THERMO REGULATION IN HUMAN BODY

A DISSERTATION

Submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
MEASUREMENTS & INSTRUMENTATION

By

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CONTENTS

ABSTRACT

Thermo-regulation in human body has been discussed from various angles. The need of thermo-regulation studies has been stressed upon. The internal thermo-regulatory mechanism of the body under abnormal atmospheric conditions has been discussed. In case of atmospheric conditions going beyond the control of internal thermo-regulation, external means of thermal-regulation becomes necessary. Anatomical and physiological aspects have been discussed to give due preparatory importance.

A number of mathematical models developed for studying the behaviour of human body under various atmospheric conditions as well as under different metabolic activities have been reviewed for steady state and unsteady state conditions. Some of these models include physiological parameters of the body also.

A new improved model of human thermo-regulatory system is suggested under steady state conditions. With the help of this model temperature distribution in head and total metabolic heat generation in the body with changing body temperatures have been calculated. Also one scheme of external thermo-regulation needed under extreme working conditions has been considered to find out the relationships among coolant mass flow rates, coolant temperatures and the body temperature to put the body in Thermal Comfort i.e. near 98°F. All results have been summarized at the end.

ACKNOWLEDGEMENT

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(R.K. Agarwal)

<u>**CERTIFICATE**</u>

This is to certify that the dissertation entitled 'Thermo-Regulation in Human Body' which is being submitted by Sri RAMA KANT AGARWAL in partial fulfilment for the award of the degree of Master of Engineering in Electrical Engineering (Measurements and Instrumentation) of the University of Roorkee, is a record of student's own work carried out by him under our supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or diploma.

This is to further certify that he has worked for a period of five months for preparing this dissertation at this university.

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CHAPTER - I

INTRODUCTION

Human organism is one of the most intricate organisms developed in the nature. Since the current model of the human organism is the result of evolutionary processes over millions of years, it has developed substantial adaptibility to the environmental variables within the world in which we live, including its atmosphere. There are, however, certain natural environmental conditions that are outside the reach of the human beings range of adaptibility. But in the present age of fast development in Engineering and Technology, people are becoming much more concerned about victory over such environmental conditions. Of the various atmospheric variables, the temperature and its regulation and associated factors related to human thermal equilibrium, probably are of most universal concern to people.

1.1 TEMPERATURE REGULATION

There are two types of creatures in the world.

(i) Cold Blooded or poikilothermic e.g. Lizard, fish.

(ii) Warm Blooded or homothermic e.g. man.

In the first case, animals adjust their temperature and bring it equal to environmental temperature i.e. their temperature and outside temperature is always same.

In the second case, the body has got certain fixed temperature which, of course, varies with age, sex, and season. The human body is continuously generating heat. In the state of rest, an adult male generates about 70 K cal/hr. of heat.

Under the conditions of activity, more heat will be generated; for example under conditions of severe exercise the heat production can increase to 700 K cal/hr or 10 times the basal metabolic rate.(This has reference to Appendices I and II). The body operates most effectively where its rectal temperature is about 98°F and by various methods it is continually in the process of attempting to maintain body temperature within a close tolerance of that level. This adjustment process involves continuous thermal exchange with the environment. So somehow the temperature in the body is regulated if the atmospheric variations are under limits.

1.2 IMPORTANCE AND NECESSITY OF THERMOREGULATION STUDIES

If a man is to stay alive, his internal organs must maintain a body (rectal) temperature of 98°F. Even though a variation of ±5°F can be tolerated by a healthy man, noticeable discomfort and danger is usually caused by such a deviation. If the temperature is more than 103°F, the brain cells will be damaged irreparably. And if the temperature is below 94°F, the activities of the man are reduced to a great extent.

When the human body temperature falls to about 24°C (77°F) and when this temperature is maintained for several hours, death occurs. On the other hand, a temperature higher than 44 or 45°C (111°F to 113°F) maintained for more than a brief period becomes fatal [22].

When the humidity is zero, quite high temperature can be sustained by a person for a considerable length of time. However, profuse sweating occurs in such an environment which may dehydrate the body to such an extent which may endanger circulation of blood to the skin. If it is prevented by copious drinking of water, the loss of NaCl in the sweat may induce heat cramp, which developed much pain and perhaps spasmodic (sudden) contraction of muscles.

A high degree of external temperature, coupled with high humidity renders it difficult for the body to lose heat by either radiation or vaporization, sunstroke may then occur. This causes cessation of sweating (therefore dry, hot skin) and a very sharp rise in body temperature. Pulse rate and blood pressure go above normal. The person becomes unconscious, with muscles becoming inactive, he may be delirious (mental disorder) or in convulsions (fits of laughter or hysteria). The body temperature may rise to 110°F. At this temperature, the brain cells are quickly affected and irreparably destroyed, unless the temperature is quickly reduced by ice packs and cold baths.

In contrast to the conditions mentioned in above paragraph, the body temperature may be normal or even a bit below normal, and the skin is cool and moist (clammy). Under these conditions, the blood pressure goes low and pulse becomes very rapid, weak and soft. Elderly people and those in enfeebled health are more prone to suffer from this trouble, known as Heat Exhaustion.

The above discussion shows quite clearly how important the thermoregulation studies are. If a man has to work efficiently in odd atmospheric conditions, and under sudden changes of environments, the thermo-regulation mechanism should be studied in detail.

In most natural environments, rectal temperature of 98°F can usually be maintained by wearing clothes. If, however a man is exposed to a very hostile environment such as space exploration, under water activity or hazardous industrial conditions such as steel mill operation or mining work, the wearing of clothes and physiological thermo-regulation (which regulates the physiological thermal behaviour) cannot maintain the inside body temperature within ±5°F tolerance. An external thermal regulation device will then be needed. In order to design or control such an external thermal regulation device, extensive knowledge is required of internal body heat transfer and its relationship with environment. This will necessitate the development of mathematical models of-

(i) human systems which describes the phenomenon of heat transfer inside the body, and

(ii) the external thermal regulation device which controls the ambient (adjacent to skin) temperature.

1.3 EXTERNAL THERMAL REGULATION MEANS

It has already been noticed that under abnormal conditions, body creates its own microenvironment to have satisfactory thermo-regulation. Shivering is there for cold weather and sweating is associated with hot one. But when the conditions go beyond the scope of microenvironment, it is necessary to provide external means for regulation purpose. For cold weather, of course, clothes can provide good thermo-regulation. But in extremely cold surroundings some extra heating means is necessary. That is why the people sit near fire in winters. Quite opposite is the case for hot environmental conditions. Cooling of body becomes necessary. This is the reason why 2-3 baths gives comfort in summer.

Stolwijk and Hardy [6] used the thermal sensation scales for temperature to designate the thermal state of the man i.e. how a man feels under hot and cold conditions. These were the ASHRAE scale with 'NEUTRAL' instead of 'COMFORTABLE' and a second sensation scale for comfort as follows.

COMFORTABLE - Slight UNCOMFORTABLE - UNCOMFORTABLE - VERY UNCOMFORTABLE.

There is one good example of typhoid fever in which case inside temperature of body goes upto undesirable extent or other examples of paratyphoid where the body temperature goes down to undesirable extent. In both cases external means to regulate this temperature is essential. In the former case it is attempted to reduce the temperature of body by keeping wetted strips of clothes and in later one it becomes essential to increase the temperature by some other heating mechanism.

Skin sweating is both a protection as well as a stress to an astronaut. On one hand it is his best protection against sudden body heating, on the other hand it causes discomfort and dehydration in a sealed chamber or cabin and constitutes an undesirable type of heat load on any accompanying air-conditioning equipment. Cooling effectiveness of skin sweating i.e. the ability to evaporate sweat at skin surface depends wholly on environmental factors (e.g. the use of ventilated clothing, the presence of low ambient humidity and air movement).

Royal Aircraft Establishment [6] found a novel way of thermo-regulation of a pilot by developing one type of undergarment. The undergarment uses conduction cooling as an external means of thermoregulation. The external thermo regulation device is considered to consist of a network of tubes which is held in contact with the skin of the person. Liquid coolant is assumed to be flowing constantly inside the tube. The control of external thermal regulation device is performed in such a way that the requirement of body thermo-neutrality is satisfied. The skin temperature corresponding to comfort conditions would minimise the natural thermo-regulatory mechanism of shivering, sweating and vascular adjustments.

In the present work the author has tried to analyse some results for such scheme of external thermal regulation to show how the varying amounts and varying inlet temperatures of coolant may be employed to maintain a microenvironment near human body to keep him in thermal comfort. Also the effect of change in metabolism (which may be caused by any reason say heavy work, exercise etc.) on the variation of body temperature is studied.

CHAPTER - II

ANATOMY AND PHYSIOLOGY OF THERMOREGULATORY SYSTEM

2.1 ANATOMY OF THE HMO REGULATORY SYSTEM

The body is a material mass with a corresponding heat capacity, that is, at any time an amount of thermal energy is stored which is approximately proportional to temperature. When there is temperature equalibrium, the body must steadily dissipate heat at a rate equal to the internal generation rate. If these rates become mismatched, the internal temperature starts a corresponding change (either rising or falling). The gross information flow diagram for the complete control system is shown in Fig.1.

2.1.1 Controlled Process and Actuators

For thermo-regulatory modelling purposes, the controlled process can be divided into three different regions [15] and these necessarily incorporate the following actuating mechanism.

2.1.1.1 The deep body or core : Comprises all the body except the skelatal muscle and skin, but in particular includes the viscera and the CNS (CENTRAL NERVOUS SYSTEM). The fact that the material is definitely not homogeneous add to the difficulty of mathematical modelling (Chapter III). Much of the basal metabolic rate (BMR) is generated here and must be dissipated to the environment. The BMR is controlled by the endocrine system and thus to some extent can provide an actuator for thermo-regulation.

