. COMPUTER MODELING OF PHYSIOLOGICAL RESPONSES: TRENDS FOR THE FUTURE

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DEFINITION AND PURPOSE OF A MODEL

A computer model is a simplified mathematical representation of the complex reality. The degree of simplification and the level of complexity depend on the purpose of modeling. The simplest model solving the defined problem should be the adequate one. The purpose of a model may be:

1. Summary or reduction of results, stabilizing the degree of truth (by way of exact formulation).
2. Better insight into functional mechanisms, formulation and test of hypotheses (together with an experimental program).
3. Extrapolation and prediction
    - of variables not experimentally attainable
    - of physiological behavior and performance in extreme conditions.

DESCRIPTIVE AND FUNCTIONAL MODELS

We have to differentiate between descriptive and functional models (Fig. 1). These two really represent different worlds, although both deliver mathematical equations or **diagrams.** The descriptive mathematical model is nothing but an equivalent mathematical description of a principally known relationship, which in most of the cases had been determined experimentally and represented graphically. As the mathematical expression is mostly attained by correlation and regression analysis, the result, variable **A** as **a** function of variables B, C, D (in the example of Fig. 1: mean body temperature as a function of ***air*** temperature) is not based on any causal physical law nor is anything implied about functionality or causality. It is just another form of phenomenological description. The predictive value is therefore only small, in contrast to the functional model where one starts with mathematical equations representing well-known physical laws underlying the physiological processes. Usually, these are differential equations which may reveal new insights only after they will have been solved. For instance, we may formulate the heat balance for the body tissue: Heat flow, that is tissue density **p,** times specific heat c, times time derivative of temperature T, is equal to the sum of metabolic heat production M plus conductive heat flow (a well-known physical law conductivity index λ times second spatial derivative of temperature with respect to the local coordinate x) plus convective heat flow due to perfusion with blood.

At the skin surface there is a second heat balance: heat flow which, due to conduction, is present at the surface, may be transferred to the environment according to the temperature difference of skin and air. If we assume radiant temperature to be equal to air temperature, conduction, convection and radiation to or from the environment may be defined by using an overall heat transfer coefficient h. Evaporation E has to be taken into account separately. Many models simplify these equations, e.g. by neglecting the local dependency (i.e. the local coordinate x), and by using simple substitutional processes especially for conduction and convection. However simple or complex this or that equation may be, the equations have to be solved, which is mostly done by the computer, using well-established numerical techniques. A very universal and generally applicable result, may be attained, as in the example of Fig. 1 showing the dependency of body temperature on the local coordinate x (within the body), on time t, on metabolic heat production M, evaporation E, on air temperature and more climatic variables, but also on the physical parameters of the body: density, specific heat, conductivity, heat transfer coefficient. So it is easy to recognize that by changing the independent variables or the parameters, an immense predictive value of such functional complex models may be obtained. The reliability depends on the correctness of the equations and the reasonable determination or estimation of parameters.

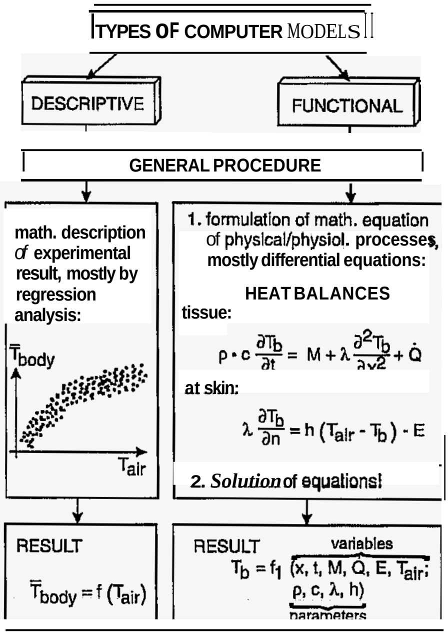

Fig. 1: Descriptive and functional models (see text)

Of course, any model has to be validated by the comparison of different sets of experimental and computational results before producing predictive results. What is needed in the future are not only computer models, but better validated models.

