with respect to the incoming air; 5) the astronaut's water loss rate based on the dewpoint temperature and a knowledge of the ventilating air flow rate; 6) the LCG inlet water temperature as determined by the automatic controller. The various heat transfer coefficients, delay times, and rise times required in the computer simulations were calculated from data obtained in the previously mentioned test program.

Comparisons between simulation and actual experimental data are described. These comparisons have yielded valuable insight into the processes occurring in the experimental system, as well as providing confidence for using the computer model in predicting system performance under new conditions.

42. Mitchell, J. W. and Myers, G. E.
An Analytical Model of the Counter-Current Heat Exchange Phenomena.
Biophysical Journal, vol. 8, 1968, pp. 897-911.

Authors' Results and Conclusions

The following are the results of the analysis presented in this paper and the conclusions that can be drawn:

Nondimensional parameters governing counter-current heat exchange in extremities have been determined. The normalized temperatures are functions of normalized distance and, in general, three nondimensional conductances. These nondimensional conductances are the ratios of the heat transfer conductances between vessels, and between vessels and the environment, to the product of the blood flow rate and specific heat.

An analytical model for counter-current heat exchange has been formulated and solutions obtained. Graphical results are presented for two representative physiological systems. These results are valuable in delineating those situations in which counter-current heat transfer is important, and in quantitatively predicting the heat transfer and the temperature distributions. Performance parameters are also presented to aid in this evaluation.

The conductance between the vessels and the environment controls the heat loss from a limb. Tissue is a poor conductor of heat and the usual anatomical arrangement of vein and artery is not conducive to heat transfer. Significant counter-current heat exchange occurs only if the conductance between veins and arteries is high. In general, specialized anatomical structures (e.g., a rete) are needed in order to reduce heat loss through this mechanism.

Heat transfer calculations are presented for three physiological situations. The method of calculating the heat transfer conductances and the use of the theory are demonstrated.

The data currently available are insufficient for an adequate comparison with the theory developed in this paper. Additional experimentation, in which the quantities incorporated in this theory are measured, is needed in order to gain further insight into the counter-current mechanism.

The counter-current effect becomes more significant as the blood flow rate decreases. In terms of the parameters of this analysis, reduced blood flow increases the nondimensional conductance between the veins or arteries and the environment (N_o), the ratio of conductances (N_1/N_o) remaining the same. This effect has been noted by Scholander and Krog in their experiments with the sloth. Thus, the vasoconstriction response to cold serves to protect the animal in two ways. The blood flow rate in the limb, and, correspondingly, the total amount of thermal energy carried by the blood, is reduced. In addition, the venous return temperature is raised more than normally through counter-current heat exchange, further reducing the heat loss.

The use of a nondimensional temperature parameter allows generalizing the results for any ambient temperature. However, as previously noted, the effect of ambient temperature on the thermal control system of the animal may produce changes in blood flow rate, blood vessel diameter and blood flow distribution and must be accounted for.

The results of this analysis indicate that there is not a significant counter-current effect in the arm of a man or the fluke of a porpoise. The effect is shown to be significant in the sloth rete, however. Further experiments in which all of the important parameters are measured are needed to confirm or disprove these condlusions.

43. Mitchell, J. W., Galvez, T. L., Hengle, J., Myers, G. E. and Siebecker, K. L.
Thermal Response of Human Legs During Cooling.
J. Appl. Physiol., vol. 29, 1970, pp. 859-865.

Authors' Abstract

An analytical model is developed to predict temperature levels as a function of time in human legs during cooling. The model results are supported by tests on patients prior to leg amputations and on healthy subjects. The leg cools passively, with blood flow rate and leg diameter having a strong influence on the temperature levels and the time to cool, while metabolism, bone size, and leg length have insignificant effects. The time to cool a leg to essentially a steady-state condition is a function of diameter only, and given by t_{ss} (hr) = 0.2 d^2 ($inch^2$) = 310 d^2(m^2), where the units of the numerical constants are ($hr/inch^2$) and (hr/m^2), respectively.

44. Molnar, G. W., Hurley, M. J., Jr. and Ford, R.
Application of Newton's Law of Body Cooling.
Pflügers Arch., vol. 311, 1969, pp. 16-24.

Authors' Summary

Newton's law of cooling was used to analyze the fall in rectal temperature *post mortem* in 55 cases during refrigeration in a mortuary. As with solids of low thermal conductivity, there was an initial curvilinearity to the semilog plot lasting 1 to 11 hours (related to pelvic circumference) while the proper internal temperature distribution was becoming established. Thereafter, there was a linear trend representing a constant percent cooling rate r_1 which lasted up to 24 hours for adults. This was followed by a less steep trend of cooling rate r_2, which was 37% less than r_1. This diminution in cooling rate occurred when the rectal temperature fell below 10°C and was ascribed to a reduction in the thermal diffusivity of fat. r_1 had the highest correlation with pelvic circumference. For the nude body in still air r_1 = 15.6% to 18.4% ($T_r - T_a$)/hour for children, 3.8% to 9.4% for adults. Wind increased r_1; the decrease due to clothing was questionable because of the paucity of cases.

45. Molnar, G. W.
Analysis of the Rate of Digital Cooling.
Proc. Symp. Inter. de Thermoreg. Comp., 1971, pp. 350-352.

Author's Introduction

In a cold wind a finger cools rapidly to the freezing point. To correlate the elapsed time to freezing with the rate of cooling, it is necessary to have a numerical value for the rate. Since cooling proceeds with deceleration, rate cannot be expressed as a constant number of degrees/time. It is necessary to assume the applicability of Newton's law:

$$\ell n \frac{(T_s - T_a)t}{(T_s - T_a)_o} = -kt \qquad \text{Eq. 1}$$

T_s = skin temperature. t = time ℓn = natural log.

T_a = air temperature. o = zero time

-k is the slope of the linear trend of the semilog plot and is the cooling constant; it serves as the measure of the relative cooling rate. It can be converted to percent rate of change per unit of time by the equation:

$$r\ \%/t = [I - \text{antilog}\ (-k)] * 100 \qquad \text{Eq. 2}$$

Equation 1 holds only when heat conduction from center to surface is instantaneous as with a stirred liquid. For a solid with low conductivity the semilog trend is initially nonlinear; the subsequent linear part has a slope -k. If there is heat input, cooling proceeds to $T' = (T+ + \tau)$ and the plot of Equation 1 is non-linear. Ultimate linearization can be achieved by substituting T' (found by trial) for T_a. The slope is again -k as with no heat input.

46. Morgan, L. W., Collett, G. and Cook, D. W., Jr.
Computer Program Documentation Transient Metabolic Simulation Program. *Lockheed Electronics Company. Report No. LEC/672-22-08068,* 1970.

Authors' Abstract

This program consists of a 14-node model representing the thermoregulation system of the human body, and the shirt sleeve or suited environments of the body. Calculations are made of the transient thermal effects on the man by the various environments.

Modes of operation are: (1) shirt sleeve, (2) IVA suited (intravehicular activity), (3) EVA suited (extravehicular activity), (4) IVA suited with helmet off, (5) shirt sleeve with postlanding environmental conditions, (6) IVA suited with or without helmet, under postlanding conditions.

All modes may use the liquid-cooled garment option.

Input consists of metabolic and environmental data and mode selection. The output presents the thermal properties of the man and his environment at scheduled intervals. The output also represents the reaction of the astronaut to his environment and the effects of the astronaut on the environment.

47. Nevins, R. G. and Darwish, M. A.
Heat Transfer Through Subcutaneous Tissue as Heat Generating Porous Material.
Physiological and Behavioral Temp. Regulation, 1971, pp. 281-301.

Authors' Introduction

The study of heat transfer through porous materials has had important consequence in physical structures such as turbine blades, rocket nozzles and other devices which operate at high temperatures. The application of porous cooling theory to biological systems is new even though human body tissues have been considered as capillary porous material for over 300 years. The process of solid-fluid heat transfer in porous material is complex and is further complicated in biological tissue by heat generation within the material due to metabolic activity. Heat transfer takes place by (1) conduction and by (2) convection, the latter resulting from the flow of coolant (blood) through the porous structure and its temperature change. The former results from the temperature gradient and is dependent on a composite thermal conductivity (k) of the solid-fluid matrix.

In most physical systems, the fluid in the porous material flows counter to the heat flow. In this analysis, the fluid flows from the high temperature areas within the body to the surface thereby flowing in the same direction as the heat flow.

48. Pennes, H. H.
Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm.
J. Appl. Physiol., vol. 1, 1948, pp. 93-122.

Author's Abstract

Quantitative analysis of the relationship between arterial blood and tissue temperature has not been previously attempted. Bazett and McGlone's measurements of tissue temperature indicate that the deep thermal gradient in the resting normal human forearm does not extend deeper than 2.5 cm.; deeper measurements are not reported. According to recent observations in this laboratory, the temperature gradient in intact human biceps muscle extended beyond this depth to approach the geometrical axis of the limb as would be expected if the analytic theory of heat flow by conduction is applicable to a localized arm segment. With the stimulus of this observation, the temperatures of the normal human forearm tissues and brachial arterial blood have been measured to evaluate the applicability of heat flow theory to the forearm in basic terms of local rate of tissue heat production and volume flow of blood.

49. Perl, W.
Heat and Matter Distribution in Body Tissues and the Determination of Tissue Blood Flow by Local Clearance Methods.
J. Theoret. Biol., vol. 2, 1962, pp. 201-235.

Author's Abstract

Differential forms of Fick's perfusion principle are combined with the heat conduction and matter diffusion equations and a metabolic term to give partial differential equations for the distribution in space and time of heat and matter in living, perfused tissues at the millimeter level of observational detail. The theory is characterized by well-known parameters; local rate of blood flow per unit volume of tissue, diffusion, heat conduction and solubility coefficients of the substance of interest in the tissue, rate of production or consumption of the substance of interest per unit volume of tissue, and a venous exit parameter relating instantaneous concentrations in a volume element of tissue and in venous blood issuing from that volume element. The heat distribution case is illustrated by analyzing existing steady state (time independent) and transient (time dependent) data obtained by the Gibbs thermoelectric probe method for determining tissue blood flow. Fluctuation properties of capillary blood flow are used to help explain the steady state data. A possible general role of such fluctuations in tissue metabolic regulation is conjectured. Methods are given for analyzing the transient data to obtain tissue blood flow. The matter distribution case is illustrated by application to Kety's radioactive tracer local clearance method.

50. Perl, W.
An Extension of the Diffusion Equation to Include Clearance by Capillary Blood Flow.
Ann. of the N. Y. Academy of Sciences, vol. 108, 1963, pp. 92-105.

Author's Conclusions

(1) A theory of heat and matter distribution in living tissues has been presented, intended for use where large scale diffusion over millimeter distances is comparable in effect with small scale diffusion, exchange, and convection over micron distances.

(2) The theory is in the form of a partial differential equation in-

cluding the Fourier-Fick diffusion equation and Fick's perfusion principle in differential form.

(3) The theory is experimentally testable. It is compatible with Kety's radioactive tracer local clearance experiment and agrees at least qualitatively with steady-state experiments based on use of the Gibbs thermoelectric probe.