2.1.1.2 The Skeletal Muscle : generally surround the core and

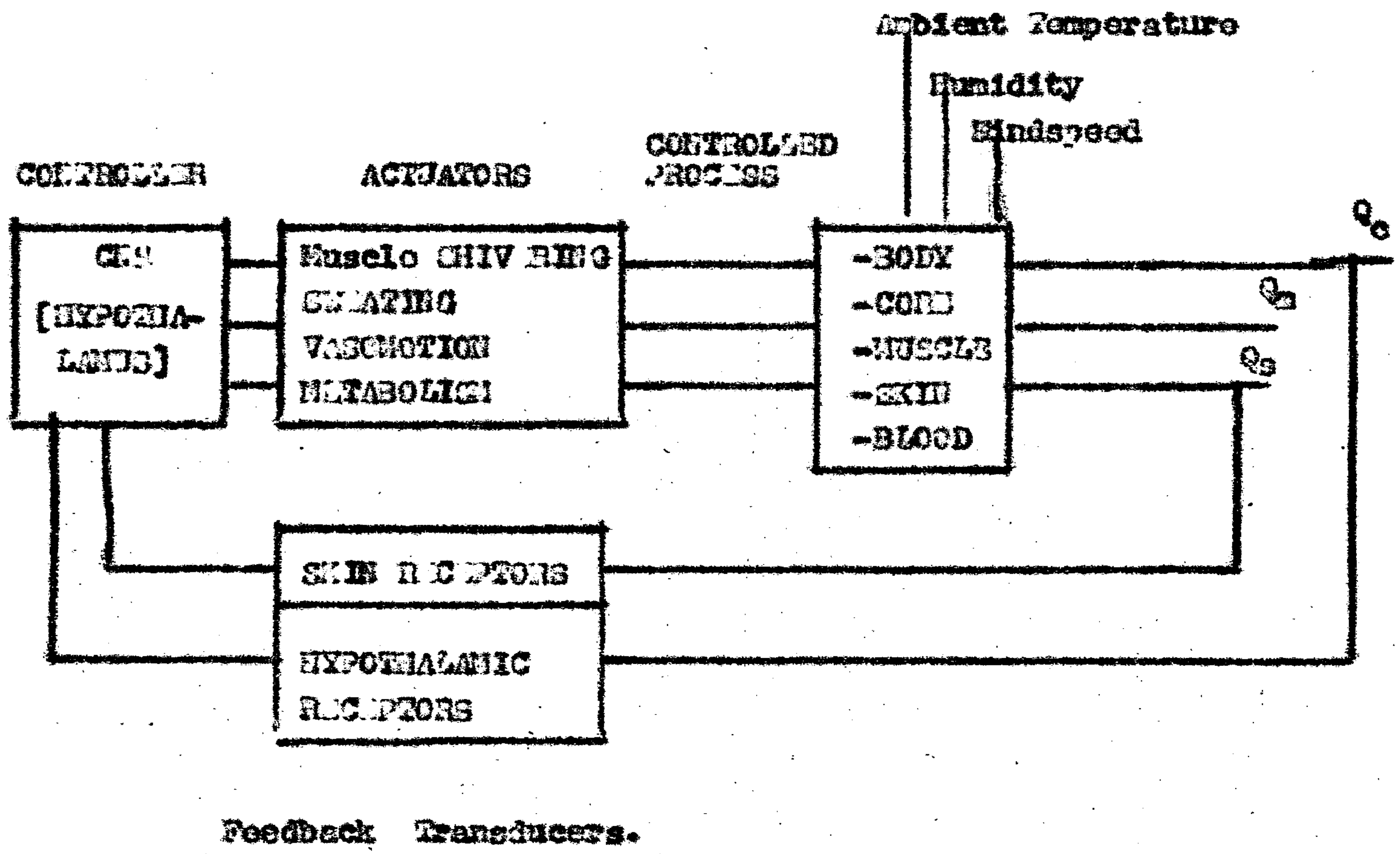


Fig.1 GROSS INFORMATION FLOW DIAGRAM OF THERMOREGULATORY SYSTEM.

comprise rather more than one third of main body weight. They are of particular interest in temperature regulation because they shiver when the system cools. This shivering is unco-ordinated (normal tension producing operation of an antagonistic pair is co-ordinated), so that all the energy input appears as a heat flow instead of some as mechanical work. The economy of component design is worth nothing here, that is the muscle serves a second useful purpose as <u>actuator</u> in the temperature control system in addition to its presumed primary but different purpose of skeletal posture and movement. The tonic contraction of skeletal muscle , muscles, combined with their inherent inefficiency in converting chemical energy to mechanical energy, also makes the muscle region one of continuous HF.

2.1.1.3 <u>The Skin</u> : provides external cover to the muscle and core. Disregarding other functions it is therefore a thermal insulator for the temperature control system, although a very actively variable one. The insulation effect is directly varied by the vasomotor effect which decreases blood flow to the surface (vaso-constrictional) where heat loss is to be reduced, and vice-versa (vaso-dilatoral). In addition there is a mechanism of sweating through the skin pores to produce water evaporation and therefore increased heat loss. Apart from evaporation, the skin also loses heat by convection and radiation, when the skin is hotter than the environment. Evaporation allows the organism to survive against an adverse temperature gradient (ambient higher than skin surface) when the other modes produce a net gain of heat to the body.

For furry animals, hair erection is another surface phenomenon which reduces heat loss against cold weather. However, such animals can not sweat profusely in hot weather (for example the dog has no sweat glands except on the paw pads) and hence the panting phenomenon has been evolved to increase evaporation from the respiratory region, especially the tongue. However, the last two effects are not applicable for human beings.

The circulating blood plays a large part in achieving heat transfer among these three regions, and therefore should ideally be considered a fourth mechanism in thermo-regulation.

2.1.2 Feed-back Transducers - Temperature Measurement

It has been satisfactorily determined that the body contains both deep central and skin thermo-receptors, as well as some others for example in the respiratory tract. The central receptors are obviously analogue to the thermostat, and the skin receptors provide as close information to ambient air conditions as can conveniently be obtained physiologically.

2.1.2.1 Cutaneous Thermo-receptors : Two types of thermoreceptors have been identified in the skin [17,20], viz. cold receptor and hot receptors.

The cold receptor responds particularly to decreasing skin temperature, but there is steady-state tonic discharge which varies with temperature. The skin is more profusely supplied with these cold receptors than with warmth receptors.

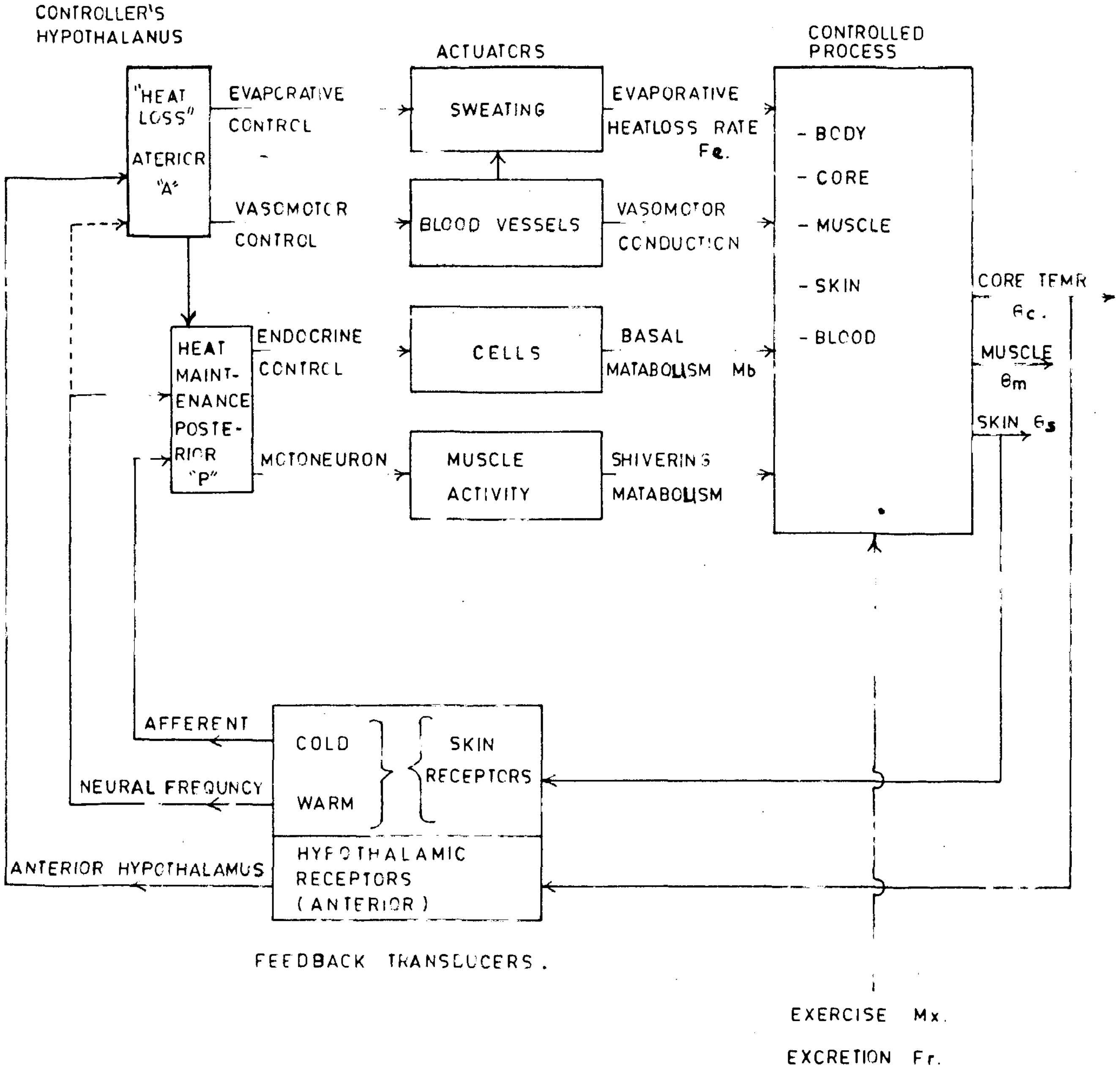
The warmth receptor responds particularly to increasing skin temperature, but also exhibits steady state discharge.