TYPES OF FUNCTIONAL MODELS IN ENVIRONMENTAL ERGONOMICS

There are different types of functional models especially useful in environmental ergonomics: models of heat transfer processes in compartments of the body or in the whole body (Fig.2). A very simple one is the core/shell model: two simple equations for the body, one for core temperature, the other for skin temperature. Cylinder-models represent the complex geometry of the body by one or multiple cylinders. Mostly they are one-dimensional, i.e. they take into account only the radial dependency of temperature to the skin surface. A three-dimensional model taking into account the true geometry of the body was first introduced in 1988 [1]. Compartmental models are used primarily for problems of heat transfer in hypo- and hyperthermia. These are thermal models for the arm and hand, for the finger, the foot, various organs, muscle tissue or the thermal transition between vessels and tissue. The problems of heat and mass (vapor) transfer through clothing are also tackled both by mathematical models and by measurements on manikins. Sometimes several types of mathematical models are linked together, the final aim being to integrate thermoregulatory, circulatory and other models.

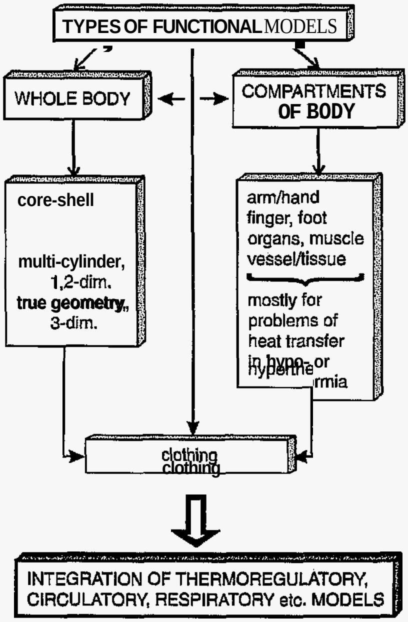

Fig.2: Types of functional models (see text)

WHOLEBODY-MODELS

Milestones of thermoregulatory modeling were the 3-cylinder, 2-3 layer model of Stolwijk and Hardy [2] and the multi-cylinder model of Wissler [3]. Further attempts were e.g. the two-dimensional cylinder approach of Kutznetz [4] and the THERMOSIM-model [5,6], see Fig.3, which is available for use on any IBM-compatible personal computer and, for convenience, is embedded in a WINDOWS-shell. From this 6-cylinder model a comparison of experimental and computational results is shown in Fig.4. The experiments were done by Savourey and Bittel [7]. Ten unclothed subjects were transferred from thermoneutral conditions very quickly to 1°C air temperature with 0.8 m/s air velocity for two hours. The experimental and the computational results show good agreement.

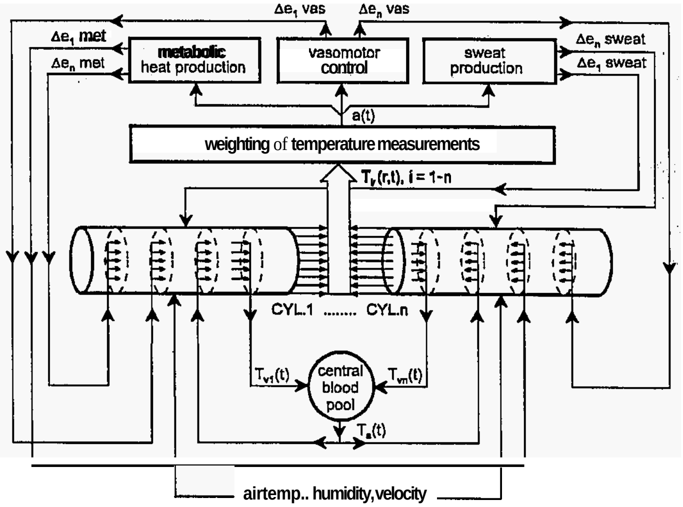

Fig.3: Scheme of the six-cylinder THERMOSIM model

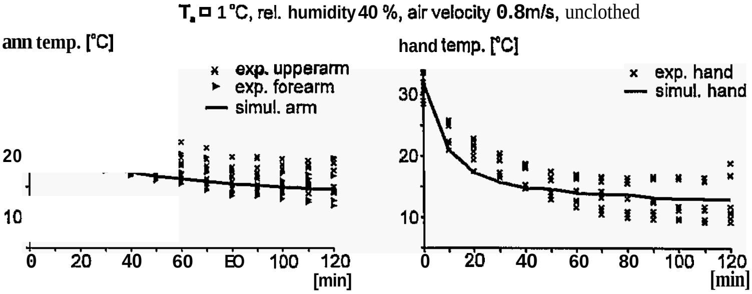

Fig. 4: Comparison of experimental and computational results (THERMOSIM) [6, 7]