(4) The theory suggests an absolute method for determining capillary blood flow per unit volume by the transient response of a Gibbs thermoelectric probe.

(5) The possible significance and measurability of fluctuation in capillary blood flow are pointed out.

51. Perl, W. and Cucinell, S. A.
Local Blood Flow in Human Leg Muscle Measured by a Transient Response Thermoelectric Method.
Biophys. J., vol. 5., 1965, pp. 211-230.

Authors' Abstract

The initial transient response of a Gibbs type thermoelectric probe embedded in human resting leg muscle was used for absolute quantitative measurement of local blood flow per unit tissue volume (local perfusion). The probe consisted of two thermistor-containing needles, one of which was heated by a constant electrical power input. The temperatures of both thermistors were recorded continuously on a two-channel, fast-response recorder. Upon sudden occlusion of the blood flow to the leg, each temperature *vs.* time record exhibited a change of slope. The change in slope of the temperature difference, divided by the temperature difference, (degrees/minute degree) was identified with the local perfusion (milliliters/minute milliliter) existing just before occlusion. The local perfusions determined agreed in range and mean with literature values of average perfusion by venous occlusion plethysmography. The nature of the local blood flow measured by the present method is discussed relative to that by other methods.

52. Perl, W. and Hirsch, R. L.
Local Blood Flow in Kidney Tissue by Heat Clearance Measurement.
J. Theoret. Biol., vol. 10, 1966, pp. 251-280.

Authors' Abstract

The transient response heat clearance method of Stow and Schieve for measuring local tissue blood flow was tested on dog and rabbit kidney. Heat is injected continuously into a small volume of tissue and the temperature difference between heated and unheated tissue regions is monitored. The blood flow to the tissue is suddenly stopped for a few seconds. A sudden change in time rate of change of the temperature difference is thereby produced, which is a measure of the local blood flow per unit tissue volume just before stoppage. This method was compared with a para-aminohippurate clearance method for total kidney blood flow. Satisfactory agreement was found at low blood flow. A systematically increasing divergence with increasing blood flow could be interpreted as a decreasing extraction ratio for injected heat by the blood flow in the afferent arterioles. It was concluded that the method is capable of absolute and quantitative measurement of local tissue blood flow. The method was used to calibrate *in vivo* the Gibbs steady state method and the calibration curve was analyzed theoretically.

53. Piironen, P. and Takalo, K.
Assessment of Regional Heat Losses for Verification of Mathematical Analogues of the Human Thermal System.
AD 720830., 1970.

Authors' Summary

For the purpose of programming the skin temperatures of the head, trunk and extremities and of continuous measurement of their separate heat losses, an exposure and measuring device was elaborated, which is called the control and calorimetry suit (CCS).

The method involving use of the CCS was applied in determinations of the passive heat losses of different parts of the human body at rest and during exercise. By means of lowering the skin temperature by consecutive steps and observing the heat losses and thermal conductance, that skin temperature value was identified on each energy level at which the decrease of conduction resulting from reduction of active heat transport turned into increase at onset of thermoregulative heat production. The heat losses at this limiting value were considered to be passive in character.

A simple mathematical model was devised to describe the passive heat losses from different parts of the body depending on variations of structure and function. The degree of agreement between theoretical calculations and experimental observations was judged to be encouraging.

54. Piironen, P. and Takalo, K.
The Control of Human Thermoregulatory Heat Production.
AD 720831, 1970.

Authors' Abstract

Experiments were carried out for the study of control of thermoregulatory heat production, in which continuous records were made of the test subject's oxygen consumption and of the different body temperatures. The skin temperature of the subject was controlled during the experiment by conducting temperature-controlled water onto the skin, with the aid of a special exposure suit. In the first experimental series, the subject's skin temperature was kept constant during the test and the blood temperature was allowed to decrease slowly; the results obtained by this procedure were considered to correspond to control in steady state situations. In the second series, the skin temperature was varied in programmed manner. Analysis of the results revealed that both the steady-state and dynamic experiments can not be explained with the same quantitative control assumptions if the hypothalamic and skin temperatures are assumed to be the sole controlling variables. When as a third controlling variable the gradient of skin temperature was taken into consideration, the dynamic experiments could be considerably better accounted for.

55. Priebe, L. and Betz, E.
Heat Transport in Homogeneously and Isotropically Perfused Tissue.
Arztliche Forschung, vol. 1, 1969, pp. 18-30.

Authors' Abstract

The theory of stationary heat transport from a heated probe of spherical dimension located in the centre of a spherical volume of homogeneously and isotropically perfused tissue is presented. The theory gives the possibility to estimate the local blood flow. The mathematical treatment of the heat transport is based on the assumption that the discrete capillary heat sinks, as well as the discrete venous heat sources, are "smeared" over the whole tissue volume.

In this study the arterial blood is assumed to have no thermal interaction with the tissue. The strength of the punctiform sinks and sources are of approximative character. The differential equation is extended to include the sink and source strengths. From the solution results the thermal conductivity increment as a function of the specific blood flow.

56. Priebe, L.,
Heat Transport and Specific Blood Flow in Homogeneously and Isotropically Perfused Tissue.
Physiological and Behavioral Temperature Regulation, 1971, pp. 272-280.

Author's Summary

The essential points of the theory on determination of blood flow by means of heat conducting probes in homogeneously and isotropically perfused tissue can be recapitulated in short. The fundamental geometrical conception is that of a spheric probe situated in the center of a spheric tissue volume. The blood flow in the vessels which are situated before the capillaries takes place without exchange of heat with the tissue. The primary transfer of heat between tissue and blood occurs at the capillaries. At the capillary exit, there is a thermal balance between blood and capillary wall. This makes it

possible to specify the strength of the discrete capillary sinks.

The venous blood, heated by the capillary sinks, gives the heat back to the tissue. The heat quantity and thus the yield of the discrete venous sources, which are taken as being constant in space, results from the condition that there is no divergence of temperature between the venous blood leaving the tissue volume and the tissue at the surface of the perfused sphere.

The capillary sinks as well as the venous sources must be taken as being "smeared" over the whole tissue volume, so that the sinks and sources are punctiformly distributed. Thus, mathematical treatment of the conventional problem in the tissue is made possible.

The distinctive result of the theory is the pseudolinear course of the thermal conductivity increment in the physiolocical region of specific blood flow, which is observed very frequently in perfusion experiments *in vivo*.

57. Richardson, P. R. and Whitelaw, J. H.
Transient Heat Transfer in Human Skin.
J. Franklin Inst., vol. 286, 1968, pp. 169-181.

Authors' Abstract

Experiments are discussed which assess the influence of sudden, localized changes of thermal load on the conductance of human skin; the conductance is expected to change due to the thermal regulatory role of skin. The changes are produced by placing local areas of skin in contact with passive probes which are pre-heated or pre-cooled. It is found that the change in conductance is effectively independent of the surface temperature (and of the surface heat flux) to which the skin is exposed at the beginning of each test, for elapsed times exceeding one minute.

58. Seagrave, R. C. and Miller, N. C.
A Model of Human Thermoregulation.
Proc. 24th Annual Conf. on Eng. in Med. & Biology, 1971, p. 56

Authors' Article

A mathematical model has been constructed to describe human thermoregulation. It is of sufficient detail to test proposed control mechanisms, including acclimatization effects.

The model conceptually consists of nine interconnected cylinders. Each cylinder represents a body segment, and has the same surface area and volume as the segment it represents. The cylinders are divided into layers. Each layer, and the blood leaving that layer, is at a uniform temperature. Heat transfer between adjacent layers is by conduction and convective blood flow. Thermal contact between cylinders is only through the effects of convective blood flow. Metabolic heat is generated within the layers and is ultimately dissipated to the surroundings through the surface layer by convection, radiation, and evaporation, and the rate of blood flow to the surface layers.

The head, thorax, and abdomen are each represented by a three-layered cylinder. The upper and the lower extremities are each represented by three two-layered cylinders. The surface layer of each cylinder represents skin and subcutaneous fat, with a small metabolism and a widely varying blood flow rate depending on thermal status. The middle layer includes skeletal muscle and bone, with a minimum metabolism and variable additional metabolism to represent muscular work. Blood flow varies to meet metabolic demands. In the three layered cylinders, the core layer includes the deep organs of the region being described, and has a constant metabolic level and blood flow rate.

An energy balance may be made on each layer of each cylinder. By approximating the conductive heat flux between layers by a finite difference form of Fourier's Law, a first order differential equation results for each layer. Due to the convective blood flow the equations are coupled. By allowing temperature dependence of surface blood flow, metabolism, and evaporation, non-linearities are introduced. Thus, a set of twenty-one first-order non-linear coupled equations results. Transient solutions are obtained numerically. By equating the time derivatives to zero, a steady state solution may be obtained by matrix techniques. This steady state solution is used to check consistency of the various parameters.

Efforts have been concentrated on finding a consistent set of values for parameters in the equations, such as regional metabolism and flowrate, which are within published ranges.

The model has been used to elucidate a probable control mechanism for skin-blood flow response to cyclically varying temperatures in a water bath. This information will then be available to obtain correlation between surface flow and such postulated variables as brain temperature, skin temperature, and rates of change of various temperatures.

59. Shitzer, A. and Chato, J. C.
Analytical Modeling of the Thermal Behavior of Living Human Tissue.
Proc. 4th International Heat Transfer Conference, 1970, pp. Cu 3.9 1-10.

Authors' Abstract

The thermal behavior of living biological tissues has been modeled. The model allows for inclusions of the effects of internal heat generation and blood flow. Steady state analytical solutions have been obtained for several boundary conditions and for various values of the parameters involved. These solutions show the significance of the blood flow on the temperature distribution. Particular applications were directed to the problem of cooling of the skin surface by direct contact, such as with cooling tubes used in extravehicular space suits. Temperature profiles obtained by these analytical methods compared favorably with the scant experimental data and previous numerical solutions obtained. The results in general provide insight into the

influence of various parameters on the effectiveness of various cooling schemes.

60. Shitzer, A. and Chato, J. C.
Further Studies on the Dimensions Parameters Associated with the "in vivo" Transport of Heat within Biological Tissue.
Aerospace Medicine, vol. 42, 1971, pp. 1279-1283.

Authors' Introduction

The importance of dimensionless parameters in analysis has long been recognized. These parameters may be used for several purposes such as 1, simulation of problems of similar nature and conditions, 2, presentation of experimental data, and, 3, presentation of analytical solutions.

The physically most significant dimensionless parameters emerge usually from either an analytical solution or a preliminary dimensional analysis of a problem. In those cases where a problem proves to be too involved to be tackled analytically, one has to use the latter method in order to obtain a set of dimensionless parameters pertinent to the problem.

A number of dimensionless parameters associated with the steady state transport of heat in biological tissue has already been reported by the authors. In the present work both analytical solution and dimensional analysis are employed to obtain additional dimensionless parameters of the problem. These parameters, which apply to steady as well as transient cases, are presented and interpreted.

