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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the work accomplished during the six years covered by this contract. A mathematical model of the human thermal system was developed, validated for accuracy under conditions typically encountered in Navy diving operations, and applied to several problems of current interest. The following problems were analyzed: (1) prediction of the performance of a new passive diver thermal protection system developed at NCSC, (2) analysis of the "lost bell" problem of saturation diving, (3) analysis of heat stress in hyperbaric environments, and (4) prediction of survival time for various

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20. accidents involving immersion in cold water.

DEVELOPMENT OF A MATHEMATICAL MODEL OF THE HUMAN THERMAL SYSTEM - FINAL TECHNICAL REPORT

Eugene H. Wissler
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I. Objective of the Project.

The objective of the work performed under this grant was to develop and validate a mathematical model of the human thermal system. Since it is generally difficult and expensive to conduct experimental studies on human subjects under conditions involved in diving, it is important to relate the results of experimental studies to a theoretical model. Of course, all thermal physiologists have theoretical models, but they are generally more qualitative than quantitative, and have little predictive value for situations other than those closely related to previous laboratory studies. Therefore, it was considered to be worthwhile to develop a model firmly based on the principles of heat transfer and incorporating as much thermal physiology as possible.

It was intended that the model could be used in three ways. One is to evaluate physiological phenomena which are not amenable to direct evaluation, such as the effect of countercurrent heat exchange between arteries and veins during cold exposure. Another is to predict behavior for conditions outside of the range studied in the laboratory, after prior evaluation using laboratory studies. For example, diver performance was predicted for various conditions while wearing the new Thinsulate dry suit developed at the Naval Coastal Systems Center, after it was established that computed results were in agreement with measured values for conditions studied in the laboratory. The third application is prediction of human behavior under circumstances that cannot be studied experimentally. Typical among these are various survival situations, such as accidental immersion in cold water and entrapment on the bottom of the sea in a "lost bell." Ethical considerations severely limit the duration of experiments involving exposure of human subjects to conditions which eventually become life threatening and, therefore, prediction of survival time involves a considerable extrapolation of experimentally measured values. If the prediction is to be meaningful, the extrapolation must be based on a firm theoretical basis, which implies that a mathematical model must be used. During the course of this contract, development and application of the model progressed as planned.

II. Summary of Work Completed.

Since the work completed under this contract has already been reported in progress reports and scientific papers, a complete discussion will not be included in this report. Instead, the work will only be summarized and references provided to principal papers in which more complete discussions are to be found. Anyone who wants copies of these papers can obtain them from the principal investigator.

Ref. A: Wissler, E. H., "Mathematical model of the human thermal system," Bull. Math. Biophysics, 26: 147-166 (1965).

The basic mathematical model of the human thermal system was developed by the principal investigator in 1965. This model was basically a passive physical model in which such physiological parameters as the perfusion and sweat rates were specified a priori as appropriate for the particular situation being simulated. Although this model was rudimentary in many respects, it provided the basic framework for subsequent developments which led to the current model. In this model the human is modeled geometrically as 15 elements which represent the head, upper and lower trunk, and proximal, medial and distal segments of each arm and leg. Each element is further divided into 15 concentric shells, and standard finite-difference techniques are used to approximate the heat conduction equation as applied to living systems. Heat generation by metabolic reactions, convective transport of heat by circulating blood, and variable physical properties were included explicitly in the original model.

Ref. B: Wissler, E. H., "Simulation of thermal transients during deep diving," pp. 477 to 488 in Proceedings of the 1977 Summer Computer Conference, Chicago, July 18-20, 1977.

During the intervening years, the original model was improved by incorporating additional elements of thermal physiology into the model. Included were control equations for cardiovascular responses to thermal stress and exercise, sweating, shivering, and ventilation. Since cardiovascular and ventilatory controllers respond to humoral factors, adding material balances for oxygen, carbon dioxide, and lactic acid was thought to be worthwhile. A simplified set of metabolic reactions was developed based on glucose as the substrate and allowing complete oxidation to CO_2 and H_2O for the aerobic production of ATP or yielding lactate for anaerobic production.

In addition to the biochemical additions made to the model, techniques were developed for simulating various garments, including liquid perfused suits for cooling astronauts during extravehicular excursions and heating divers working in cold water. The work referred to in Refs. A and B was completed before Navy sponsorship of the project was initiated.

Ref. C: Wissler, E. H., "A mathematical model of the human thermal system with reference to diving," pp. 187 to 212 in Thermal Constraints in Diving, L. A. Kuehn, editor, Undersea Medical Society, Bethesda, Sept. 3, 1980.