2.1.2.2 <u>Hypothalamic Thermo-receptors</u> : These receptors [7] are near the site of the controller for the temperature regulation system. Their mode of action is not well understood but a good correlation has been demonstrated between interior hypothalamus temperature and the level of local 'slow potential' in this region.

Fig. 2 shows the gross information flow diagram and includes the individual feed back paths.

2.1.3 <u>HYPOTHALAMUS - The Controller and Comparator</u>

The hypothalamus is sought to be the 'controller' for thermoregulation, having two complementary sites, the heat maintenance centre situated in the posterior hypothalamus, and the heat loss centre situated in the anterior hypothalamus. By experimental calorimetric work, it has been found that the heat loss centre uses core temperature information (by hypothalamic thermoreceptors) to drive the actuating variables of heat loss. Sweating is the primary mechanism for augmenting heat loss, but this is aided by vasodilation (discussed in next part of this chapter) which increases skin temperature and also provides the necessary fluid for evaporation. The heat maintenance centre however controls muscle metabolism on the basis of both skin and core temperature information. Fig. 2 shows the pathways in an information flow diagram. (The place of termination of warmth receptors has not been identified yet).



HUMAN THERMOREGULATION — DETAILED
INFORMATION FLOW DIAGRAM.

FIG. 2.

Temperature regulation is a highly co-ordinated function depending fundamentally on the activity of Central Nervous System. Two mechanisms are involved :

Reflex and Central.

1. Stimulation of cutaneous temperature nerve endings reflexly sets up appropriate bodily response e.g. sweating, vasomotor changes, panting or shivering.

2. The temperature of blood bathing the hypothalamus directly affects it and likewise sets up appropriate reactions, thus heating the region of the anterior hypothalamus, results in the manifestation of heat loss, e.g. cutaneous vaso dialation and sweating. An injury to the Anterior hypothalamus in animals does not impair the normal reaction to external cold, but annuls the normal increase in heat loss which occurs in hot environments. An injury to the Posterior hypothalamus likewise abolishes the responses to external heat because the descending fibres from the Anterior hypothalamus are interrupted, but in addition the response to cold is also abolished. The Anterior hypothalamus is thus the 'centre' for responses to 'rising temperatures' and the posterior hypothlamus the centre for responses to 'falling temperatures'.

The hypothalamus, because of its close connections with the thalamus, receives all the appropriate afferent nerve impulses. On the efferent side, it has access to both the somatic and the autonomic nervous system and can thus modify muscular and grandular activity, cutaneous circulation, sweat secretion and pulmonary ventilation.

The animals respond appropriately to external heat and cold, but cools down if left for a long time in a cold room. A mid-brain preparation (i.e. with hypothalamus cut-off) is cold blooded i.e. it passively follows the temperature of its surroundings. As a result of injuries in man to the pons and medulla, a rise or fall of body temperature may result. The greater part of body is paralysed and is cut off from the heat regulating centres, and therefore follows passively the temperature of the surroundings. If the weather is warm, the room over heated, and the patient well wrapped up and surrounded by hot bottles, the temperature of the paralysed region rises. No afferent impulses can pass up from this region to the centres at the base of the brain, nor can efferent impulses reach the affected muscles or blood vessels. The temperature of the whole body therefore rises. Similarly if the paralysed regions are cooled, the general temperature falls.

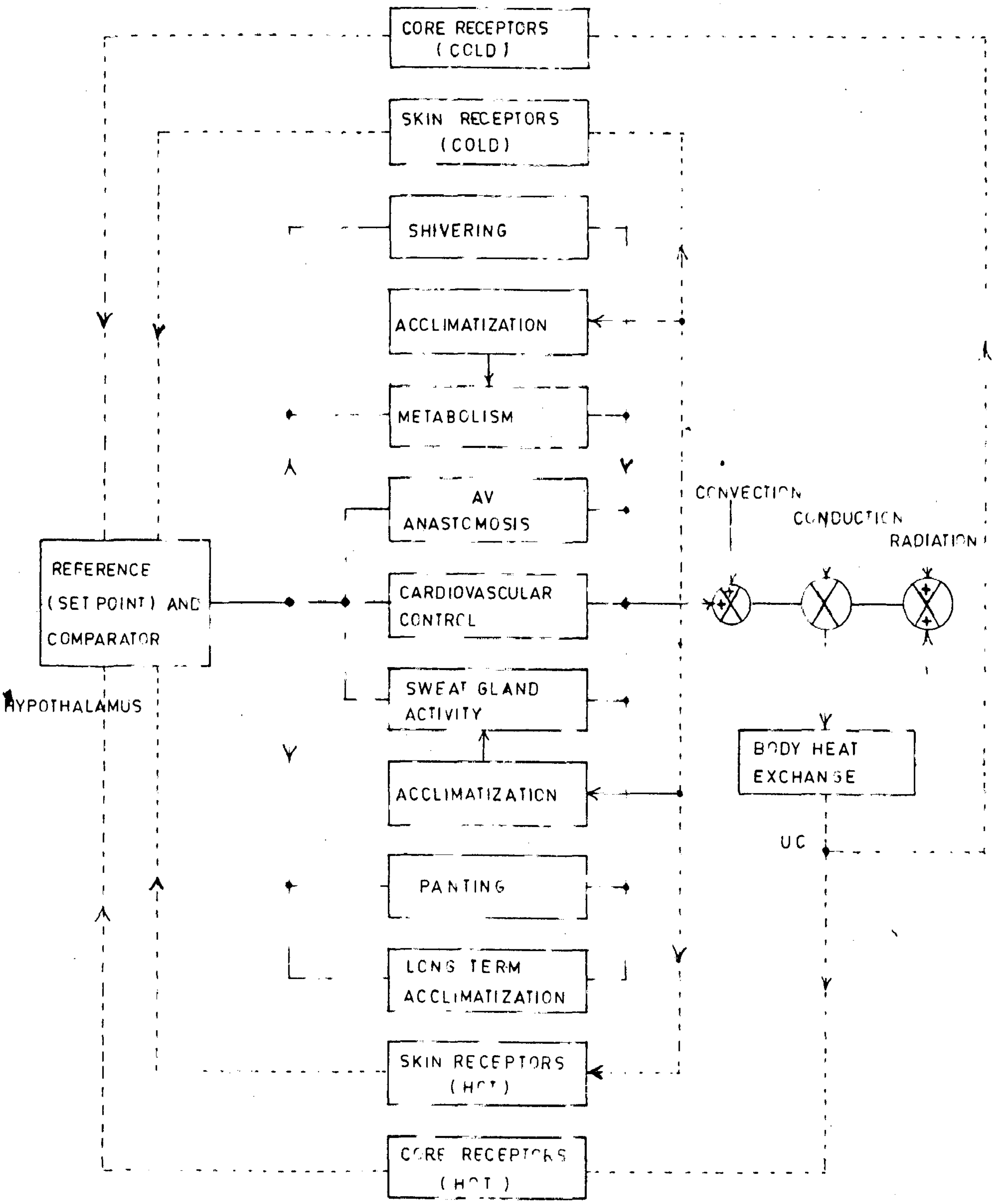
2.1.6 Thermoregulatory Control System - An Analysis

The body, so far as temperature regulation is concerned, can be divided into a central region (the core) where the temperature varies within narrow limits, and the outer shell, which consists of more periferal tissue where there are considerable variations in temperatures [12]. The body responds in a number of ways to thermal changes, it being understood that the various types of response are not sharply divided but subject to some degree of overlap. When the degree of thermal stress (hot or cold) is insufficient to activate the sweat glands or cause shivering, the physical regulation of body temperature depends mainly on the physiological control of peripheral circulation, this is achieved by adjustment in vasomotor tone.

The fact that core temperature varies within only a small range, even in the presence of wide variation of thermal stress, has been used to determine the presence of a regulating system for internal body temperature of the negative feedback type. Stolwijk (1970), [18] considered that the efferent activity associated with thermo-regulation could be divided into three basic ranges, sweating, shivering and vasomotor activity. Afferent information is derived from two sources, thermal skin receptors and deep body receptors (which are situated in the hypothalamus). The block diagram which relates all these parameters is shown in Fig.3.

How the various afferent and efferent pathways interact, led many workers to seek an overall strategy describing the operation of the system. It is understood that the thermoregulation in humans is emanating from two basic control systems, which influence each other. These control systems are core system and the peripheral system and are considered to be the second and the first line of defence respectively.[12]

The first line of defence (peripheral system) refers to the body's critical reactions in the face of environmental changes. The overriding algorithm of thermal control seems to be that heat should always be preserved in the core. Because of its role as a first line of defence, the efferent activity



MECHANISM OF THERMOREGULATION IN HUMAN BODY

—— EFFERENT NEURAL PATHWAYS.

- - AFFERENT NEURAL PATHWAYS.

FIG. 3.

associated with this thermal control system is considered to be primarily vasomotor activity. Similarly, in this control system, the prime sources of afferent activity are the skin receptors. Thus when a change occurs in the environmental temperature, the skin receptors detect this change and the control system responds by producing the appropriate degree of vaso constriction or vaso dialation. If these measures are effective, homeostasis will be maintained and the core temperature will remain in a steady state. However, if such vasomotor adjustments prove to be inadequate, the thermal equilibrium of the core will be upset, and the receptors in the hypothalamus will presumably detect a change in temperature.