61. Shitzer, A. and Chato, J. C.
Effect of Variable Blood Supply Temperature Distribution in a Biological Tissue.
Proc. 24th Conf. on Engineering in Medicine and Biology, 1971, p. 57.

Authors' Introduction

Models of the thermal behavior of living biological tissue have been presented by a number of investigators. In many of these models the tissue is assumed to be perfused by blood that enters the tissue at some constant temperature, usually the temperature of the artery. Upon leaving the tissue, the blood is assumed to have attained the temperature of the tissue (perfect heat exchange). An analytical solution is presented here for a steady state model in which an arbitrary, variable blood supply temperature is assumed.

62. Shitzer, A. and Chato, J. C.
Steady-State Temperature Distribution in Living Tissue Modeled as Cylindrical Shells.
SAME Paper No. 71-WH/HT-34, 1971.

Authors' Abstract

Closed form, analytical solutions to the problem of steady-state heat transfer in living tissue modeled as cylindrical shells are presented and discussed. These solutions are particularly useful for the study of temperature distributions in the extremities. Metabolic heat generation, conduction, and heat transported by the blood perfusing the tissue are considered in the model. The results demonstrate the important role that the blood stream plays in the transfer of heat inside living tissue. Solutions are also presented for the limiting cases of diminishing blood flow that would occur during vasoconstriction or occlusion of blood by external means.

63. Shitzer, A. and Chato, J.C.
Analytical Solutions to the Problem of Transient Heat Transfer in Living Tissue.
ASME Paper No. 71-WA/HT-36, 1971.

Authors' Abstract

The paper considers an analytical model of transient heat transfer in living biological tissue. The model includes storage, generation, conduction, and convective transport of heat in the tissue. The authors discuss solutions for rectangular and cylindrical coordinates. Transient times for reaching the "locally fully developed" temperature profile were found to be of the order of 5 to 25 min. These transients are dominated by a geometrical parameter and, to a lesser, extent, by a parameter representing the ratio of heat supplied by blood flow to heat conducted in the tissue.

64. Smith, P. E. Jr.
Analog Simulation of the Physiological Responses of Men Working in Hot Environments.
Proc. San Diego Symposium for Biochemical Eng., 1962, pp. 117-125.

Author's Abstract

A dynamic mathematical model of the human heat transfer system has been developed. The model is capable of exhibiting both transient and steady state responses. This model includes the following factors: 1) the distribution of metabolic heat generation; 2) convective transport of heat by the blood stream; 3) conductive transfer of heat through the tissues; 4) storage of heat in the tissues; 5) loss of heat through the respiratory tract; and

6) loss of heat from the skin by radiation, conduction and evaporation. The rational of the model is presented, together with an indication of the method of programing used. Techniques of validating the model by comparison with data obtained on human subjects are discussed, and the results presented. Conclusions based on the use of the model are given.

65. Smith, P. E. and James, E. W.,
Human Responses to Heat Stress-Simulation by Analog Computer.
Archives of Environmental Health, vol. 9, 1964, pp. 332-342.

Authors' Introduction (Modified)

In the technical language of today, a simulation is a representation, mathematical or otherwise, of a physical system. Such a representation of the human heat transfer system using familiar electrical symbols was proposed by MacDonald and Wyndham in 1950. Included are the sources of metabolic heat contained within the body. These may or may not be constant, depending upon the activity under consideration. From these sources, heat flows into the core temperature, which in the human may be measured rectally. Normally, this temperature will be greater than the skin temperature, and heat will flow through the conductive path into the skin. From here, heat is normally lost to the environment through conductive paths for sweating and convection-radiation.

The conductive paths are shown as variables, largely determined by the flow of blood within the tissues, which, in turn, is subject to control by various body functions. The external conductive paths are functions of clothing and wind velocity, and they deliver heat to the environment which may be considered as infinite sinks for vapor, operating at a vapor pressure and for heat operating at a temperature T_{ext}.

Passive analog models based on these concepts have been constructed using electrical resistors and capacitors. Notable is that developed by Alan Woodcook and his associates at the Quartermaster Research and Engineering Command formerly located at Natick, Mass., for the study of Arctic clothing combinations. Such models are of limited usefulness. They suggest little in the way of dynamic mechanisms to explain the multiplicity of reactions which the living organism marshals to meet the exigencies of its environment.

More fruitful are the dynamic techniques made possible through the use of modern analog computers. In these, variables are represented by voltages which may be added, subtracted, multiplied, divided and transformed through the use of an infinite variety of mathematical functions. Accordingly, a dynamic mathematical model of the human heat transfer system has been developed and programmed for analog simulation. The model is capable of exhibiting both transient and steady state responses.

66. Stoll, A. M.
A Computer Solution for Determination of Thermal Tissue Damage Integrals from Experimental Data.
IRE Transactions on Medical Electronics, vol. ME-7, 1960, pp. 355-393.

Author's Summary

In the course of a study on the relationship between tissue damage and pain sensation due to thermal stimulation, a computer method was developed for the analysis of the experimental data. Considerable interest in the details of this method has been expressed by various investigators who encounter similar data analysis problems. This report is written, therefore, to state the problem and its solution as an indication of some of the possibilities computer methods offer the biological investigator having little or no previous experience in the use of computers. The rationale, physiological observations and results of the study itself have been reported elsewhere so that only those facts necessary to an understanding of the computer solution are noted here.

67. Stoll, A. M. and Chianta, M. A.
Heat Transfer Through Fabrics as Related to Thermal Injury.
Trans. New York Academy of Sciences, Series II, vol. 33, 1971, pp. 649-670.

Authors' Abstract

Heat is transferred through fabrics by convection, conduction, and radiation, and, under certain circumstances, by vaporization. Each mode is subject to different physical principles, but the effect of the total heat absorbed by underlying skin is the same: If the resultant skin temperature rise is sufficiently high and maintained sufficiently long, injury results. The extent of injury is predicted under certain controlled conditions, and these conditions may be used to disclose protection principles appropriate to each mode of transfer.

68. Stolwijk, J. A. J.
A Mathematical Model of Physiological Temperature Regulation in Man.
John B. Pierce Foundation Laboratory, Report Number NAS-9-9531.

Author's Introduction

The deep space environment is a very hostile one for life as it exists on earth. The protection of space travelers from this hostile environment is a challenge to biology and technology in which both disciplines are dealing in largely uncharted territory. Solutions require communication between these disciplines of unprecedented effectiveness. In technology, the analysis of the behaviour of complex systems is a well-developed technique which yields many benefits. An important benefit is the ability to simulate the behaviour of a complex system under almost any imaginable set of circumstances using mathematical models with great savings in time and expense. The accuracy of such models of technological systems can be very high since the characteristics of their components are well known, and the controlling systems have known structure and characteristics.

It is highly desirable to develop similar mathematical models of biological systems for obvious reasons: simulations of the biological responses to dynamically varying sets of environmental circumstances would allow savings in time and expense required for evaluating the effects of such environments. Another very attractive feature of mathematical models of biological systems is that they can be made to communicate with models of technical systems, and it thus becomes possible to simulate the combined system of man with his life support system.

There are serious difficulties in constructing mathematical models of biological systems. These difficulties rest in the complexity of biological systems with respect to the number of identifiable components, but they are especially due to a great deal of redundancy in the control systems. This redundancy results in control systems with many multiple control loops. In a multiple control loop system, it is hard to study the system by opening one or more control loops since one cannot be sure that there are no remaining loops and that a particular component under study is really isolated.

It is thus not surprising that a mathematical model of thermoregulation of man, such as is described in this report, is far from accounting completely for all thermoregulatory responses ever reported. It can, however, give reasonable estimates of dynamic thermophysiological responses to a variety of environmental conditions and rates of internal heat production. This report is intended to present the current status together with the experimental findings which form the basis of much of the structure of the current model.

69. Stolwijk, J. A. J. and Hardy, J. D.
Temperature Regulation in Man - a Theoretical Study.
Pflügers Archiv., vol. 291, 1966, pp. 129-162.

Authors' Summary

For the purposes of theoretical analysis of experimental results and evaluation of hypothetical concepts a mathematical model of thermoregulation in man is presented. The human body is represented by three cylinders: the head, the trunk, and the extremities. Each cylinder is divided into two or more concentric layers to represent anatomical and functional differences in so far as they are of primary importance in thermoregulation. Heat flow between adjacent layers is by conduction, and all layers exchange heat with the environment by convection with a central blood compartment. All three skin layers exchange heat with the environment by conduction, convection, radiation and evaporation. Signals which are proportional to temperature deviations in the brain and to deviations in average skin temperature are supplied to the regulator portion of the model. The regulator then causes

evaporative heat loss, heat production by shivering or changes in the peripheral blood flow to occur in the appropriate location in the body. If a proposed mechanism of thermoregulation is expressed in quantitative form it describes the relationships between the input signals and the resulting thermoregulatory response; the model can be used to compare the quantitative response resulting from a proposed mechanism with the responses obtained by measurement. A number of experimental results are compared with prediction furnished by the mathematical model using a regulator with an output which is proportional to the product of the input signals. It is emphasized that models of this type should be used in close connection with an experimental program to attain their full usefulness.

70. Stolwijk, J. A. J. and Hardy, J. D.
Skin and Subcutaneous Temperature Changes During Exposure to Intense Thermal Radiation.
Thermal Problems in Aerospace Medicine, J. D. Hardy ed., 1968, pp. 31-46.

Authors' Introduction (Modified)

The temperature of the human skin is one of the basic physiological parameters but its accurate measurement is so difficult that in many instances thermocouples, thermistors, resistance elements, etc. have been used in various applications, to provide an index of skin temperature and skin temperature change. In view of the urgent requirement for accurate data on skin temperature and the lack of proved experimental methods for obtaining them, it appeared appropriate to report another advance in the technical methodology which permits the accurate measurement of skin temperature under the conditions of exposure of the skin to intense thermal radiation from a broad spectrum source. As shown by Cobet and Bramigk and confirmed by a detailed series of sutdies, the skin temperature can best be determined radiometrically by quantitatively measuring the emitted infrared radiation from the skin by a radiometer at a distance. Such a measurement of skin temperature requires a knowledge of the emissivity of the skin and the penetration of the emitted radiation through the skin. The optical properties of the skin have been the subject of research for the past forty yeats resulting in general agreement that the human skin in the spectral region beyond 3μ is black (emissivity 0.985 irrespective of visual color), and that the skin absorbs within a few microns of the skin surface all of the radiation within its spectral emission hand, 4-40μ. These facts permit the use of radiometric devices for skin temperature measurement provided the skin is not being irradiated with significant amounts of visible, near infrared and far infrared radiation.

Along with the experimental observation the authors present a mathematical model for predicting skin and subcutaneous temperatures. The model was solved with the aid of an analog computer. Agreement between theoretical and experimental results was found to be good.