A reasonable complete description of the model as it finally evolved is presented in this paper. During the period of this contract, many improvements were made in the physiological control equations used to define local perfusion rates, intensity of shivering, and rate of sweating. Comparison of computed thermal responses with measured values for a number of cases allowed improvement of the cardiovascular controller for situations involving exposure of both resting and working subjects to cold stress. Briefly stated it was found that cold induced vasoconstriction causes perfusion rates to be reduced to the minimum level necessary to support metabolism. It was also found necessary to invoke countercurrent heat exchange between adjacent arteries and veins in order to conserve heat during exposure to extreme cold, such as immersion in 10^{o}C water. However, countercurrent heat exchange caused excessive central temperatures to occur when simulations were conducted for situations involving heat stress. This provided the motivation for adding vasomotor control equations which cause venous return from the extremities to pass through deep veins lying adjacent to arteries when it is desireable to conserve heat and through superficial veins near the surface when it is desireable to enhance heat transfer to the environment.

In addition to vasomotor response, human thermoregulation involves shivering during exposure to cold. Several control equations for shivering have been proposed by various investigators, but none of them appeared capable of describing all of the available data. Therefore, nine sets of published data were selected as a basis against which possible control schemes could be compared. In this way, a shivering controller was developed which described quite satisfactorily all nine sets of data. Afferent signals processed by the controller included the mean skin tenperature, hypothalamic temperature and their rates of change. A unique feature of the new controller is that it correctly predicts the transient peak in shivering metabolism which occurs during the first five minutes of exposure to fairly intense cold stress. The new controller, which has proven to be quite satisfactory in subsequent applications, is described in detail in this paper.

Another interesting feature of the shivering controller is that it allows for fatigue during prolonged intense shivering. The motivation for including this factor is that shivering is essentially a form of muscular work which is known to be limited by fatigue if sufficiently intense, and experiments involving long-term immersion in cool water have had to be terminated when the subjects developed severe cramps which could not be relieved. The basic premise of the fatigue model is that for metabolic rates in excess of approximately 50 percent of the maximum rate for a particular activity, glycogen is consumed at a rate sufficient to deplete the muscle stores and produce a state of fatigue. This concept appears to be consistent with experimental data relating to endurance studies for running, bicycling, lifting and shivering. However, there is a real need for additional data which could be used to validate the fatigue model more fully or to reveal its deficiencies so that they can be corrected. Survival studies to be discussed later in this report indicate that survival time in situations which involve moderate cooling rates is often determined by one's ability to maintain an elevated metabolic rate by shivering. When this ability is lost owing to fatigue, a state of deep hypothermia develops rapidly. Details of the fatigue model are presented in Ref. C, and examples of its application in two survival studies will be discussed later.

Several papers dealing with survival have stated that shivering is inhibited when the central temperature falls below 35°C. Although this feature was incorporated into earlier versions of the model, serious questions about the validity of the concept were raised by several physiologists who had observed unimpaired shivering at considerably lower central temperatures. Therefore, it was removed from the model at about the same time that fatigue was added.

Ref. D: Nuckols, M. L., "The development of thermal protection equipment for divers," pp. 132-166 in Thermal Constraints in Diving, L. A. Kuehn, editor, Undersea Medical Society, Bethesda, Sept. 3, 1980.

During the period of this contract, the principal investigator cooperated with the group at the Naval Coastal Systems Center which was developing new thermal protection equipment for divers. The model was used to define design parameters during the initial phase of the project, to analyze experimental data obtained on prototype systems, and to evaluate the performance of the final system for conditions other than those studied in the laboratory. This activity provided an excellent example of the value of such models in designing and evaluating systems containing a human as one component. This paper describes the development of the new system and presents an illustration of the capability of the model for describing human thermal response under various circumstances.

Ref. E: Nunneley, S. A. and E. H. Wissler, "Immersion Hypothermia: Validation of Computer Model and Prediction of Cooling Rates," pp. 213-239 in Thermal Constraints in Diving, L. A. Kuehn, editor, Undersea Medical Society, Bethesda. Sept. 3, 1980.

One of the survival situations analyzed using the model involves accidental immersion in cold water. Since human response can be studied only briefly under the conditions encountered in such accidents, prediction of survival time inevitably involves use of a mathematical model to extend the experimental observations. After establishing that the model developed under this contract is in reasonable agreement with the results of experimental studies involving subjects immersed in 5 to 18°C while nude, lightly clothed, or wearing anti-exposure suits, it was used to predict survival time for various water temperatures and clothing ensembles. The validation studies and predictions are discussed in detail in this reference.