Once the receptors in the hypothalamus detect a change in temperature, the so called second line of defence is thought to be activated. By virtue of the fact that the thermal equilibrium of the hypothalamus has been disturbed at all, the degree of thermal stress must be significant and the resulting efferent activity would therefore be likely to produce gross control actions such as shivering or sweating. On the other hand, the peripheral control system would be primarily involved in minimizing the effects of environmental changes in temperature by adjustments in vasomotor tone, which in turn produce alterations in superficial blood flow.

2.2 PHYSIOLOGY OF THERMO REGULATORY SYSTEM

Man is homoeothermal, i.e. he maintains his body temperature constant inspite of wide variations in environmental temperature. The term body temperature refers to the temperature of deeper structure (e.g. viscera, liver, brain). The skin usually has a lower temperature than the depths at the body. This provides a temperature gradient which leads to heat loss from the depths to the surface of the body and thence from the surface to the environment. In hot countries, these temperature gradients may be reversed.

The normal deep body temperature in man at rest is 97°F - 99.5°F (36°C - 37.5°C). In a healthy individual, it is always kept fairly close to the level by maintaining a balance between heat gain and heat loss.

2.2.1 Heat Gain

The heat gains is due to,

1. Heat produced in the body,
2. Heat taken up under certain circumstances from the environment.

2.2.1.1 Heat Production : Heat production in the body may be due to three reasons,

a. Metabolic heat generation
b. Exercise
c. Shivering.

Heat is produced by the metabolic activities of the body.

In some organs, such as liver and heart, heat production is relatively constant. On the other hand, skeletal muscle makes quite a variable contribution to heat production, at rest very little, in exercise, a great deal. Muscular contraction of shivering takes place in cold environments to produce heat and plays an important part in preventing a fall of body temperature under such environments.

Heat production under standard resting (basal) conditions is one K cal/Kg of body weight per hour or 37 - 40 K cal (depending on sex) per sq. meter of surface area/hr. (This has reference to Appendix II). This output works out at about 1700 K cal/day in an average man and 1500 K cal/day in an average woman. Moderate physical activity increases heat production to a total of 6000 K cal/day. If very heavy work is done, the total heat output may rise to 16000 K cal or more per day. Short burst of extremely severe exercise may increase heat production temporarily to 10 - 16 times the basal level. The specific heat of water is 1 i.e. one (small) calory raises the temperature of 1 gm of water by 1°C. The specific heat of physiological saline and therefore of the body (which is 80 per cent water) is also approximately 1. Therefore if there were no heat loss, the temperature of the body under basal condition would rise by 1°C per hour and under conditions of normal activity would rise by 2°C per hour. But so efficient are the mechanism for bringing about heat loss that only when work is heavy or when the environmental conditions interfere with heat loss mechanism, does the body temperature rise well above the normal range.

On sudden exposure of a nude man to mild cold (10 -15°C) the internal body temperature rises initially and may remain elevated for many hours during such exposures. The skin temperature falls giving rise to intense sensation of cold and periodic shivering. Heat production is raised due to shivering. The falling skin temperature stimulates the strong phasic response in the periferal receptors which in turn tightens vasoconstriction causing the subject to curl up and causes bouts of shivering. The -ve feedback nature of this response first was pointed out by Eacott [27] is important. Each bout of shivering causes a rise in skin temperature with an associated feeling of warmth and a cessation of shivering. Heat loss is increased, skin temperature again falls and shivering is again stimulated. After many hours, the core temperature may also drop and shivering becomes continuous. Eventually the receptors of hypothalamus may assist in this stimulation of shivering.

2.2.1.2 <u>Chemical Control of Heat Production</u> : Practically all the heat in human body is derived from the oxidation of food stuffs. The amount taken in with warm food and drink is almost negligible. The amount of heat produced varies with circumstances (Appendix III) Oxidations and thereforeheat production takes place in the tissues themselves. Every tissue contributes about one half of the active structures of the body, they furnish the largest amount. Glands are of minor importance. Increasing heat production is, therefore, achieved, principally by increasing the activity of muscle.

When a cold blooded animal, for example a frog, is subjected to cold environment, the amount of metabolism gradually decreases. The heat production is correspondingly reduced; this results in fall of body temperature. The poikilotherm (cold blooded) follows the rule that chemical action varies directly as the temperature of the reacting agents.

In warm blooded animals (Human also), matters are more complicated, for in them both the amount of heat produced and heat lost can, within limits, be regulated.

The onset of chemical regulation is ushered in by an increase in muscle tension shivering, chattering of teeth, and goose pimples [22]. Shivering (which may be called involuntry exercise) usually begins when the skin temperature has dropped to approximately 19°C (66°F) and may increase oxidations by as much as 400 per cent.

2.2.1.2 <u>Heat Gained from the Environment</u> : The body can take heat from the objects hotter than itself, such as by direct radiation from the sun and heated ground. In many instances, particularly in direct sunlight and in industry, radiation is the largest element in the heat load.

Farmers and military personnel are exposed to direct and reflected energy from the sun. The direct radiative load of full sunlight on a nude man may exceed 1000 Btu /hr. White clothing will reflect the energy in the shorter wavelengths, thereby reducing the solar load by as much as 50 per cent. A sunshade can remove most of this solar load if it is at some distance from the wearer and if free convection is provided underneath so that build up of air temperature is avoided.

Large equipments operating at high temperature dominates the scene in metal ore reduction, foundry operations, glass manufacture and the like. Paint and porcelain ovens are major contributors in the home appliance industry. In many instances, shielding can be introduced between the source and the worker to interrupt the transmission of the radiant energy. Surface treatment of the source (Paint, insulation) or worker (reflective clothing) offer alternative solutions under certain special circumstances.

This type of heat intake is independent of the temperature of air. If however, the air temperature exceeds that of the skin, the body surface takes up additional heat from ~~its~~ immediate surroundings, this sort of heat gain is a great burden to people living in hot climates.

2.2.2 Heat Loss

Heat is lost from the body in several ways.

1. By radiation from the body to cooler objects at a distance.
2. By conduction and convection to the surrounding atmosphere if its temperature is lower than that of the body (or rather that of skin). The air in immediate contact with skin is warmed; the heated molecules move away and cooler molecules come into take their place, those in turn are warmed and so the process goes on. These air movements constitute

convection currents.

3. By evaporation of water. The fact is that when 1 gram of water is converted into water vapor 0.58 K cal of heat is needed and has to be taken up from the environment, this heat being known as latent heat of vaporization and is measured in K cal/gram. One interesting fact is worth quoting here, in relation to evaporation. The evaporation depends on shape and size of a man. For a very fat man, the volume of body is more than the surface area. Hence the heat dissipation area is less and hence they feel more discomfort in odd seasons. The case is opposite in thin persons.

Evaporation of water takes place from the lungs and from the skin. Evaporation of sweat is the principal means of heat loss when the body temperature tends to rise.

The different methods and routes of heat loss are considered more fully below.

2.2.2.1 Radiation : The magnitude of heat loss or gain by radiation depends on the size of the body surface (as mentioned above) and on the average temperature difference between the skin and the surrounding objects. The part played by the radiation varies widely with the climatic conditions. In a hot climate, resting person (wearing ordinary clothes) loses about 60 per cent of his heat production by radiation. If he is working, although heat production is increased, there is no great increase in the absolute amount of heat lost by radiation because the skin temperature rises only slightly (During work the percentage of the total heat loss which is due to radiation obviously becomes smaller).

2.2.2.2 Lungs : The expired air leaving the lungs is saturated with water vapor at body temperature. This water is derived by vaporisation from the moist mucous membranes of the respiratory passages. The amount of water vapor taken up depends on the initial state of the inspired air; when dry it takes up a good deal but when saturated with water vapor it takes up none at all. On the average the water loss from the lungs is about 300 ml per day, equivalent to a heat loss of nearly 200 K cal i.e. (300 x 0.58 K cal).

Some body heat is also lost via the lungs by raising the temperature of the inspired air to body temperature, therefore an increase in pulmonary ventilation (especially when the air is dry and cool) increases heat loss.

2.2.2.3 Skin : Heat loss from the skin occurs by conduction-convection to a degree which varies with the temperature gradient between the skin and surrounding atmosphere. Skin temperature varies directly with its blood flow; the calibre of the skin vessels, especially those in the hands feet and face which are under intense vasomotor control, can be nicely adjusted to varying body needs. The zone of vasomotor control for man is the narrow range of ambient temperature between 29 and 31°C [27] and temperature regulation effects are minimal involving slight alternation in vasomotor tone to keep the heat loss and heat production in accurate balance. External cold produces cutaneous vaso constriction and consequently reduces skin blood flow and decreases heat loss; external heat has the opposite effect. The flow of heat from the body depths to the skin is mainly due to convection within the body i.e. the carriage of heat from the depths to the surface by the warm blood.

2.2.2.4 Evaporation of Water : Water is lost from the skin by

a. insensible perspiration

b. sweating.

2.2.2.4.1 Insensible perspiration : This consists of the passage of water by diffusion through the epidermis (it is called insensible because it can not be seen or felt); the fluid lost is not due to sweat glands. It amounts to 600 - 800 ml/24 hrs , equivalent to heat loss by evaporation of about 400 K cal. It is produced over the whole body surface at a fairly uniform rate and is largely independent of the environmental conditions.

2.2.2.4.2 Sweating : Because of its outstanding importance in temperature regulation, this mode of heat (and water) loss requires detailed discussion.