71. Stolwijk, J. A. J.
A Mathematical Model of Physiological Temperature Regulation in Man.
NASA CR-1855, 1971.

Author's Abstract

A dynamic mathematical model is presented of physiological regulation of body temperature in man. A total of 25 nodes is used to represent the thermal characteristics of the body, with four nodes each representing the head, trunk, arms, hands, legs and feet. The twenty-fifth node represents the central blood. Each node has the appropriate metabolic heat production, convective heat exchange with the central blood compartments, and conductive heat exchange with adjacent compartments. The outer nodes represent the skin and exchange heat with the environment via radiation, convection and evaporation. In the model the thermoregulatory system receives temperature signals from all compartments and after integration and processing the system causes appropriate commands to be sent to all appropriate compartments changing metabolic heat production, blood flow or the rate of sweat secretion. The model is presented in the form of a documented FORTRAN program. Simulations of experimental exposure to step changes in environmental temperature at rest and of 30 minute exercise bouts at 25, 50 and 75 percent of maximum aerobic capacity at different ambient temperatures are compared with actual results.

72. Stolwijk, J. A. J.
Mathematical Model of Thermoregulation.
Physiological and Behavioral Temp. Regulation, 1971, pp. 703-721.

Author's Introduction

As we progress in the study of body temperature regulation, it is evident that the complexity of the system is such that it becomes increasingly difficult to rely on our intuitive approach to the design of optimal experiments or to the interpretation of experimental results.

Of course, thermoregulation has this characteristic in common with most physiological control systems. At the same time, however, it has the distinction that parts of the overall system obey the simple physical laws which are relatively easy to evaluate in quantitative form. Since temperature, heat capacitance and heat conductance are not very different for many tissues and organs, we can construct a mathematical model of heat production, heat transport and heat loss in the body, and such a model can still be useful even if it is considerably simplified. This is probably an important reason why it is relatively easy and profitable to formulate quantitative models of the thermoregulatory control system. Such models have been presented by Wyndham, *et al.*, Wissler, E. H., Smith and James, Stolwijk and Hardy, Crosbie, *et al.*, and others.

Although the formulation and development of a mathematical model of thermoregulation is an educating experience, the most important contributions such a model can make are in the areas of evaluation and interpretation of experimental results and in the suggestion of suitable experiments to challenge expressed concepts. Of necessity, this results in continuous interaction between experiment and theory and in continuous change and gradual improvement of the predictive capabilities of the model.

It is one of the objectives of this chapter to contribute to yet another potential benefit of mathematical models of thermoregulation. It is impressive to observe how effectively a model can communicate the exact concept of thermoregulation and all of its quantitative implications as held by one investigator, to another or to those whose interest are in the applied area. Exchange of computer programs containing such models is a more disciplined form of communication than is usually possible in the book form.

73. Trezek, G. J. and Jewett, D. L.
Thermal Modeling of Cylindrical Source Transient Temperature Fields in Brain.
Proc. 21st Conf. on Engineering in Med. & Biology, 1968, pp. 53.4.

Authors' Introduction

In-vivo measurements of transient temperature fields have been modeled for point source cold probes and parallel plane probes. Here we present results and a model for transient fields generated by a cylindrical source using a finite difference numerical solution. The cylindrical source has been used for *in-vivo* thermal property studies, but that study did not attempt to account for all of the following three major factors in biological heat transfer: conduction, metabolic heat generation, and blood flow heat transfer.

74. Trezek, G. J. and Cooper, T. E.
Analytical Determination of Cylindrical Source Temperature Fields and Their Relation to Thermal Diffusivity of Brain Tissue.
Thermal Problems in Biotechnology, ASME Symposium Series, 1968, pp. 1-15.

Authors' Abstract

A one-dimensional integral solution for the transient temperature field generated by a cylindrical source of finite radius in an infinite medium is presented. The temperature at any position and time is given for the situation of a time dependent surface temperature which is expressed as an arbitrary polynomial in time. The solution is limited to early times in the transient or to times corresponding to one-dimensional behavior of the resulting temperature field. The thermal properties of the medium are assumed to be constant. An asymptotic approximation for the combination of Bessel functions appearing in the integrand is also presented. Various numerical calculation schemes for evaluation of the temperature fields are discussed. The relationship of the proposed analytical situation to the evaluation of the thermal diffusivity of biological materials is also considered.

75. Trezek, G. J.
Thermal and Electrical Modeling for Brain Surgical Probes.
ASME Paper No. 69-WA/HT-40, 1969.

Author's Abstract

The general problems associated with the generation of temperature fields in brain are considered. These include the determination of the thermal properties, the role of blood flow and metabolic heat generation and computer modeling. For the purpose of aiding in the clinical application of surgical probes, the calculation of electrical fields generated by a dipole source is also considered.

76. Trezek, G. T. and Jewett, D. L.
Nodal Network Simulation of Transient Temperature Fields from Cooling Sources in Anesthetized Brain.
IEEE Trans. on Biomedical Eng., vol. BME-17, 1970, pp. 281-286.

Authors' Abstract

Transient thermal gradients in the brains of anesthetized cats and rabbits due to localized cooling to 5°C with probes of two different shapes were modeled successfully to within 0.5°C by a computer program utilizing a finite difference method and thermal coefficients of water, without addition of a term for metabolic heat or blood flow. Input data to the program required temperature measurements in the brain away from the probe, although in the cylindrical case it was possible to use the probe temperature as the forcing function by assuming that the probe had a larger diameter than was actually the case. The results indicate that for the experimental conditions, metabolic heat and blood flow can be adequately accounted for by means of a rather small adjustment of the thermal diffusivity term in a general diffusion equation, without need of an explicit term for such distributed sources.

77. Weaver, J. A.
Calculation of Time-Temperature Histories and Prediction of Injury to Skin Exposed to Thermal Radiation.
NADC-MR-6623, 1967, pp. 1-27.

Author's Introduction

This report contains a description of a digital computer program that can be used to evaluate theoretical equations associated with the time-temperature histories of skin exposed to various levels of thermal radiation and to predict the injury due to such exposures. The program is written for a Control Data Corporation 3200 Computer System using the Fortran 3200 language. In the study of thermal tissue damage it is of interest to obtain the time-temperature history at some depth below the surface of the skin such as at the dermis-epidermis interface and also to obtain the time-temperature history at the surface of the skin. For this reason the computer program incorporates the feature of obtaining the time-temperature history at depth and at the surface.

78. Weaver, J. A. and Stoll, A. M.
Mathematical Model of Skin Exposed to Thermal Radiation.
Aerospace Med., vol. 40, 1969, pp. 24-30.

Authors' Abstract

Prediction of dermal injury resulting from exposure to thermal energy of any given intensity and duration depends entirely upon the resultant skin temperature-time history. Means are now available for assessing heat transfer by low temperature radiation, convection and conduction to the bare skin and through thin protective coverings of known physical properties. However, thermal effects of nuclear detonations constitute a special problem because much of the radiation lies in the visible range where the optical properties of the skin and its coverings, if any, greatly influence the heating pattern. Blackening of the skin eliminates effects due to its optical properties but enhances the ever-present variations in the thermal "constants" of the skin. The present report describes the utilization of a mathematical equation and computer techniques for extracting these variations from empirical data obtained at relatively low levels of radiation (<0.5 cal./cm.^{2} sec.), and applying extrapolations of these values in calculations of temperature-time histories at higher levels of irradiance where empirical data are lacking. This procedure is subject to validation by experimentation within a limited range of exposures. If validation is achieved in the blackened skin then the entire system may be utilized in the determination of optical properties of unblackened skin.

79. Winton, H. J. and Linebarger, R. N.
Digital Simulation of Human Temperature Control.
Proc. Summer Comp. Simul. Conf., vol. 2, 1970, pp. 830-836.

Authors' Abstract

A feedback control system model of human temperature regulation is developed. Body thermal properties are represented by an electric circuit analog. The sudomotor, vasomotor, and metabolic parameters in this circuit are made to nonlinear functions of an error signal derived from hypothalamic and cutaneous thermoreceptors. The system state equations are derived and digital simulation of the model using System 360/CSMP is discussed. An analog simulation of the same problem is also given along with an evaluation of the advantages and disadvantages of each approach. Comparison of model static and dynamic response with published data from physiological experiments shows reasonable agreement over a broad spectrum of conditions including exposure to heat and cold, humidity, ice ingestion, and exercise.

80. Wissler, E. H.
Steady-State Temperature Distribution in Man.
J. Appl. Physiol., vol. 16, 1961, pp. 734-740.

Author's Abstract

A steady-state, mathematical model for the human heat transfer system has been developed. This model includes the following factors: a) the distribution of metabolic heat generation, b) conduction of heat in tissue, c) convection of heat by flowing blood, d) loss of heat by radiation, convection and evaporation at the surface, e) loss of heat through the respiratory tract, and f) countercurrent heat exchange between large arteries and veins. Computed results were compared with experimental results for the nude basal man and found to be satisfactory.

81. Wissler, E. H.
An Analysis of Factors Affecting Temperature Levels in the Nude Human.
Temp. Its Meas. & Control in Science and Industry, J. D. Hardy ed., vol. 3, part 3, 1962, pp. 603-611.

Modified Author's Introduction

The purpose of this paper is to define a model containing the following factors: (1) local generation of heat by metabolic reactions, (2) conduction of heat due to thermal gradients, (3) convection of heat by circulating blood, (4) the geometry of the body, (5) the existence of an insulating layer of fat and skin, (6) countercurrent heat exchange between adjacent large arteries and veins, (7) heat loss through the respiratory tract, (8) sweating, (9) shivering, (10) the storage of heat, and (11) the condition of the environment, including its temperature, wind speed, and relative humidity. Although an attempt has been made to build some degree of flexibility into the equations, it is not proposed that this model should represent the final solution for all problems posed by thermal physiologists. Future work will be directed toward extending the applicability of the model. In particular, it is anticipated that the model will serve as a useful new tool for studying temperature regulation in the human. Since it treats explicitly those factors which are controlled by the body in attempting to maintain a constant central temperature, it will be easy to check the validity of various hypotheses relating the controlled variables to the temperature of receptors located in various areas of the body.

82. Wissler, E. H.
A Mathematical Model of the Human Thermal System.
Bulletin of Mathematical Biophysics, vol. 26, 1964, pp. 147-166.

Author's Abstract

This paper describes a mathematical model developed to simulate the physical characteristics of the human thermal system in the transient state. Physiological parameters, such as local metabolic heat generation rates, local blood flow rates, and rates of sweating, must be specified as input data. Automatic computation of these parameters will be built into the model at a later date when it is used to study thermal regulation in the human.

Finite-difference techniques have been used to solve the heat conduction equation on a Control Data Corporation 1604 computer. Since numerical techniques were used, it was possible to include many more factors in this model than in previous ones. The body was divided into 15 geometric regions, which were the head, the thorax, the abdomen, and the proximal, medial, and distal segments of the arms and legs. Axial gradients in a given segment were neglected. In each segment, the large arteries and veins were approximated by an arterial pool and a venous pool which were distributed radially throughout the segment. Accumulation of heat in the blood of the large arteries and veins, and heat transfer from the large arteries and veins to the surrounding tissue were taken into account. The venous streams were collected together at the heart before flowing into the capillaries of the lungs. Each of the segments was subdivided into 15 radial sections, thereby allowing considerable freedom in the assignment of physical properties such as thermal conductivity and rate of blood flow to the capillaries.