Information about longitudinal temperature gradients along the central axis of the elements of the body is scarcely available. Fig.5. shows some predictive results from a three-dimensional model [8] which is based on the method of photogrammetry of physical (anatomical) models: head, arm, leg, and trunk temperature along the central axis for an ambient temperature of 40°, 30°, 20°, 10°C. Interesting details may be recognized, e.g. lower temperature in the bony knee area. The dominant trend for the future of whole-body-models will be the use of modern imaging techniques, especially magnetic resonance imaging (MRI) to get precise mathematical phantoms of the body and its parts ("VOXEL-MAN"). The adequate computing techniques are the finite-element methods in contrast to the finite-difference methods used in classical modeling.

VASCULAR AND NON-VASCULAR MODELS

Present efforts insolve the attempted solution of the intricate problem of heat transfer from and into networks of vessels of medium diameter. Brinck and Werner [9] developed a three-dimensional "vascular model" (Fig.6) in which convective heat transfer in a human extremity was explicity quantified taking into

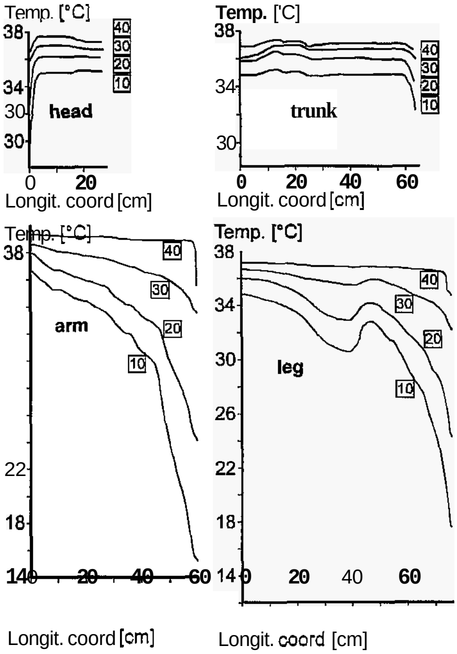

Fig.5: Central longitudinal temperature profiles at various ambient temperatures from 3-D model [1,8]

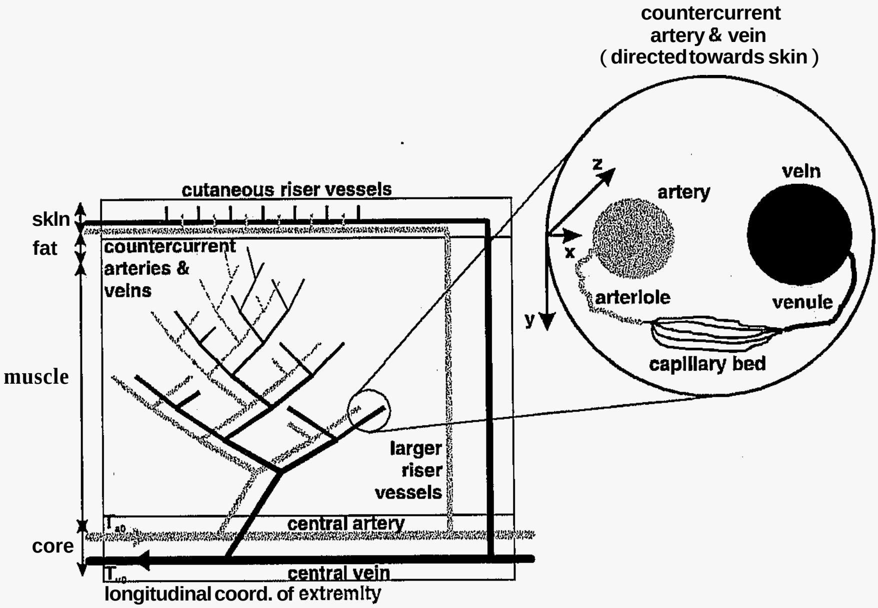

Fig.6: Scheme of vascular model in the extremity [9]