SWEAT GLANDS

There are two types of sweat glands in man

1. ECCRINE : which are distributed generally over the body surface and secrete a dilute solution containing sodium chloride urea and lactic acid. The NaCl concentration is variable i.e. 0.1 - 0.37 per cent. Eccrine glands are densest on the palms and soles, dense on the head and much less dense on trunk and extremities. Eccrine glands are supplied by cholinergic fibres

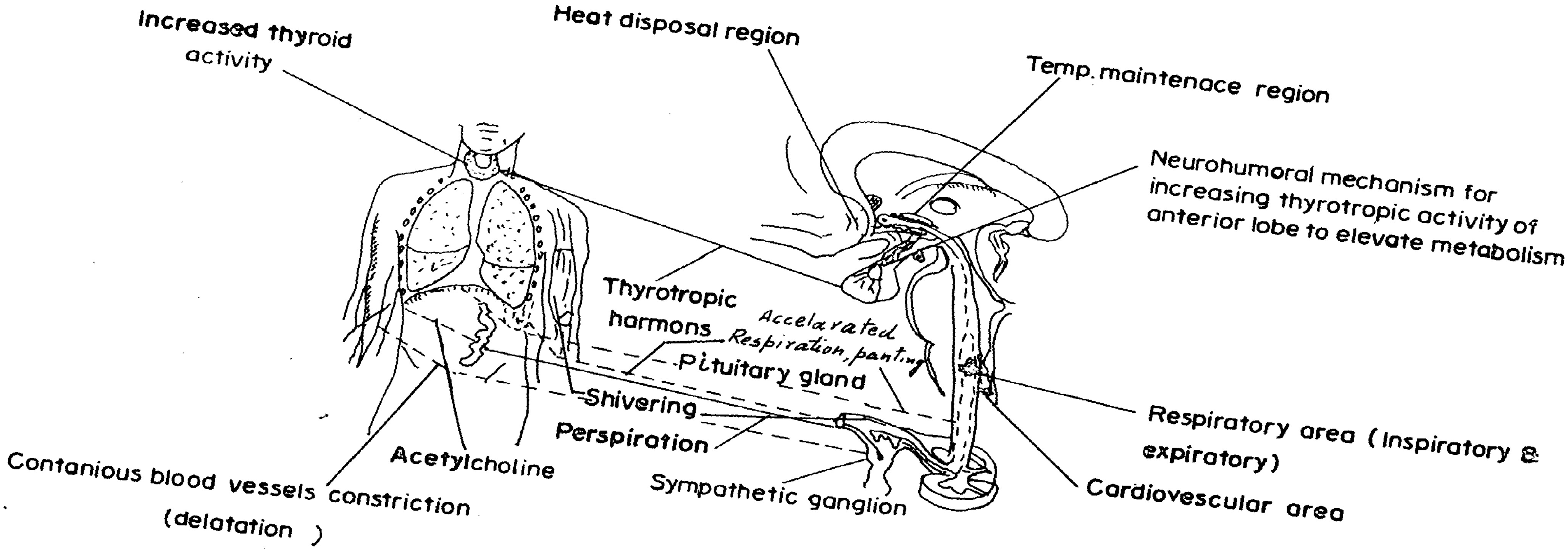


FIG.4 TEMPERATURE REGULATION IN HUMAN BODY. [8]

present in sympathetic nerves. Atropine inhibits eccrine sweating.

2. APOCRINE GLANDS : develop from hair follicles. They are found mainly in the axilla (though eccrine glands also occur here) round the nipples.

Apocrine glands are not supplied by secretory nerves, but are stimulated by adrenaline carried in the blood stream. Atropine does not inhibit this secretion.

In the human axilla apocrine sweat is a milky odourless fluid. The typical axillary odour develops as the result of bacterial action.

2.2.3 Secretion of Sweat

Secretion is produced by direct or reflex stimulation of the centres in the spinal cord, medulla, hypothalamus or cerebral cortex. Eccrine sweat secretion is increased in the following conditions.

1. With rise of external or the body temperature, this, socalled, thermal sweating is produced in two ways -
   i) by the rise of body temperature directly affecting the hypothalamic centres and
   ii) reflexly from the stimulated 'warm' nerve endings in the skin.

2. In emotional states (mental sweating); this type is limited, as a rule, to the palms, soles and axillae, though in extreme cases it may become more generalised. Mental sweating is due impulses sent out from the nervous system.

The term 'hyperhydrosis' is used to describe excessive sweating in the region usually involved in mental sweating. The condition is due to over-activity of centres controlling sweat secretion and not to any abnormal behaviour of the glands themselves. Hyperhydrosis is reduced by atropine or by ganglion blocking drugs.

3. In exercise, both thermal and mental factors play a part. Skin sweating at parametrically chosen levels of exercise and ambient air temperature has been studied by Stolwijk[29].

4. Sweating also occurs in nausea and vomiting, in fainting, in hypoglycaemia and in asphyxia. This is due to sympathetic activity.

5. Gustatory sweating occurs in hot climates when spicy foods are eaten. Pain nerve endings in the mouth are stimulated to produce reflex sweating in the head and neck.

2.2.4 Thermal Sweating

The maximum rate of thermal sweat secretion in an hour may be as high as 1.7 litre; 8 - 11 litre may be lost in 5 - 8 hours. More usually the 24 hour maximal secretion is 12 litres. Every litre of sweat which is evaporated from the skin leads to the loss of 580 calory of heat from the body. The evaporation of 1.7 litres (the maximum value for 1 hour) results in a heat loss of 1000 cal. that of 12 litres (the maximal for one day) gives a heat loss of 7000 K cal. If the sweat does not evaporate from the skin but is wiped away or merely runs down the body, no heat loss occurs at all. Sweating under such conditions is just useless form of fluid loss [26].

By varying the amount of sweat secreted, the amount of heat which the body can lose can extend over an immense range. When the external temperature exceeds that of the body, evaporation (which in practice means evaporation of sweat) is the only method of heat loss available. Heavy sweating involves a rapid loss of water together with salt from the body; dehydration and also salt deprivation will occur, with the usual consequences of low cardiac output, fall in blood pressure, giddiness, fainting and cold sweat, headache etc., unless enough water is drunk and adequate amounts of salt are taken.

When the external air is not only hotter than body but is also saturated with water vapor, heat loss becomes impossible because the sweat cannot evaporate. Thus in a dry room at temperature of 240° - 260°F, no rise in body temperature occurs; on the other hand, a stay of 15 minutes in a moist room at 130°F may rise the body temperature to 100°F.

Temperature regulation has priority over the maintenance of water and salt balance, sweating will thus continue even though it produces severe dehydration and marked salt loss, it is arrested only by circulatory failure.

As sweat comes from the blood, rapid sweating demands a large cutaneous blood flow; and therefore dilation of the skin blood vessels. This vasodilatation is brought about by

1. External heat acting directly on vessels.
2. Reflexly from cutaneous warm endings,

3. By the rise of blood temperature acting directly on vasomotor centre.

Patterns of sweating and cutaneous vascular response in a subject exposed to heat show marked regional variations. Vasodilation in skin areas possessing potent vasomotor control, such as the fingers and toes, are not necessarily associated with similar responses in areas having weak vasomotor Representation [13]. Cutaneous vasodilation is responsible for the liberation of a vasoactive substance (brady kinin). Also vasodilation is dependent primarily upon sympathetic sudomotor fibres. Some vasodilation in the hand and forearm may be due to release of sympathetic vasoconstrictor tone, but the main vasodilation of the forearm is due to the formation and action of bradykinin.

The cutaneous vasodilation decreases the peripheral resistance lowering the diastolic pressure, but is accompanied by an increase in the cardiac output.

2.2.5 <u>Effect of Local Conditions on Mouth Temperature</u>

The mouth temperature reading (oral temperature) is affected by local conditions:

i) A misleadingly high reading is obtained immediately after a hot drink when the temperatures of the temporarily warmed mucous membrane is being recorded (and not that of blood).

ii) A misleading low reading is obtained

(a) after a cold drink, which cools the mucosa of the mouth,

(b) if the nose is blocked, preventing the mouth from being closed.

Diurnal Variation

A diurnal variation of $3^{o}F$ may occur in any normal person [26]. The possible extent of the tolerated diurnal variation is not always fully appreciated, because it is very unusual to take records at frequent intervals during the night. Also it is commonly at the inconvenient hours of 2 to 6 A.M. that the minimum temperatures are observed.

As the oral temperature rises, the heart rate increases, and vice versa.

The normal temperature rise during the day is due to muscular activity and associated heat production. During sleep, the temperature falls, partly because of bodily inactivity and partly because of less perfect temperature regulation. When a healthy man is kept in bed, the normal type of diurnal temperature variation takes place.

A reversal of ordinary daily routine, e.g. on going on to night work, ultimately reverses the temperature variation. This does not occur during the first night, for at the hour of the usual minimum (e.g. 3-4 A.M.) there is an imperative desire to sleep. After a few days, acclimatisation takes place and the sleepiness passes off.

Following are the factors affecting the diurnal variation of mouth temperature:

<u>Age</u> : The temperature in infants is irregular at first, but periodicity gradually sets in. Temperature regulation is imperfect; a fit of screaming causes a rise, and a cold bath may lower the temperature by 7°F. In the aged the temperature is subnormal, the body is less active, the circulation is feeble and there is less power of compensation for changes in external temperature.

<u>Menstruation</u>: During menstruation, the average temperature is at a minimum. It rises slightly during the next 14 days; the waking temperature shows a distinct rise at about the time of ovulation. During the second half of the menstrual cycle, the waking temperature is 98° - 99°F.

<u>Exercise</u> : As discussed previously, exercise raises the metabolic heat generation to a great extent. Thus temperatures as high as 103 - 105°F have been recorded in atheletes after a race of 3 miles.

2.2.6 Role of Ductless Glands

On cooling a dog, the metabolic rate increases by 7 per cent before any indication of increased muscle activity sets in. This is probably a measure of the extent to which the ductless glands help in the 'fine regulation' of the body temperature.

1. <u>Adrenal Medulla</u> : Exposure to external cold reflexly stimulates secretion of adrenaline which stimulates metabolism and decreases heat loss.