The program has been carefully checked for errors, and it is now being used to analyze some problems of current interest.

83. Wissler, E. H.
A Mathematical Model of the Human Thermal System.
Chem. Eng. Progress Symp. Series, vol. 62, 1966, pp. 66-78.

Shortened Author's Introduction

In order to survive, the human organism must maintain a central temperature that is close to 37°C. Deviations of ±3°C can be tolerated by healthy individuals, although there is usually noticeable discomfort associated with the extreme conditions. The neutral environment for a nude, resting human is about 30°C, but he can survive over a range of environmental temperatures extending from 10°C to 50°C, depending on other factors such as wind speed and relative humidity. Of course, man can remain comfortable in even more extreme environments by using clothing to maintain a private microenvironment near the neutral point.

The basic problem of thermal physiology is to define in adequate detail the mechanisms by which man maintains a tolerable central temperature under varying environmental conditions. In this paper the most important features of this problem will be discussed briefly before describing a mathematical model into which these features have been incorporated.

84. Wissler, E. H.
The Use of Finite Difference Techniques in Simulating the Human Thermal System.
Physiological and Behavioral Temp. Regulation, 1971, pp. 367-388.

Author's Introduction

Thermal regulation in the human depends on many factors which are interrelated in a complex manner. These factors can be divided into two groups, physical and neurological. Included in the first group are the mechanisms for heat transfer, both within the body and between the surface of the body and its environment, the rate of heat generation by metabolic reactions, and the rate of change of stored heat content. Since other chapters included in this book present an excellent summary of current thinking on these matters, we will proceed directly to a discussion of the methods that can be used to incorporate these factors into a rational mathematical model of the human thermal system.

85. Woodcock, A. H. and Breckenridge, J. R.
A Model Description of Thermal Exchange for the Nude Man in Hot Environments.
Ergonomics, vol. 8, 1971, pp. 223-225.

Authors' Abstract

A theoretical model based on the physical laws of heat and moisture exchange is developed to describe the energy exchange between nude man and a hot environment. Equations are presented which express the heat loss from a heated moistened 'skin' in terms of ambient temperature, humidity and wind. Two different situations are considered, the first where secreted sweat is all evaporated and cooling depends on the amount secreted; and the second, where the skin is wet and cooling limited by the amount of sweat which can be evaporated. In the first case, heat dissipation depends on air temperature and amount of sweat secretion, which varies among individuals. In the second, wet-bulb temperature is shown to be a determining factor, as has already been observed in studying man's tolerance to heat. Graphical presentation is used to demonstrate the individual and combined effects of various environmental factors and to interpret the experimental results of other investigators.

86. Wyndham, C. H. and Atkins, A. R.
An Approach to the Solution of the Human Biothermal Problem with the Aid of an Analogue Computer.
Proc. 3rd Inter. Conf. on Med. Electronics, 1960, pp. 32-38.

Author's Conclusion

Though the cylindrical thermal model is very different from the human body, it is a start in representing the average conditions of the body. With experience, the model might have to be altered considerably. It is possible that the cylinder should contain more than three sections or that the heat transfer by the blood stream and by conduction through the tissues should be represented by two separate conductances. The effect of a change in thermal capacitance, or of acclimatization, might also be included.

Our first hope is that the analogue will provide further information on the regulatory system. It should indicate whether the blood flow and sweat rate are predominantly controlled by the core or skin temperature, what their characteristics are and what the effect of the time-constant is. A mathematical analysis of this is practically impossible.

Ultimately we hope that the analogue computer will assist in predicting what a man's response might be in any climatic conditions, and how much work he can safely do under such conditions.

The results at the moment can only be compared with a wide variety of published figures which apply to many different types of people and are of limited accuracy. The Transvaal and Orange Free State Chamber of Mines are constructing a climatic chamber where more accurate experiments will be performed on a particular type of person. Results from these experiments, in which heat loss by convection, radiation and evaporation can be measured to an accuracy of 5% on men at work, ought to test the validity of the thermal model.

87. Wyndham, C. H. and Atkins, A. R.
A Physiological Scheme and Mathematical Model of Temperature Regulation in Man.
Pflügers Arch., vol. 303, 1968, pp. 14-30.

Authors' Summary

Mean skin temperatures, rectal temperatures and sweat rates were measured on four highly acclimatized subjects. They were exposed for 180 minutes to 16 different combinations of 4 metabolic rates and 4 air temperatures, ranging from cold (10°C) to hot (49°C). Mean sweat rates for the second hour were plotted against mean rectal temperatures for 4 different levels of skin temperature and vice-versa. These graphs indicate, firstly, that sweat rate does not increase until rectal temperature rises above a threshold of 36.5°C; thereafter the increase in sweat rate depends upon the level of mean skin temperature, being greater the higher the mean skin temperature is. Secondly, sweat rate does not increase markedly until mean skin temperature rises above 33°C but the increase in sweat rate above 33°C depends upon the level of rectal temperature, being greater the higher the rectal temperature is. The interrelated effects upon sweat rate of mean skin temperature and core temperature can be explained by means of a relatively simple physiological system, comprising temperature sensors in the hypothalamus and skin, and a heat loss and a heat conservation integrating centre. Mathematical equations have been developed to express the relationships between sweat rate, core, and mean skin temperature for cool conditions, but these relationships are so complex that it is preferable to use an analogue computer for these purposes.

1. Collins, J. C.
   A Model of Respiratory Heat Transfer in the Kangaroo Rat.
   Ph.D. Thesis, Duke Univ., Durham, N.C., 1970, also *Dissertation Abstracts International*, vol. 31, No. 10, 1971, p. 5936B.

   Author's Abstract

A steady state model of the heat and water transfer occurring in the upper respiratory tract of the kangaroo rat, *Dipodomys spectabilis*, is developed and tested. The purpose of the model is to account quantitatively for observed variations of expired-air temperature and respiratory water loss as environmental conditions are varied.

Conceptually, the model consists of the respired air stream passing back and forth over a single liquid stream which represents the heat and blood flow from the body core to the nasal passage area. The model is described by a steady-state energy balance equation, in which the rate of energy transfer to the air stream plus the rate of thermal conduction through the nose tip. By expressing the stream flow rate as a linear function of nose tip temperature, body temperature as a linear function of ambient temperature, and ventilation rate as a piecewise-linear function of ambient temperature, expired air temperature and rate of water loss are predicted for three animals as functions of ambient temperature and humidity. The model predictions and experimentally measured values of expired-air temperature are all within 1.2°C with a standard deviation of 0.73°C. Predictions of respiratory water loss rate and estimates based on physiological measurements and assumptions are all within 20 percent with a standard deviation of 10.4 percent. Expired-air temperature predictions using the linearized data from these three rats are compared with the measured expired-air temperatures of eight additional animals. The predicted and measured values all agree within 3.2°C with a standard deviation of 1.0°C. The agreement between predicted values and values based on physiological measurements and assumptions suggests that the model is both self-consistent and a useful predictor.

The model illustrates the importance of nasal passage geometry in enhancing the recovery of water from air expired by the kangaroo rat. In addition, the study suggests that the absence of a highly-vascularized lining in the entry region of the nasal passages affects the temperature distribudion in the nose tip region. The model should be directly applicable to other small species with similar passage geometries.

2. Cooper, T. E.
   Bio-Heat Transfer Studies. I. A Method for Determining the Thermal Properties of Biological Tissue. II. Analytical Prediction of the Temperature Field Emanating from a Cryogenic Surgical Probe.
   Ph. D. Thesis, Univ. of Cal. at Berkeley, 1970, also Dissertation Abstracts International, vol. 31, no. 7, 1971, p. 4000B.

   Author's Abstract

Two essentially different topics are examined in this thesis. In Part I a

small, needle-like, probe has been developed to measure the thermal properties of biological tissue. The probe has been used to measure the thermal diffusivity of a one percent agar-water mixture and the values obtained are within five percent of the value for pure water. Thermal diffusivity, specific heat and density values for human brain, liver, kidney and spleen were also obtained *in-vitro*. Part II of the thesis presents a method for developing nomograms for predicting lesion sizes in tissue due to the application of spherical, hemispherical and cylindrical cryosurgical cannulas.

The needle probe is simply a copper-constantan thermocouple in the shape of a long, thin cylinder. When the probe is suddenly plunged into a medium with an initial temperature different than the probe temperature, the probe responds, that is, the probe temperature changes with time until it reaches the medium temperature. The probe temperature response is recorded with a high speed strip chart recorder and matched to an analytically determined response curve to obtain the thermal diffusivity of the medium. The analytical response curve has been developed by considering not only conductive effects but also the effects of blood flow and metabolism. This allows property determinations to be made on *in-vivo* tissue as well as *in-vitro*. The results of this parameter study are presented in tabular form for ease of use. The experiments performed on human tissue indicate that biological tissue is perfectly suited for a probing technique since it readily accepts the probe and closes tightly around the probe after insertion. The needle probe technique is quite attractive from the standpoint that: 1) it requires relatively simple instrumentation, 2) an experimental run takes less than two minutes, 3) the data reduction method is simple.

The lesion size nomograms that are present in Part II were developed by solving the steady state heat conduction equation in both the frozen and unfrozen tissue surrounding a cryogenic surgical cannula. The solution yields the position of the ice front as a function of the probe geometry, probe surface temperature, blood flow rate, metabolic heat generation rate and the thermal conductivities of the frozen and unfrozen tissue. The steady state ice front position, in effect, represents the maximum attainable lesion size for a particular probe at a particular surface temperature.

The rate of lesion growth has also been considered through the numerical solution of the transient heat conduction equation for both spherical and hemispherical insulated stem cryosurgical cannula. A comparison of these temperature fields indicates that the more easily obtained spherical solution yields a reasonable prediction of the location of the ice front in the region below the hemisphere. Metabolic heat generation and blood flow were treated as having a temperature dependence of $Q_{10} = 3$. The temperature dependence of these quantities can be treated in the steady state solutions by introducing an average value of the blood flow rate.

In general, the analytical predictions are in good agreement with existing experimental data for maximum lesion sizes for various probe surface temperatures. The transient predictions indicate that 80 percent of the steady state size is reached rather rapidly while the remaining 20 percent requires approximately a three-fold increase in time. This is also consistent with experimental observations.

A method of developing a cryosurgical atlas is proposed.

3. Darwish, M. A. H.
Heat Transfer in Porous Material and its Application to Biological Systems.
Ph.D. Thesis, Kansas State University, Manhattan, Kansas, 1969, also *Dissertation Abstracts International,* vol. 30, no. 12, 1970, p. 5513B.

Author's Abstract

The application of porous cooling theory to the analysis of heat transfer in biological tissues provides an improved means for considering, in quantitative fashion, the role of blood flow in biological problems. This work has application in areas such as cryosurgery, measurements of thermal conductivity in biological tissues, and estimation of blood flow in deep tissues.