Ref. F: Wissler, E. H. and S. A. Nunneley, "Human Thermal Response to Accidental Immersion in Cold Water: A Theoretical Study," Preprints of the Scientific Program of the 1983 Aerospace Medical Association Meeting, Houston, May, 1983.

Ref. G: Wissler, E. H., "An analysis of the 'lost bell' problem." pp. 315-345 in Thermal Constraints in Diving, L. A. Kuehn, editor, Undersea Medical Society, Bethesda, Sept. 3, 1980.

Another survival situation analyzed during this grant involves an isolated personnel transfer capsule trapped on the ocean floor. One of the serious, life-threatening factors in such accidents is exposure to severe cold which can rapidly produce hypothermia in inadequately protected divers. The importance of this problem became apparent several years ago when two divers perished in each of two accidents which occurred in the North Sea with hypothermia implicated as contributing strongly to the deaths.

Subsequently, experimental studies were conducted at the Norwegian Underwater Technology Center in Bergen and by the Royal Navy which conducted an open-sea trial. The mathematical model developed under this contract was used to simulate various conditions in order to provide a theoretical basis for interpretation of the experimental studies and to analyze other conditions which were not studied directly.

In this paper, detailed results are presented for one set of conditions which are typical of those existing in the North Sea. The following assumptions summarize these conditions:

1. There is complete loss of contact between the PTC and the surface support vessel.
2. The bell contains two divers.
3. The bell is 1.7 m inside diameter, has a steel wall 20 mm thick, and is insulated on the outside with a 22 mm thick layer of foam.
4. The atmosphere within the bell is 20 ata heliox initially at a temperature of 28^{o}C.
5. The temperature of the ocean is approximately 2^{o}C.
6. Survival for at least 24 hours is necessary.

In analyzing this problem, one must consider a number of factors, each of which potentially affects in a significant way the final conclusions. When there are no external sources of heat available, the divers must generate metabolically all of the heat which is transferred to the sea. If there is sufficient thermal resistance between the divers and the sea, they will be able to maintain body temperatures within an acceptable range; otherwise, generalized cooling will occur. The following factors must be taken into consideration.

1. Excessive loss of heat becomes life threatening to the divers. Enhanced heat generation owing to shivering, and vasomotor action serve to reduce the rate of bodily heat loss.
2. Heat transfer from the body can be reduced by increasing the thermal resistance of the diver's garment.
3. The gas space which surrounds the divers can provide an appreciable thermal resistance between the external surface of the garment and the interior surface of the bell. However, natural convection and heat transfer by radiation tend to reduce the resistance of the gas space.

4. If the bell is warm when contact with the surface is lost, several hours will pass before the walls cool to nearly the temperature of the sea. Even after the wall cools, it still provides some thermal resistance. Rigid foam applied to the exterior of the bell can significantly prolong the cooling time and enhance the thermal resistance of the wall.
5. Although it is generally small, there will be some thermal resistance at the bell-sea interface.

Results presented in this paper define in quantitative terms the factors mentioned above. Parameters which are not accurately known were allowed to vary over the expected range of values to determine the sensitivity of final conclusions to assumptions made in the analysis. Fortunately, those parameters which are known least accurately have a relatively small influence on the final result, and, therefore, the conclusions drawn from the study have value.

Following the presentation of this paper at the Undersea Medical Society Workshop on Thermal Constraints in Diving, the model was modified slightly, and additional cases were considered. In particular, suppression of shivering metabolism at central temperatures below 35°C was removed from the model, but fatigue was still considered to be an important factor in determining one's ability to survive. These results are described in two additional papers listed below.

Ref. H: Wissler, E. H., "An Analysis of the 'Lost Bell' Problem," in Workshop B - Aids to Underwater Operations, Proceedings of the Divetech '81 International Conference, Society for Underwater Technology, London, Nov. 1981.

Ref. I: Wissler, E. H., "Predicted Survivability of 'Lost Bell' Accidents under Various Conditions," to be published in Proceedings of the 8th Symposium on Underwater Physiology, Undersea Medical Society.

The second reference summarizes the results of the experimental and theoretical studies completed to date. It has been established that the theoretical model yields results which are consistent with a 24-hour survival test conducted at the Norwegian Underwater Technology Center. The adequacy of commercially available systems was also evaluated for situations other than those used in the laboratory study - 16 bars and chamber temperature decreasing from 30°C to 7°C. The "worst case" was found to be a welding habitat employed at a depth of 300 meters, for which standard systems are marginally safe. It is believed that this paper and the companion paper describing the experimental study provide most of the information needed to specify adequate survival systems for conditions likely to be encountered in current diving operations.