2. <u>Thyroid</u> : External cold (via pituitary thyrotrophin)

stimulates thyroid secretion which increases heat production, mobilises liver glycogen and stimulates neoglucogenesis.

3. When the animal is transferred to a cold environment, there is histological changes in the thyroid indicative of functional activity. The gland becomes intensely congested, the amount of colloid decreases and loses its affinity for haematoxylin; the lining cells become columnar and the mitochondria enlarge and become more distinct.

4. _Adrenal Cortex_ : Exposure to external heat or cold stimulates secretion of adrenal corticoids.

2.2.7 _Fever_

This term is defined as a raised central temperature. It results from a disturbance of the temperature regulating centre. Fever is most commonly caused by :

1. Infections due to bacteria (e.g. pneumonia), viruses (e.g. influenza) and protozoa (e.g. malaria).
2. Tissue distribution, as for example in cardiac interaction, uninfected neoplasms, serum sickness and rheumatic fever.

In fever there is increased heat production but this alone does not account for the pyrexia ; because the changes are of such a magnitude which could be easily compensated for under normal conditions but heat loss is decreased simultaneously, fully accounting for the rise of body temperature. Heat regulation in states of fever is therefore disordered body temperature is adjusted to a higher level than normal. The normal diurnal variation is still present and the patient responds in the usual way to applications of heat and cold.

In the critical stage, a rigor or shivering often occurs. The skin vessels are constricted, minimising heat loss, a rapid rise of temperature therefore takes place and the blood pressure rises. During the defervescence, where the temperature falls, marked sweating occurs, and heat loss is now greater than heat production.

Some of these phenomenon are well demonstrated during a malarial rigor. During the shivering attack, there is a sudden marked increase in heat production e.g. from 80 to 230 K cal/per hour, heat loss on the other hand, is unchanged or decreased because of cutaneous vasoconstriction so that all the extra heat liberated is stored in the body. The body temperature may rise to 105°F as temperature regulation is not in action. After an interval the 'thermostatic' control is adjusted to 98°F ; sweating sets in and with increase vaporisation, there is additional heat loss, bringing the body temperature down to normal once more.

The general manifestations of fever are due to the pyrexia, dehydration, disturbed electrolyte balance in the blood (e.g. Na^+ and Cl^- loss, alkalaemia) and the action of toxins.

CHAPTER - III

REVIEW OF MATHEMATICAL MODELS

3.0 One of the earliest workers in this area was Pennes [4] who developed a model that applies to the human forearm. Although the suitability of the model has been tested by numerous experimental data for the forearm, the model is essentially applicable to the cylinderical element of the body. One of the earliest models by Wissler [25] appears to be a modification of Pennes model.

Machle and Hatch [4] were the first to introduce the concept of core and shell by using rectal temperature and mean skin temperature as measures of the core temperature and shell temperature. By considering the rate of change of body heat content as a function of increments of rectal and mean skin temperature, they established the first model to use the differential form. Partial skin wetness is considered in this model. Kerslake and Waddell [4] modified Machle and Hatch's model to take into account complete skin wetness.

Gagge's Model [5] considered the human body as a single cylinder with two concentric layers -one inner central core and outer skin shell. Heat production (metabolism) takes place in the core; metabolic heat is transferred to the skin surface by convection (blood flow) and by conduction. At the skin, heat is transferred to or from the environment by convection, conduction, radiation or sweat evaporation. The model predicts mean skin temperature, core temperature, total evaporative heat loss, skin wettedness and skin blood flow. It is for steady state conditions and for estimates of comfort and thermal sensation for normal environments.

Wyndham and Atkins [4] model predicted the transient responses of the human body. They approximated the human body by a single cylinder and devided the cylinder into a number of thin concentric layers. The finite difference technique was used to approximate the equation. A set of resulting first order differential equations was then solved by using an analog computer. This model was also modified by Wissler [23].

Wissler modified the models developed by Pennes and Wyndham and Atkins and interrelated each element of the human body by a heat transfer equation between each one of the elements and the centre of the body, namely, heart and lung. Wissler explicityly considered the effects of interdependence by taking into account the blood flowing between adjacent elements, local blood flow rate, and local rate of heat generation by metabolic reactions.

The physiological thermal regulation mechanism had not been taken into account in modelling until Crosbie et al. [3] approximated the values of the thermal conductivity of tissue, metabolic rate and the rate of heat loss by evaporation as a function of the mean body temperature. Stolwijk and Hardy also considered the local blood flow rate, metabolic rate, and the rate of heat loss by evaporation to be a function of brain temperature, muscle temperature and skin temperature.

The physical shape of the body was represented by a slab by Crosbie et al.[3], whereas Stolwijk and Hardy [21] used the core and shell model to approximate the shape of human body

Yamamoto et al.[4] also established a cylinderical model by discretising the radial distance of the cylinder. Their work currently under progress, is in the direction of developing a model which includes the dynamic characteristics of the physiological thermal regulation mechanism.

Relating the human thermal model to the external thermal regulation device was first done by Buchberg and Harrah [2]. They considered the conduction cooling of the human body as an external thermal regulation device. By controlling the coolant temperature and its mass flow rate, they were able in their model, to minimise the natural thermoregulatory mechanisms of shivering, sweating and vascular adjustments.

3.1 MATHEMATICAL MODELS FOR A SINGLE ELEMENT OF THE BODY

A. STEADY STATE MODEL

3.1.1 Pennes Model

Pennes proposed a model for the human forearm. He approximated the forearm as a cylinder and considered the following factors :

a. conduction of heat in the radial direction of the cylinder.

b. metabolic heat generation in the tissue.

c. convection of heat by the circulating blood.

d. heat loss from the surface of the skin by convection, radiation and evaporation.

Pennes model, representing the relationship among the temperature of the normal human forearm tissue T, the local metabolic rate h_m, and the heat transfer accompanied by the local blood flow to tissue h_b, is written as follows

$$- K \left[\frac{d^2T}{dr^2} + \frac{1}{r} \cdot \frac{dT}{dr} \right] = h_m + h_b \qquad (1)$$

where,

K - Thermal conductivity of the tissue

r - Radial distance from the centre of the cylinder.

Equation (1) is a mathematical statement of the first law of thermodynamics i.e. the energy balance of the forearm. The terms on the left hand side represent the rate of heat conduction. The first term on the right hand side is the rate of heat generation due to metabolic reactions and the second term is the rate of heat transfer from blood to tissue in the capillary bed.

Equation (1) is subject to the following boundary conditions,

$$- K \left[\frac{dT}{dr} \right]_{r=a} = H(T_s - T_o) \qquad (2)$$

Equation (2) states that at the surface of the skin the rate of heat transfer from the tissue to the skin surface (left side of equation) is equal to the rate of heat loss from the skin surface to its surroundings environment (right side of equation).

Equation (1) together with its boundary condition given by (2), was solved by Pennes for the case in which both h_m and

h_b are uniform throughout the cylinder. The solution is

$$T = \left[T_s - \frac{(h_m + h_b)}{4K} a^2 \right] - \frac{h_m + h_b}{4K} r^2 \qquad (3)$$

or

$$T = T_{ax} - \frac{(h_m + h_b)}{4K} r^2 \qquad (4)$$

where

$$T_{ax} = T_s - \frac{(h_m + h_b)}{4K} a^2 \qquad (5)$$

Equation (3) represents the tissue temperature T in terms of the skin temperature T_s, the local metabolic rate h_m, the heat transfer due to local blood flow to tissue h_b, and the radial distance r. Equation (4) gives the tissue temperature in terms of h_m, h_b and T_{ax}, the temperature at the axis of the cylinder.

When h_b, the heat transfer rate due to local blood flow to tissue, is a function of the difference between tissue temperature T and the temperature of the arterial blood T_a,

$$h_b = V_1 C_p (k-1)(T - T_a)$$

Equation (1) then becomes

$$\frac{d^2T}{dr^2} + \frac{1}{r} \frac{dT}{dr} + a_1 T = b_1 \qquad (6)$$

where,

$$a_1 = \frac{V_1 C_p (k-1)}{K} \; ; \; b_1 = V_1 C_p \frac{(k-1)T_a - h_m}{K}$$

in which C_p is the specific heat of blood and V_1 is the volumetric blood flow rate in the capillary bed. The solution of (6) is

$$T = \frac{\left(T_o - \frac{b_1}{c_1}\right) J_o\left(i\sqrt{c_1}\, r\right) + \frac{b_1}{c_1}}{J_o\left(i\sqrt{c_1}\, a\right)} \qquad (7)$$

The relationship between the skin temperature T_s and the effective environmental temperature T_e was also derived by Pennes by substituting the boundary condition (2) into (7).

B. UNSTEADY STATE MODELS

3.1.2 Machle and Hatch's Model

Machle and Hatch of the Pierce Laboratory presented the following mathematical model as the basic equation of heat balance.

$$M + D - V = R + C + E \qquad (8)$$

This equation states that the metabolic rate M plus the rate of change of body heat content D minus the rate of heat loss by respiration V is equal to the sum of the rates of heat exchange with the environment by radiation R, convection C, and evaporation E. The terms on right hand side can then be written as

$$R + C + E = K_r \cdot A \cdot (T_s - T_w) + K_c A (T_s - T_a) + K_e A_e (WP_s - WP_a) \qquad (9)$$

The rate of change in body heat content D can be represented by (10). Rectal temperature T_r and the mean skin temperature T_s designate the core and shell temperature

$$D = C_p W \, (\bar{a} \; \Delta T_r + \bar{b} \, \Delta T_s) \tag{10}$$

By substituting (9) and (10) into (8), using the empirical formula $V P_a = 2.5 \; T_s - 45$, and taking the limit of $\Delta t \to 0$, the following differential equation is obtained

$$- \frac{C_p W}{A} (\bar{a} dT_r + \bar{b} dT_s)$$

$$= [(M-W)/A + K_r T_w + K_c T_e + K_e \frac{A_e}{A} (45 + VP_a)$$

$$- (K_r + K_c + 2.5 \; K_e \frac{A_e}{A}) \; T_s \;] \; dt \tag{11}$$

The rectal and skin temperatures are mutually dependent and have the following linear relationship over a limited range of temperatures,

$$T_r = m + n \; T_s$$

or

$$dT_r = n dT_s$$

where m is a constant and n is the slope of the linear relationship.