In earlier studies, the complex process of solid-fluid heat transfer in porous material required a number of simplifying assumptions. Heat conduction in both the fluid and the solid parts of the system or in the fluid only was neglected. These assumptions restricted the use of the results to certain physical systems. In most biological tissues these assumptions are not valid. Biological tissues have been treated as pure solid in most heat transfer analysis even though they have been described as porous material for more than three hundred years.

The purpose of this study is to discuss the assumptions that can be applied to biological tissues, finding solutions based on these assumptions, and applying the results to real problems.

Biological tissues were considered to be porous material of high specific surface, generating heat, and transpiring fluid (blood). Heat transfer takes place within the material by conduction in the solid and fluid parts of the system and convection which results from the blood flow through the tissues. The temperature of both the solid and fluid at any point was assumed to be the same.

Heat transfer in the classical geometrics (plane wall, cylindrecaicall wall and spherical shell) of porous material were studied. The density, specific heat, thermal conductivity, porosity and the fluid inlet velocity were considered constant.

Steady and unsteady state solutions were obtained for different boundary conditions: Specified temperature, specified temperature gradient, and convective, evaporative, and radiative heat transfer at the surface. Direct integration, separation of variables, special transformations, Laplace transforms, Fourier-Bessel expansion, and numerical methods were used to obtain the solutions. Twenty-two different solutions which have applications to biological tissues were obtained.

The role of blood flow in thermal regulation was discussed. As an application, a mathematical model for blood flow and heat transfer in the human head was presented. The model demonstrated the use of the solutions obtained in this study. A differentiation between the deep tissues and the outer layers was made since these layers have different values of blood flow, thermal conductivity and heat generation. The calculated values of temperature and heat flow were compared with experimental data and showed good agreement.

4. Harrah, C. B.
Biothermal Analyses of Conduction Cooling of the Human Body.
M. Sc. Thesis, Univ. of Calif. at Los Angeles, 1967.

Author's Abstract

To simulate the transfer of heat from man by the conduction mode, utilizing a liquid-cooled garment, a mathematical model was developed. The purpose of the model was to predict the water inlet temperature as a function of metabolism which is required to maintain the body in a state of thermoneutrality. This functional relationship was dependent upon the parametric values of mass flow rate and contact surface area between the tube and skin.

The development of the mathematical relationships relating inlet water temperature to metabolic rate consisted of essentially three phases of work. First, the heat transport loop was analyzed to determine the heat transfer characteristics of the tubing network. Secondly, a slab model of the biothermal man was developed and analyzed by digital techniques to determine the interface conditions of contact surface area and contact surface temperature required for thermoneutrality. Metabolic rates range from 320 BTU/hr to 2600 BTU/hr for the slab analysis. The third phase of the development consisted of mathematically coupling the slab model to the coolant tubes by makins use of the interface conditions obtained from the slab analysis. Upon completion of the coupling procedure, the inlet water temperature was readily related to metabolic rate.

The results of the analysis were validated by comparing the predicted inlet water te]97]ature, as a function of metabolism, with human calorimetric data. The results were satisfactory.

The primary usefulness of the developed model in duplicating experimental results is that a technique was provided for analysis of a liquid loop cooling process. Consequently, a better understanding of the parameters and their evaluation was made available.

5. Hsu, F. T.
Modeling, Simulation, and Optimal Control of the Human Thermal System.
Ph.D. Thesis, Kansas State Univ. Manhattan, Kansas, 1971, also *Dissertation Abstracts International*, vol. 32, no. 2, 1971, p 959B.

Author's Abstract

The purpose of this study is to formulate, simulate, and verify the mathematical models of the human thermal system and the integrated human thermal system and to find optimal policies for controlling the operating variables of the external thermal regulation device to satisfy the thermoneutrality of the human body under specified environmental conditions. This study is performed by the system engineering approach. The system analysis, formulation of the mathematical model, simulation, optimization, and control of the human thermal system for both nude man and man with an external thermal regulation device are carried out.

The literature on mathematical models of the human thermal system is thoroughly reviewed and systematically classified. The models included in this review are: (a) models for a single element of the body, (b) models for the entire human body, and (c) models which incorporate the human thermal systems and the external thermal regulation devices.

A mathematical model of the human thermal system and the results of simulation of its thermal responses to a specific environmental condition under steady-state and unsteady state conditions are presented. The model is based on one of Wissler's models. The present model assumes the existence of an arterial pool and a venous pool in the torso and considers the heat exchange of the torso with its adjacent elements only through the pools. Wissler's model considers the heat exchange of the torso with adjacent elements through the pulmonary capillaries. The geometry of the human body on which the system equations are based consists of six cylindrical elements (arms, legs, torso, and head). Each element, consisting of tissue, fat, and skin, has a vascular system which is divided into three subsystems representing the arteries, the veins, and the capillaries. Three differential equations representing the thermal behavior for each element are derived and are approximated by a set of algebraic equations which resulted from the application of the finite-difference method. The models are then simulated under a specific condition in which a nude human body is exposed to an environmental temperature of 107.6°F (42.0°C), except the head which is exposed to a lower environmental temperature of 77.0°F (25.0°C).

The steady-state and unsteady-state mathematical models of an integrated human thermal system are formulated. The system consists of an external thermal regulation device and the human thermal system. The models describe quantitatively the phenomenon of heat balance inside the human body and the heat exchange between the human body and its external thermal regulation device. The external thermal regulation device contains a network of cooling tubes which is held in contact with the surface of the skin. A liquid coolant inside the tubes is assumed to be flowing constantly. The liquid coolant temperature and its mass flow rate are the operative variables of the device. The purpose of the device is to maintain the human body in a state of thermoneutrality by properly controlling its operating variables. The integrated human thermal system is simulated for a variety of combinations of the operating variables and for a number of metabolic rates. A situation in which the external thermal regulation device is placed only on the head and the other portions such as the torso, arms, and legs are exposed to an effective temperature of 107.6°F (42.0°C) is investigated. Another situation in which a device is placed on the head and another on the torso but the arms and legs are insulated from their environments is also examined. The results of the simulation indicate that the human body can be protected under different levels of activity by employing the localized cooling if the external thermal regulation device and the operating variables are properly designed and controlled.

To verify the simulation results of the integrated human thermal system they are compared with the results of the experiments which were carried out in the KSU-ASHRAE test facility. The experiments employed nine human subjects who were exposed to a heat stress environment with an external thermal regulation device on the head. The comparison indicates that the simulation of the mathematical model of the integrated human thermal system generates reasonably acceptable results.

The application of an optimal control technique (linear programming) to the steady-state and unsteady-state control of the integrated human thermal system is investigated. The objective of the control is to maintain the temperature of the human body in a state of thermal comfort (thermoneutrality) and to minimize the control effort imposed on the operation of the external thermal regulation device. A situation is examined in which a device is placed on the head and another on the torso but the arms and legs are insulated from their environments. The optimal inlet coolant temperature and coolant mass flow rates for the devices on the head and torso as well as the optimal temperature profiles in the various elements of the human body are obtained.

6. Osman, D. B.
An Electrical Analog of the Biothermal System.
M. Sc. Thesis, Univ. of Calif. at Los Angeles, 1962.

Author's Abstract

To simulate man's complex interior and exterior heat transfer, a simple electrical model was developed. All elements of the biothermal system were represented in the model with some idealizations and simplifying assumptions. Electrical characteristics of semiconductors were utilized to duplicate thermoregulatory processes.

The analog was provided with a wide range of thermal variables, activity (rest, low, medium, heavy), uniform (nude, desert, temperate, wet-cold, arctic), air movement (1000-12000 Kg/m^{2}hr), air temperature and wall temperature (-30°C to + 60°C). Core temperature, skin temperature, and skin heat flow could be obtained from the analog.

The analog was then built using standard electrical components and tested by obtaining some of its characteristics. To evaluate the analog, human data was compared with analog data. The results were very satisfactory. Qualitatively the results showed close correlation and were within the ±10% acceptable analog tolerance.

The utility of the analog is in duplicating past experimental findings and to provide reasonable, and rapid approximations of the thermal situation was demonstrated by a selected problem simulation. The analog could serve also as an educational tool as well as in parameter evaluation and research planning at minimum cost and effort.

7. Shitzer, A.
A Study of the Thermal Behavior of Biological Tissue with Application to Thermal Control of Protective Suits.
Ph.D. Thesis, Univ. of Illinois, Urbana, Ill., 1971, also
Dissertation Abstracts International, vol. 32, no. 2, 1971, p. 971B.

Author's Abstract

A biothermal model of living tissue has been studied. This model allows for the inclusion of the effects of blood flow, local heat generation, conduction, and storage of heat on the heat transfer processes occurring in the living tissue. A second order, partial differential equation, referred to as the "bio-heat" equation, was obtained for the model.

Due to the lack of reliable and detailed data on the thermophysical properties involved, the tissue was assumed to be isotropic and homogeneous and all properties were assumed to be constant. Transient, as well as steady-state, closed form, analytical solutions were obtained for different geometries (cylindrical and rectangular) and parameters.

Based on the analysis, a few observations were made:

(1) Blood flow plays a significant role in the transfer of heat inside the living tissue.
(2) Transient times for reaching a so-called "fully developed" temperature profile in the tissue were estimated to be of the order of 5-20 minutes.
(3) The transient changes were found to be strongly dominated by a geometrical parameter.
(4) At elevated metabolic rates, maximum temperature may occur in the tissue rather than in the inner core.
(5) Knowledge of the exact shape of the heat flux on the skin was found to be unimportant for the determination of the temperature distribution away from the skin surface.
(6) Results obtained for the cylindrical and rectangular models were remarkably close for the practical range of variables. The rectangular geometry, however, is easier for computation.

Particular applications of the biothermal model were directed to the problem of extending the thermophysiological capabilities of man. Providing a "micro-climate" to man by means of cooling tubes that are in direct contact with the skin, e.g., extravehicular space suits, was a major concern in this study. Two lines of experimental investigations were pursued:

(1) Individual cooling pads were constructed and tested in a series of experiments on the thigh of a test subject. Temperature profiles on the skin between two adjacent tubes were obtained. Good agreement was found between the experimental and analytical results, thus partially validating the theoretical predictions.
(2) A cooling garment, including a cooling hood, was constructed. The garment consisted of sixteen individual pads made of Tygon tubes. These pads were grouped to provide independent supply of cooling water to six separate regions of the body: head, upper torso, lower torso, arms, thighs, and lower legs. Experiments with the cooling garment were directed at exploring the characteristics of independent control

of temperature and removal of excess heat from separate regions of the body. Five activity schedules were used with five test subjects. The activity schedules consisted of alternate sessions of standing and treadmill walking. Quasi-steady state and, to some extent, transient characteristics of the proposed scheme of independent regional cooling were studied. The results show that there are regions that require more cooling than others (thighs, lower legs, head). It was also demonstrated that heat strain was reduced as a result of wearing the cooling garment.

In summary, the analytical study resulted in temperature profiles that were partially validated by the experiments. Extension of the analysis to include more realistic and detailed values of the parameters invloved will have to be delayed, however, until such data become available. Independent regional cooling seems promising but requires more experimentation before any concrete conclusions can be drawn.