account the physical details of the vascular system. The spatial pattern in the arterial, venous and tissue temperatures was computed. Former approaches avoided the explicit representation of the three-dimensional vascular architecture and tried to compute the heat transfer between tissue and blood using substitutional processes, so-called "non-vascular models", either in the form of distributed heat sources and sinks (bio-heat approach [10]) or by using an enhanced thermal conductivity index [11]. For the microcirculation these models may be used, but generally not for vascular networks of vessels of medium diameter, where vascular models have to be applied. However, extremely complex vascular models, although delivering valuable results substantially more reliable than those of former non-vascular models, can hardly be used routinely, e.g. as a module for thermoregulatory whole-body problems. Therefore, based on the results of the 3-D vascular model, an efficiency function EF was computed [12] dependent on perfusion and tissue depth which compensates for the deficiencies of the bio-heat approach by multiplying the bioheat perfusion term with EF.

In this way, minimal deviations from the results of the complex vascular model are obtained by the efficiency function approach [12, 13], although its implementation is very easy, like that of the bio-heat approach. Future efforts are necessary to obtain results from vascular models based on various vessel network patterns present in other tissue than muscle tissue of the extremities.

CONCLUSION

Computer modeling used in combination with experimental projects and making use of modern imaging techniques (MRI) will be an even more powerful tool than ever before. Nevertheless, objections against modeling are always present. The forefathers of modeling had to face the classical objection that, in view of the complex and precise reality, the models were too simple and inexact. Recently one anonymous referee criticized: "Your model is too complex and precise in view of the possibilities of inexact measurements of reality". I am thus convinced and conclude that the problems of reliability of good models are not greater than those of experimental results. However, I recommend firmly that both experimental and modeling research are done and the results integrated. Both techniques used in an integrative manner are the prerequisites of future progress in environmental ergonomics.

REFERENCES

1. Werner, J. and Buse, M. 1988, Temperature profiles with respect to inhomogeneity and geometry of the human body. ***Journal of Applied Physiology,*** 65, 1110-1118.
2. Stolwijk, J. A. J. and Hardy, J. D. 1966, Temperature regulation in man - a theoretical study. ***Pflügers Archiv,*** 291, 129-162.
3. Wissler, E. H. 1964, A mathematical model of human the thermal system. ***Bulletin of Mathematical Biophysics,*** 26, 147-166.
4. Kuznetz, L. H. 1979, A two dimensional transient mathematical model of human thermoregulation. ***American Journal of Physiology,*** 237, 266-277.
5. Werner, J. and Webb, P. 1993, A six-cylinder model of human thermoregulation for general use on personal computers. ***Annals of Physiological Anthropology,*** 12, 123-134.
6. Werner, J. and Xu, X. 1995, Whole-body (THERMOSIM) model, in P. Tikuisis (ed.), ***Handbook on predicting responses to cold exposure*** (NATO AC/243, Panel 8, TR/20, Brussels), 2-1 - 2-33.
7. Savourey, L. M. J. and Bittel, J.H.M. 1995, Cold air exposure of unclothed subjects, in P. Tikuisis (ed.), ***Handbook*** on ***predicting responses to cold exposure*** (NATO AC/243, Panel 8, TR/20, Brussels), 2-23 - 2-25.
8. Werner, J., Buse, M. and Foegen, A. 1989, Lumped versus distributed thermoregulatory control: results from a three-dimensional dynamic model. ***Biological Cybernetics,*** 62, 63-72.
9. Brinck, H. and Werner, J. 1994, Estimation of the thermal effect of blood flow in a branching countercurrent network using a three-dimensional vascular model. ***ASME Journal of Biomechanical Engineering,*** 116,324-330.
10. Pennes, H. H. 1948, Analysis of tissue and arterial blood temperatures in resting forearm. ***Journal of Applied Physiology,*** 1, 93-122.

11. Weinbaum, S. and Jiji, L.M. 1985, A new simplified bioheat equation for the effect of blood flow on local average tissue temperature. *ASME Journal of Biomechanical Engineering*, 107, 131-139.
12. Brinck, H. and Werner, J. 1994b, The efficiency function - an improvement of the classical bio-heat approach. *Journal of Applied Physiology*, 77, 1617-1622.
13. Brinck, H. and Werner, J. 1995, Use of vascular and non-vascular models for the assessment of temperature distribution during induced hyperthermia. *International Journal of Hyperthermia*, 11, 615-626.