Equation (11) was solved by Machle and Hatch for a specific situation where

$$[(M-W)/A + K_r T_w + K_c T_e + K_e \frac{A_e}{A} (45 + VP_a)]$$

and $C' = (K_r + K_c + 2.5 \; K_e \frac{A_e}{A})$ were considered to be constants. This give rise to

$$\frac{T_{sq} - T_{st}}{T_{sq} - T_o} = \exp \left[- \frac{A C'}{C_p W(\bar{a} n + \bar{b})} t \right] \tag{12}$$

Equation (12) relates the equilibrium skin temperature T_{sq} and time t and is independent of the environmental temperature.

The value of 2.5 in the expression for C' in (12) has been derived from the linear equation between the vapor pressure and temperature.

Machle and Hatch experimentally determined the temperature and partial pressure in (9). The coefficients of heat exchange which appear in their model are given by the following formulas.

a. Radiation :

$$K_r = K_1 (A_r/A) [\bar{T}_s^3 - 6 \bar{T}_s^2 (T_s - T_w) + 4 \bar{T}_s (T_s - T_w)^2 - (T_s - T_w)^2] \qquad (13)$$

For practical purposes, K_r can be considered to be independent of the air movement and moisture content of the air.

b. Convection : Two formulas for the coefficient of convection were adopted by Machle and Hatch. The first formula

$$K_c = 1.04 \, v^{0.5} \qquad (14)$$

where v = velocity surrounding air. The second formula

$$K_c = 0.74 \, v^{0.5} \qquad (15)$$

Both equations were developed for vertical air movement around the human subjects.

c. Evaporation : The following two empirical formulas were employed by Machle and Hatch.

(i) At the maximum evaporative capacity

$$K_e = 1.84 \, v^{0.37} \qquad (16)$$

(ii) At less than the maximum evaporation

$$K_e = E/\{\lambda_e\,(VP_s - VP_a)\} \qquad (17)$$

where E is evaporative heat loss.

Machle and Hatch's model provided a relationship among skin temperature, skin wetness, local metabolic rate, and relevant parameters of the environment. The model, however, proved to be unable to predict skin temperature in moist circumstances because of the difficulties in determining the skin wetness.

3.1.3 Kerslake and Waddell's Model

They extended the preceding model to include the case of complete skin wetness. The steady state skin temperature T_{sq} was then predicted from the local metabolic rate and the environmental condition. Machle and Hatch's equation (12) was modified to

$$\frac{(T_{sq} - T_{st})}{(T_{sq} - T_o)} = \exp\left(-\frac{AC'}{C_p W}\,t\right) \qquad (18)$$

In (18), 2.6 is used in place of 2.5 for determining C' because it leads to a more accurate representation of the vapor pressure - temperature relationship than does Machle and Hatch's model.

The experimental results which are obtained by Kerslake and Waddell indicate that (18) provides a satisfactory description of the changes in skin temperature T_{st} with respect to time. Their results also verify the prediction of final steady state skin temperature T_{sq} by (18).

3.1.b Wyndham and Atkins Model

Wyndham and Atkin's were probably the first to introduce a transient model for a single element. The equation which essentially represents the transient heat conduction in cylinder is

$$\rho \cdot C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(K_r \cdot \frac{\partial T}{\partial r} \right) + h_m \qquad (19)$$

The left hand side of (19) represents the sum of the rate of accumulation of thermal energy and right hand side is the sum of rate of heat conduction plus the rate of heat generated by metabolic reactions.

Wyndham and Atkins approximated the human body by a cylinder consisting of a number of their concentric shells. A set of first order differential equations which can be solved by an analog computer is obtained by assuming that the rate of heat transfer between any two adjacent shells is proportional to the temperature difference between them. The following are two boundary conditions.

1. At the centre of the cylinder the temperature profile is symmetrical, that is, the temperature gradient is zero.
2. At the surface of the cylinder the rates of heat loss due to convection qc, radiation qr, and evaporation qe.

The following heat exchange mechanism between the skin and atmosphere are considered in the model

(a) Radiation :

Heat exchange by radiation between the skin and atmosphere can be characterised by Stefan-Boltzman equation.

$$q_r = K_1 \cdot A_r (T_s^{4} - T_w^{4}) \quad (20)$$

(b) <u>Convection</u> :

The equation for heat exchange by convection for air velocity between 10 and 1000 ft/min and parallel to the axis of the cylinder is

$$q_c = 0.5 A_c \cdot v_1^{0.5} (T_s - T_a) \quad (21)$$

For air flows normal to the axis of a cylinder

$$q_c = 1.04 A_c v_1^{0.5} (T_s - T_a) \quad (22)$$

(c) <u>Evaporation</u> :

Heat exchange by evaporation from the saturated skin is given by (23),

$$q_e = 1.4 v_1^{0.4} A_e (VP_s - VP_a) \quad (23)$$

Equation (23) gives maximum evaporative heat loss which is determined by v_1 and VP_a. If the skin is not saturated with sweat, the corresponding equation is

$$q_e = K_e v_1^{0.4} (VP_s - VP_a) A_e \quad (24)$$

3.1.5 <u>Model of Crosbie et al.</u>

The model by Wyndham and Atkins employs a concentric cylindrical configuration to represent an element of the body. In contrast, Crosbie et al. [3] utilised the configuration of an infinite slab in their model.

atmosphere can be characterized by Stefan-Boltzmann equation.

$$q_r = K_1 \cdot A_r \left(T_s^4 - T_w^4 \right) \tag{20}$$

(b) Convection :

The equation for heat exchange by convection for air velocity between 10 and 1000 ft/min and parallel to the axis of the cylinder is

$$q_c = 0.5\, A_c \cdot v_1^{0.5} \left(T_s - T_a\right) \tag{21}$$

For air flows normal to the axis of a cylinder

$$q_c = 1.04\, A_c\, v_1^{0.5} \left(T_s - T_a\right) \tag{22}$$

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3.1.5 Model of Crosbie et al.

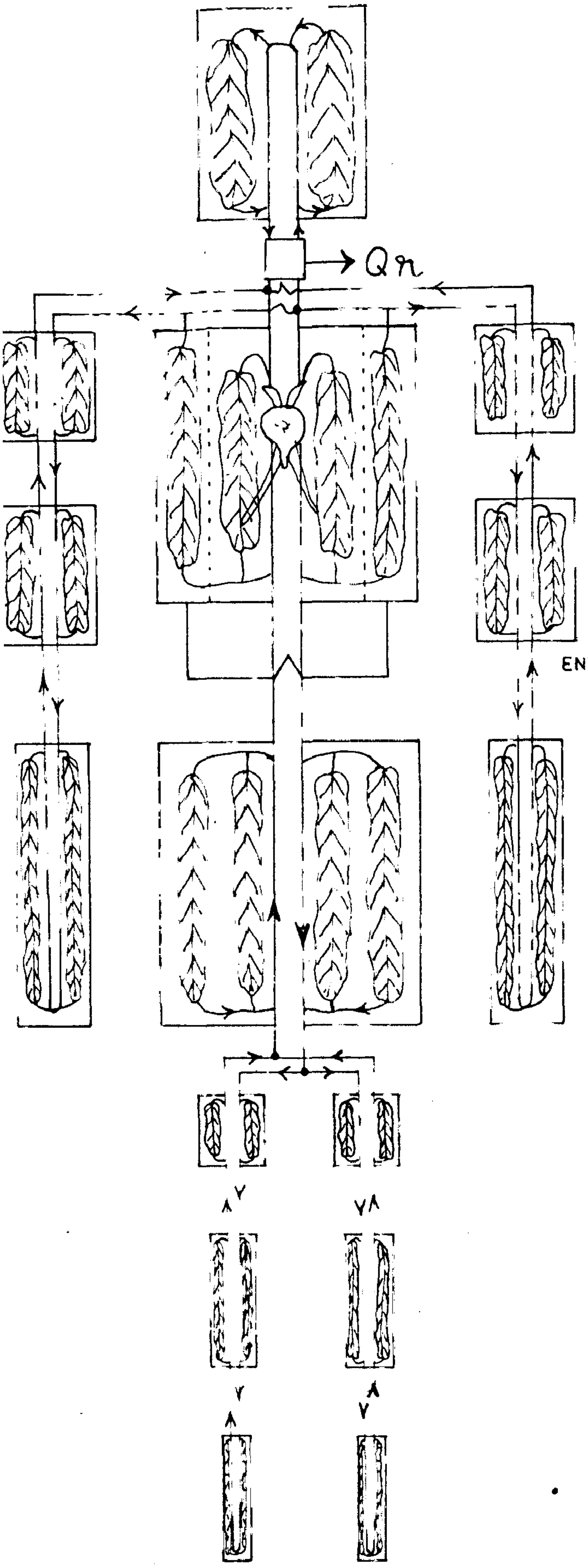
The model by Wyndham and Atkins employs a concentric cylinderical configuration to represent an element of the body. In contrast, Crosbie et al. [3] utilized the configuration of an infinite slab in their model.

By emphasizing that average skin temperature of the entire body temperature to the body heat loss, Crosbie et al. found that the physics and the physiology of the thermal regulation of the human body became more understandable and that many uncertainties, such as the rate of change of metabolic rate, were classified. The results of simulation of temperature regulation by an analogue computer were also included in their work. They compared their computer solution with their experimental observation for both steady state and transient responses to a nude man.