8. Westland, R. A.
A Biothermal Analog.
M. Sc. Thesis, Univ. of Cal. at Los Angeles, 1958.

Author's Abstract

The Biothermal Analog is a model of the complex heat trasfer mechanisms interior and exterior to man. The model, simulated by a special purpose electrical analog computer, is being developed to serve as an experimental tool in the investigation of transient human response to thermal exposure.

The investigation described was concerned with the determination of the values and temporal temperature dependencies of deep tissue conductances and the validation of the completed model. Because the conductance data is not readily obtainable in human experiments, an indirect method was proposed. The objective was to synthesize the conductance time functions that would yield known boundary, skin and core, temperature responses for a given set of environmental conditions, and to correlate these with the system variables of interest.

An analytical approach yielded the solution of the governing linear parabolic differential equations, but the complex nature of the formulation prevented the evaluation of the conductances. Secondly, a numerical analysis approach consisting of the solution of the differential equations by means of finite difference approximations was explored in detail, but did not yield the conductance data.

Although not specifically designed to solve the conductance problem, the Biothermal Analog Computer was utilized in the determination of the required functions. Dependency upon skin and core temperature was proposed, and successfully validated by comparison of human and model temperature responses in the environmental temperature range, 37.9°C to 67.9°C. The applicability of the analog to the study of biothermal problems was thus demonstrated.

C.2

9. Winton, H. J.
Computer Model of Human Thermoregulation.
Ph.D. Thesis, Univ. of Santa Clara, Santa Clara, Cal., 1970.

Author's Abstract

The physiological control system which enables man to regulate his body temperature is studied. Pertinent data on the characteristics of human thermoregulation are abstracted from the physiological literature. Based on this information a mathematical model of human temperature control is formulated. Transfer functions, nonlinear controller functions, and parameter values are then developed for the model. The structure of the model is that of a closed-loop feedback control system. Body thermal properties are represented by an electric circuit analog. The sudomotor, vasomotor and metabolic parameters in this circuit are made to be non-linear functions of an error signal derived from hypothalamic and cutaneous thermoreceptors.

System equations are derived and a digital simulation of the model using the System 360/CSMP computer language is discussed. An analog simulation of the same model is also given along with an evaluation of the advantages and disadvantages of each approach.

Comparison of model static and dynamic response with published data from physiological experiments shows good agreement over a broad spectrum of conditions including exposure to heat and cold, humidity and wind, ice ingestion, exercise and fever. The results obtained demonstrate the validity of the model and its ability to predict human thermoregulatory response.

Potential applications of the model in astronautics, medicine and physiology are discussed. The study concludes with suggestions for future research.

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REFERENCE	GEOMETRY: CYLINDRICAL	GEOMETRY: RECTANGULAR	GEOMETRY: SPHERICAL	GEOMETRY: TISSUE LAYERS CONSIDERED	THERMAL ENERGY MECHANISMS: CONDUCTION	THERMAL ENERGY MECHANISMS: METABOLIC HEAT GENERATION	THERMAL ENERGY MECHANISMS: TRANSPORT BY BLOOD	THERMAL ENERGY MECHANISMS: THERMAL INERTIA (1)	METHOD OF SOLUTION: ANALYTICAL	METHOD OF SOLUTION: NUMERICAL	METHOD OF SOLUTION: ANALOG NETWORK	METHOD OF SOLUTION: DISTRIBUTED PARAMETER	METHOD OF SOLUTION: LUMPED PARAMETER	BOUNDARY CONDITION SATISFIED AT THE SKIN SURFACE	THERMOREGULATORY MECHANISMS CONSIDERED	CLASS CATEGORY (2)	COMMENTS
1	+			CORE, MUSCLE, TISSUE, SKIN	+	+		+			+		+	LINEAR COMBINATION OF RAD., CONVEC. & EVAP.	PERSPIRATION	1	GENERAL DISCUSSION, NO RESULTS
2	+			CORE, MUSCLE, SKIN & TISSUE, OUTER SKIN	+	+		+			+		+	LINEAR COMBINATION OF RAD., CONVEC. & EVAP.	PERSPIRATION	1	INCLUDES COMPARISON WITH EXPERIMENTS
3	+			CORE, SKIN & FAT	+	+	+	+		+			+	LINEAR COMBINATION OF RADIATION & CONVECTION		1	MODEL OF A LIQUID, UNIFORM TEMP. AT EACH LAYER
4		+		CORE, MUSCLE, SUBCUTANEOUS, SKIN	+	+	+	+		+			+	HEAT EXCHANGE WITH COOLANT	RESPIRATION, PERSPIRATION	4	BODY & EXTERNAL COOLING [illegible] DIVIDED INTO ZONES
5				CENTRAL MUSCLE, SUBCUTANEOUS, SKIN	+	+		+			+		+	LINEAR COMBINATION OF RAD., CONV. & EVAP.	SHIVERING, VASOMOTOR, PULMONARY	1	
6					+	+	+	+				+				1	EQUATION FOR HEAT DISTRIBUTION IN THE BODY, NO SOLUTIONS
7				CENTRAL, MUSCLE, SUBCUTANEOUS, SKIN	+	+		+			+		+	LINEAR COMBINATION OF RAD., CONV. & EVAP.	SHIVERING, PULMONARY, VASOMOTOR	1	
8		+		CORE, MUSCULATURE, FUNCTIONAL PERIPHERY, SKIN	+	+				+			+	ISOTHERMAL BOUNDARY		4	
9		+		SKIN	+			+	+			+		HEAT FLUX, NEWTONIAN HEATING, CONST. TEMP.	NONE	3	MODEL CONSIDERED WITH SKIN TEMP. AS APPLIED TO BURN HAZARDS
10		+		SKIN	+			+	+			+		HEAT FLUX, NEWTONIAN HEATING, CONST. TEMP.	NONE	3	MODEL CONSIDERED WITH SKIN TEMP. AS APPLIED TO BURN HAZARDS
11																1&4	COMPREHENSIVE STUDY OF EXCHANGE OF HEAT WITH ENVIRONMENT
12		+			+	+			+			+		NEWTONIAN COOLING, EVAPORATION		3	TEMPERATURE DISTRIBUTION PARABOLIC
13		+		3 LAYERS	+	+		+		+		+		NOT SPECIFIED	NONE	1	
14			+		+	+	+	+	+			+			NONE	3	A METHOD FOR MEASURING THERMAL PROPERTIES "IN VIVO"
15			+		+	+	+	+	+			+			NONE	3	A METHOD FOR MEASURING THERMAL PROPERTIES "IN VIVO"
16		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+		+			+		HEAT FLUX	NONE	4	
17		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+		+			+		HEAT FLUX	NONE	4	DEFINES DIMENSIONLESS PARAMETERS ASSOCIATED WITH TRANSPORT OF HEAT
18		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+			+			+		HEAT FLUX	NONE	4	

(1) HEAT CAPACITY AND STORAGE CONSIDERED.
(2) CATEGORIES ARE: 1. ENTIRE BODY
2. SINGLE ELEMENT OF BODY, e.g., LIMB, HEAD.
3. LOCALIZED TEMPERATURE DISTRIBUTION, e.g., CRYOSURGICAL PROBE
4. BODY HEAT EXCHANGE WITH AN EXTERNAL ARTIFICIAL DEVICE, e.g., LIQUID COOLED GARMENT

TABLE OF ARTICLES & REPORTS (Continued)

REFERENCE	GEOMETRY: CYLINDRICAL	GEOMETRY: RECTANGULAR	GEOMETRY: SPHERICAL	TISSUE LAYERS CONSIDERED	THERMAL ENERGY MECHANISMS: CONDUCTION	METABOLIC HEAT GENERATION	TRANSPORT BY BLOOD	THERMAL INERTIA (1)	METHOD OF SOLUTION: ANALYTICAL	NUMERICAL	ANALOG NETWORK	DISTRIBUTED PARAMETER	LUMPED PARAMETER	BOUNDARY CONDITION SATISFIED AT THE SKIN SURFACE	THERMOREGULATORY MECHANISMS CONSIDERED	CLASSIFICATION (2)	COMMENTS
19		+			+				+			+			RESPIRATION	2	HEAT TRANSFER IN THE RESPIRATORY SYSTEM OF A SMALL MAMMAL
20	+				+	+	+	+	+			+			NONE	3	A METHOD FOR MEASURING THERMAL PROPERTIES "IN VIVO"
21		+		CORE, MUSCLE, SKIN	+	+		+			+		+	RADIATION, VAPORIZATION		1	
22		+		EPIDERMIS, DERMIS, DEEP FATTY & MUSCLE LAYERS	+			+	+			+		CONTINUITY OF TEMP. & HEAT FLUX	NONE	4	BURN HAZARD IN HUMAN TISSUE
23	+				+	+	+	+	+			+			NONE	3	DETERMINATION OF REGIONAL BLOOD FLOW IN POST-OPERATIVE PATIENTS
24	+				+	+	+			+			+			1 & 4	
25		+			+			+	+		+	+				2	PERIODIC TEMP CHANGES IN THE FINGERS' SKIN
26		+			+			+	+			+		NEWTONIAN COOLING	NONE	1	
27		+		CORE, MUSCULATURE, FUNCTIONAL PERIPHERY, SKIN	+	+				+		+		ISOTHERMAL BOUNDARY	NONE	4	
28		+		EPIDERMIS, DERMIS, FAT, MUSCLE	+			+	+			+		CONVECTION & RADIATION	NONE	1	ANALYSIS APPLIED TO THERMAL INJURY
29														RADIATION, CONDUCTION CONVECTION, EVAPORATION	NONE	1	PAPER DEALS WITH EXCHANGE WITH THE ENVIRONMENT
30														RADIATION, CONDUCTION CONVECTION, EVAPORATION	NONE	1	
31	+				+	+	+	+		+			+			1 & 4	
32	+			TISSUE, BONE FAT, SKIN	+	+	+			+			+	NEWTONIAN COOLING	NONE	1	
33														VASOMOTOR, EVAPORATION		1	THEORY FOR BODY-CLOTHING HEAT EXCHANGE
34		+			+	+		+	+			+		NEWTONIAN COOLING	NONE	1	
35		+		CORE, SUBCUTANEOUS TISSUE, SKIN	+		+		+			+		CONSTANT SKIN TEMPERATURE		1	
36		+		CORE, MUSCLE, SUBCUTANEOUS, SKIN	+					+			+	CONVECTION, PERSPIRATION RADIATION		1	
37			+	CENTRAL CORE, MUSCLE, SKIN	+	+		+		+		+		NEWTONIAN COOLING	RESPIRATION	1	SIMULATION OF A HIBERNATOR – MARMOT

(1) HEAT CAPACITY AND STORAGE CONSIDERED.
(2) CATEGORIES ARE:
1. ENTIRE BODY
2. SINGLE ELEMENT OF BODY, e.g., LIMB, HEAD.
3. LOCALIZED TEMPERATURE DISTRIBUTION, e.g., CRYOSURGICAL PROBE
4. BODY HEAT EXCHANGE WITH AN EXTERNAL ARTIFICIAL DEVICE, e.g., LIQUID COOLED GARMENT