Ref. J: Wissler, E. H., "An Analysis of Heat Stress in Hyperbaric Environments," pp. 53-74 in Hyperbaric Diving Systems and Thermal Protection," C. E. Johnson, M. L. Nuckols, and P. A. Clow, editors, OED - Vol. 6, Am. Soc. of Mech. Engrs., New York, Dec. 1978.

Although the greatest concern in diver thermal protection is keeping divers warm, there are conditions under which they may be exposed to heat stress. Hyperbaric helium is particularly difficult to deal with because of its high thermal conductivity and low diffusivity for water. Hence, the effectiveness of sweating as a mechanism for dissipating heat is greatly reduced. This problem has been carefully analyzed in Ref. J, and guidelines are presented which allow diving supervisors to identify conditions that are potentially dangerous. Since the U.S. Navy may be called upon to operate in areas where air temperatures can be quite high, this paper should be of considerable interest to those responsible for insuring that the operations are conducted safely

Papers and Oral Presentations Prepared Under this Contract

Published Papers

"An Analysis of Heat Stress in Hyperbaric Environments," in Hyperbaric Diving Systems and Thermal Protection, C. E. Johnson, M. L. Nuckols, and P. A. Clow (eds.), American Society of Mechanical Engineers, New York, 1978, pp. 53-74.

"A Theoretical Analysis of the 'Lost Bell' Problem," pp. 31-41 in Proceedings of the Eleventh Annual International Diving Symposium, Association of Diving Contractors, New Orleans, February 1981.

Published Papers (cont.)

" A Mathematical Model of the Human Thermal System with Reference to Diving," pp. 187 to 212 in Physiological Criteria of Diving Equipment--Thermal Aspects, L. A. Kuehn, ed., Undersea Medical Society, June 1981.

"Immersion Hypothermia - Validation of Computer Model and Prediction of Cooling Rate," pp. 213 to 239, ibid.

"An Analysis of the 'Lost Bell' Problem," pp. 315 to 345, ibid.

"A Theoretical Analysis of the 'Lost Bell' Problem," in Proceedings of the International Conference, Divetech '81, Society for Underwater Technology, London (November 1981).

"Estimation of the Error Involved in Using Thermal Flux Transducers Under Various Conditions," Undersea Biomedical Research, Supp. to Vol. 9, No. 1, p. 14, March 1982 (with R. B. Ketch).

Oral Presentations

(with Robert Ketch) "An Effective Temperature Scale for Characterizing Heat Stress in Hyperbaric Environments," Joint Meeting of the North Pacific and Gulf of Mexico Chapter of the Undersea Medical Soc., San Antonio, Tex., October 1978.

"An Analysis of Heat Stress in Hyperbaric Environments," Winter Annual Meeting of the American Soc. of Mech. Engrs., San Francisco, Cal., December 1978.

(with M. L. Nuckols) "Integration of Physiological and Physical Factors in the Design of Passive Thermal Garments for Divers," Annual Scientific Meeting, Undersea Medical Soc., Key Biscayne, Fla., May 1979.

"An Analysis of Emergency Heating Requirements for Personnel Transfer Capsules," Undersea Medical Society Meeting, Athens, Greece, July 6, 1980.

Oral Presentations (cont.)

A Mathematical Model of the Human Thermal System with Reference to Diving. Undersea Medical Society Workshop on Physiological Criteria of Diving Equipment--Thermal, Bethesda, Md., Sept. 3-4, 1980.

Immersion Hypothermia--Validation of Computer Model and Prediction of Cooling Rate, ibid (with S. A. Nunneley).

An Analysis of Emergency Heating Requirements for Personnel Transfer Capsules, ibid.

Mathematical Model for Predicting the Thermal Behavior of Divers: Theory, Validation and Applications, Winter Annual Meeting of ASME, Chicago, November 16-20, 1980 (with M. L. Nuckols).

A Theoretical Model of Accidental Cold Immersion, 73rd Annual Meeting of AIChE, Chicago, November 16-20, 1980 (with S. A. Nunneley).

Body Cooling Rate in Hyperbaric Heliox, European Undersea Biomedical Society Annual Meeting, Cambridge, England, July 19-23, 1981 (with A. Påsche and S. Tønjun).

"A Theoretical Analysis of the 'Lost Bell' Problem," Divetech '81 Conference sponsored by the Society for Underwater Technology, London, November 1981.

"Estimation of the Error Involved in Using Thermal Flux Transducers under Various Conditions," Annual Scientific Meeting of Undersea Medical Society, Norfolk, Va., June 1982 (with R. B. Ketch).

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