TABLE OF ARTICLES & REPORTS (Continued)

REFERENCE	GEOMETRY: CYLINDRICAL	GEOMETRY: RECTANGULAR	GEOMETRY: SPHERICAL	TISSUE LAYERS CONSIDERED	THERMAL ENERGY MECHANISMS: CONDUCTION	THERMAL ENERGY MECHANISMS: METABOLIC HEAT GENERATION	THERMAL ENERGY MECHANISMS: TRANSPORT BY BLOOD	THERMAL ENERGY MECHANISMS: THERMAL INERTIA (1)	METHOD OF SOLUTION: ANALYTICAL	METHOD OF SOLUTION: NUMERICAL	METHOD OF SOLUTION: ANALOG NETWORK	METHOD OF SOLUTION: DISTRIBUTED PARAMETER	METHOD OF SOLUTION: LUMPED PARAMETER	BOUNDARY CONDITION SATISFIED AT THE SKIN SURFACE	THERMOREGULATORY MECHANISMS CONSIDERED	CLASSIFICATION (2)	COMMENTS
38		+		CORE, SKIN	+	+	+		+			+		NEWTONIAN COOLING		1	COMPARISON WITH THERMOGRAPHIC MEASUREMENTS
39			+	CENTRAL CORE, MUSCLE, SKIN	+	+		+		+		+		NEWTONIAN COOLING	RESPIRATION	1	SIMULATION OF A [illegible]
40		+		DEEP BODY CORE, MUSCLE, SKIN	+	+		+		+			+	CONVECTION & EVAPORATION	PERSPIRATION	1	ANALYSIS RELATED TO CLOTHING - AIRSPACE - SKIN SYSTEMS
41		+		CORE, MUSCLE, SKIN	+	+		+		+	+		+	EXCHANGE OF HEAT WITH COOLING GARMENT	VASODILATION, SWEATING, SHIVERING	4	
42		+							+			+			NONE	1	COUNTER-CURRENT HEAT EXCHANGE IN BLOOD VESSELS
43	+			FEMUR, MUSCLE, SKIN & FAT	+	+	+	+		+		+		NEWTONIAN COOLING	NONE	2	LEG COOLING
44														NEWTONIAN COOLING		1	POST MORTEM BODY TEMPERATURE MEASUREMENTS
45														NEWTONIAN COOLING	NONE	2	DIGITAL COOLING
46				CORE, MUSCLE, SKIN	+	+	+	+		+			+	SWEAT, RADIATION, MASS DIFFUSION		4	INCLUDES A DETAILED LISTING OF COMPUTER PROGRAM
47	+		+	DEEP TISSUE, SUPERFICIAL TISSUE	+	+	+		+			+		CONVECTION, EVAPORATION	PERSPIRATION	2	BODY TISSUES TREATED AS POROUS MEDIA
48	+				+	+	+		+			+		NEWTONIAN COOLING	NONE	2	
49		+	+		+	+	+	+	+			+				3	
50		+			+	+	+	+				+				3	
51					+	+	+	+				+				3	
52					+	+	+	+	+			+				3	
53	+			INNER (MUSCLE & BONE) OUTER (CUTANEOUS & FAT)	+	+	+		+			+			NONE	1 & 2	
54																1	MATHEMATICAL SIMULATION OF HUMAN THERMOREGULATORY HEAT PRODUCTION
55	+		+		+	+			+			+				3	
56			+		+	+			+			+					
57	+						+									3	HEAT EXCHANGE WITH PREHEATED DISCS TO DETERMINE SKIN CONDUCTANCE
58	+			CORE, MUSCLE & BONE, SKIN & FAT	+	+	+	+		+			+	CONVECTION, RADIATION EVAPORATION		1	
59		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+		+			+		HEAT FLUX CORRESPONDING TO METABOLIC RATE		4	

(1) HEAT CAPACITY AND STORAGE CONSIDERED.
(2) CATEGORIES ARE: 1. ENTIRE BODY
2. SINGLE ELEMENT OF BODY, e.g., LIMB, HEAD.
3. LOCALIZED TEMPERATURE DISTRIBUTION, e.g., CRYOSURGICAL PROBE
4. BODY HEAT EXCHANGE WITH AN EXTERNAL ARTIFICIAL DEVICE, e.g., LIQUID COOLED GARMENT

TABLE OF ARTICLES & REPORTS (Continued)

REFERENCE	GEOMETRY				THERMAL ENERGY MECHANISMS				METHOD OF SOLUTION					BOUNDARY CONDITION SATISFIED AT THE SKIN SURFACE	THERMOREGULATORY MECHANISMS CONSIDERED	CLASSIFICATION(2)	COMMENTS
	CYLINDRICAL	RECTANGULAR	SPHERICAL	TISSUE LAYERS CONSIDERED	CONDUCTION	METABOLIC HEAT GENERATION	TRANSPORT BY BLOOD	THERMAL(1) INERTIA	ANALYTICAL	NUMERICAL	ANALOG NETWORK	DISTURBED PARAMETER	LUMPED PARAMETER				
60		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+	+	+			+		HEAT FLUX CORRESPONDING TO METABOLIC RATE		4	COMPILATION OF DIMENSIONLESS PARAMETERS
61		+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+		+			+		HEAT FLUX CORRESPONDING TO METABOLIC RATE		1	VARIABLE BLOOD SUPPLY TEMPERATURE
62	+			INNER CORE, SKELETAL MUSCL[illegible]KIN	+	+	+		+			+		HEAT FLUX CORRESPONDING TO METABOLIC RATE		4	
63	+	+		INNER CORE, SKELETAL MUSCLE, SKIN	+	+	+	+	+			+		HEAT FLUX CORRESPONDING TO METABOLIC RATE		4	
64	+			CORE, SUBCUTANEOUS, SKIN							+				SWEAT, BLOOD FLOW	1	
65	+			CORE, SUBCUTANEOUS, CORIUM, EPIDERMIS	+		+				+		+		SWEAT, BLOOD FLOW	1	
66		+		SKIN SURFACE	+			+	+			+		RADIATIVE OR CONDUCTIVE HEATING		1	THERMAL INJURY
67		+		SKIN SURFACE	+			+	+			+		RADIATIVE OR CONDUCTIVE HEATING		1	THERMAL INJURY
68		+		CORE, MUSCLE, FAT, SKIN	+	+	+			+			+	EVAPORATION & EXCHANGE WITH ENVIRONMENT	SWEATING, VASOMOTOR	1	
69	+			CORE, MUSCLE, SKIN	+	+	+	+			+		+	EVAPORATION & EXCHANGE WITH ENVIRONMENT	SWEATING, VASOMOTOR, SUDOMOTOR	1	PASSIVE & ACTIVE SYSTEMS
70				SUBCUTANEOUS, SKIN				+			+		+			1	THERMAL RADIATION
71		+		CORE, MUSCLE, FAT, SKIN	+	+	+			+			+	EVAPORATION & EXCHANGE WITH ENVIRONMENT	SWEATING, VASOMOTOR, SUDOMOTOR	1	
72		+		CORE, MUSCLE, FAT, SKIN	+	+	+			+			+			1	
73	+				+	+	+	+		+			+			3	TEMPERATURE FIELD IN THE BRAIN
74	+				+			+	+			+				3	
75	+				+	+	+	+	+			+				3	
76	+				+	+	+	+		+			+			3	
77		+		SKIN	+			+		+		+		HEAT FLUX		1	COMPUTER PROGRAM FOR CALCULATION OF THERMAL INJURY
78		+		SKIN	+			+	+			+		HEAT FLUX		1	
79	+			CORE, MUSCLE & FAT, SKIN	+	+	+	+		+	+		+	EXCHANGE WITH ENVIRONMENT	SUDOMOTOR, VASOMOTOR METABOLIC	1	
80	+				+		+		+			+		NEWTONIAN COOLING		1	

(1) HEAT CAPACITY AND STORAGE CONSIDERED.
(2) CATEGORIES ARE: 1. ENTIRE BODY
2. SINGLE ELEMENT OF BODY, e.g., LIMB, HEAD.
3. LOCALIZED TEMPERATURE DISTRIBUTION, e.g., CRYOSURGICAL PROBE
4. BODY HEAT EXCHANGE WITH AN EXTERNAL ARTIFICIAL DEVICE, e.g., LIQUID COOLED GARMENT

TABLE OF ARTICLES & REPORTS (Continued)

REFERENCE	GEOMETRY: CYLINDRICAL	GEOMETRY: RECTANGULAR	GEOMETRY: SPHERICAL	GEOMETRY: TISSUE LAYERS CONSIDERED	THERMAL ENERGY MECHANISMS: CONDUCTION	THERMAL ENERGY MECHANISMS: METABOLIC HEAT GENERATION	THERMAL ENERGY MECHANISMS: TRANSPORT BY BLOOD	THERMAL ENERGY MECHANISMS: THERMAL INERTIA (1)	METHOD OF SOLUTION: ANALYTICAL	METHOD OF SOLUTION: NUMERICAL	METHOD OF SOLUTION: ANALOG NETWORK	METHOD OF SOLUTION: DISTURBED PARAMETER	METHOD OF SOLUTION: LUMPED PARAMETER	BOUNDARY CONDITION SATISFIED AT THE SKIN SURFACE	THERMOREGULATORY MECHANISMS CONSIDERED	CLASSIFICATION (2)	COMMENTS
81	+				+	+	+	+		+			+	NEWTONIAN COOLING		1	
82	+				+	+	+	+		+			+	NEWTONIAN COOLING		1	
83	+				+	+	+	+		+			+	NEWTONIAN COOLING		1	
84	+				+	+	+	+		+			+	NEWTONIAN COOLING		1	COMPARISON BETWEEN TWO MODELS
85														EVAPORATION		1	ONLY EXCHANGE MAN-ENVIRONMENT
86	+			CORE, MUSCLE, SKIN	+	+		+			+		+	RADIATION, EVAPORATION, CONVECTION		1	
87																1	PROPOSED CONTROL FUNCTION FOR THERMOREGULATION

(1) HEAT CAPACITY AND STORAGE CONSIDERED.
(2) CATEGORIES ARE:
1. ENTIRE BODY
2. SINGLE ELEMENT OF BODY, e.g., LIMB, HEAD.
3. LOCALIZED TEMPERATURE DISTRIBUTION, e.g., CRYOSURGICAL PROBE
4. BODY HEAT EXCHANGE WITH AN EXTERNAL ARTIFICIAL DEVICE, e.g., LIQUID COOLED GARMENT

ACKNOWLEDGMENT

This work has been carried out at Ames Research Center, NASA, while the author was a National Research Council Postdoctoral Associate. The useful comments and suggestions of Dr. A. B. Chambers and Dr. B. A. Williams are gratefully acknowledged. Thanks are also due to Mrs. Ann L. Ritchie for typing the rough draft of the manuscript, and to Mr. Ernie N. Hedges for an excellent job in typing the final copy. This work could not have been accomplished without the assistance of Dr. John E. Greenleaf, which is gratefully appreciated.