The thermal properties and internal metabolic rate which appear in their model vary as a function of skin temperature

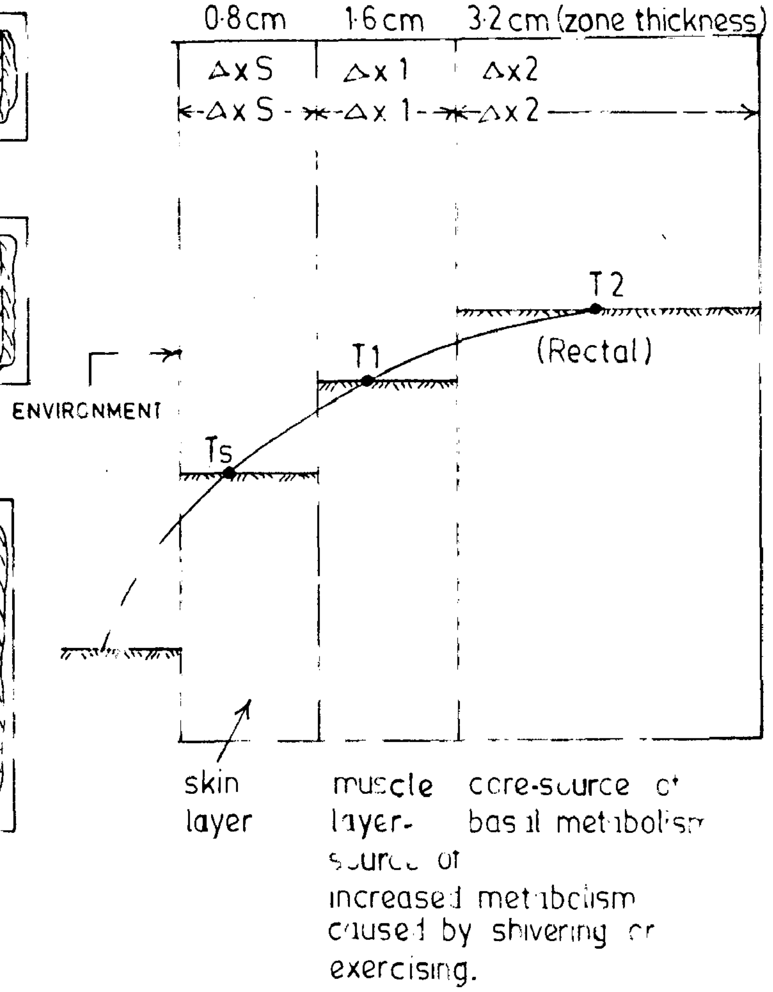
$$c_p \frac{\partial T}{\partial t} = K \cdot \frac{\partial^2 T}{\partial x^2} + M' - R' - V_o' \qquad (25)$$

Equation (25) states that the rate of thermal energy accumulation in a unit volume is equal to the rate of heat conduction into the system plus the rate of heat generated by metabolic reactions M' minus the heat loss by radiation and convection R', minus the rate of heat loss by evaporation V_o'. Equation (25), a partial differential equation has two independent variables X and t and cannot be solved easily by an analog computer. It can be approximated by three first order differential equations which represent the outer, middle and inner layers of the tissue Fig. 5 provides a geometric description of model' The following equations represent the heat transfer from the skin layer, muscle layer, and core.



WISSLER'S MODEL

FIG. 6



MODEL OF PHYSIOLOGIC TEMPERATURE REGULATION.

FIG. 5.

$$\rho \cdot C_p \cdot \Delta X_0 \; \frac{dT_0}{d\theta} = \frac{K}{\Delta X_{01}} (T_1 - T_0) - h(T_0 - T_o) - V_0 \qquad (26)$$

$$\rho \cdot C_p \cdot \Delta X_1 \; \frac{dT_1}{d\theta} = \frac{K}{\Delta X_{12}} (T_2 - T_1) - \frac{K}{\Delta X_{01}} (T_1 - T_0) + \Delta M \qquad (27)$$

$$\rho \cdot C_p \cdot \Delta X_2 \frac{dT_2}{d\theta} = M_0 - \frac{K}{\Delta X_{12}} (T_2 - T_1) \qquad (28)$$

It is worth noting that the heat loss by radiation and convection $h(T_0 - T_o)$ and that by evaporation V_0 occur only at skin layer, and that additional metabolic heat ΔM generated by shivering or exercise originates only at the muscle layer. The inner layer considers only the basal metabolic rate M_0 and heat conduction.

The mean body temperature T_B can be obtained by properly weighting the skin temperature, temperature of the middle layer, and the temperature of the core layer i.e.

$$T_B = \frac{\Delta X_0 \cdot T_0 + \Delta X_1 \cdot T_1 + \Delta X_2 \cdot T_2}{\Delta X_0 + \Delta X_1 + \Delta X_2} \qquad (29)$$

T_B can be assumed to be regulated variable. Physical properties of a human body such as thermal conductivity K, heat generation by metabolic reactions ΔM, and evaporation loss V_0 are considered to be function of T_B and can be represented by the following relationships.

If T_B is greater than basal

$$\left.\begin{aligned} K &= K_0 \{1 + \alpha_{K+} \cdot \Delta T_B + \gamma_K \cdot \frac{dT_B}{d\theta} \} \leq 1.7\, K_0 \\ \Delta M &= EX \\ Ve &= Veo + \delta EX\, (\alpha v \cdot \Delta TB + \lambda v \;\; \Delta T_B^4) \leq 50\, Veo \end{aligned}\right\} \qquad (30)$$

If T_B is less than basal

$$\left.\begin{aligned} M &= M_0 \left\{ 1 + \alpha_{M-} \cdot \Delta T_B + \gamma_M \cdot \frac{dT_B}{dt} \right\} \geq 0.56\, M_0 \\ \Delta H &= -\alpha_D \cdot \Delta T_B + \Delta M \\ V_0 &= V_{C0} \end{aligned}\right\} \quad (31)$$

The model can be simulated on an analog computer. The effect of environmental temperature on human subjects and the transient responses of a nude man were represented in their works. Also included were the computed results of vasomotor responses, transient response of the total heat loss, vaporization, and transient response of the metabolic rate of a nude subject.

Crosbie et al. are considered to be the first to simulate the physiological temperature regulation on an analog computer. In their model the thermal properties of the body and the source of internal heat are considered to vary as a function of the body's temperature variation. This model does not include the regional variation in heat and blood flow rates.

3.2 MATHEMATICAL MODELS FOR THE ENTIRE HUMAN BODY

A. STEADY STATE MODELS

3.2.1 Wissler' Model

Wissler developed a series of mathematical models of the human body. His earliest model is a direct extension of Pennes model. Wissler [22] extended Pennes model of the forearm to obtain the temperature distribution of the entire body.

In addition to the factors considered by Pennes, Wisslers model taken into account the heat loss through the respiratory system and the counter current heat exchange between the large arteries and large veins. The human body is subdivided into six elements; head torso, two arms and two legs. Each element is assumed :

(a) to have a uniformly distributed metabolic heat generation.

(b) to have a uniformly destributed blood supply.

(c) to be homogeneous and

(d) to be an isotropic cylinder.

The heat conduction equation which is equivalent to (1) for the i th element of the body is written as.

$$K_i \left(\frac{d^2T_i}{dr^2} + \frac{1}{r} \frac{dT_i}{dr} \right) + h_{mi} + (V_i \cdot \rho \cdot C_p)_i \cdot (T_{ai} - T_i) = 0 \qquad (32)$$

Where subscript i denotes the i th element and ρ is the density of the blood. Equation (32) states that the sum of the rate of conduction of heat into a unit volume, the rate of heat generation in a unit volume due to metabolic reaction and the rate of heat transfer from blood to tissue in the capillary bed in the unit volume is equal to zero.

The boundary condition of (32) is

$$-K_i \left(\frac{dT_i}{dr}\right)_{r=a_i} = H_i (T_i - T_{oi}) \qquad (33)$$

which states that the rate of heat transfer to the surface of skin through the tissue is equal to the rate at which heat is transferred from the surface of the skin to the environment. The effective heat transfer coefficient at the surface of i th element H_i is the sum of the effective heat transfer coefficients for radiation H_r, convection H_c and evaporation H_e and is given by[29]

$$H = H_r + H_c + H_e \qquad (34)$$

Conduction is disregarded in (34) due to its negligible magnitude.

Equation (32) was solved analytically and the steady state temperature profiles for various environmental condition were presented graphically by Wissler.

The heat transfer coefficient for radiation H_r, can be approximated by using the mean radiation, absolute temperature of skin $\bar{T}_s$ and surrounding wall temperature $\bar{T}_w$.

$$H_r = 1.356 \times 10^{-12} (\bar{T}_s + \bar{T}_s^2 T_w + \bar{T}_s \bar{T}_w^2 + \bar{T}_w^3) \qquad (35)$$

This equation is valid if the ratio of the area of the walls to the surface area of subject is large.

The heat transfer coefficient for convection H_c can be represented in many forms. The simplest form is given as a function of the diameter of the cylinder D_1, the velocity with which the fluid approaches the cylinder V_2, the thermal conductivity of the fluid K_f, and the viscosity of the fluid μ_f

$$\frac{H_c \cdot D_1}{K_f} = 0.26 \left(\frac{DV_2 \cdot \rho}{\mu_f} \right)^{0.6} \cdot \left(\frac{C_p \cdot \mu_f}{K_f} \right)^{0.3} \qquad (36)$$

where fluid properties indicated by subscript f are to be evaluated at mean surface temperature and undisturbed air temperature. Equation (36) is applicable to the fluid which is flowing in the direction normal to the axis of the cylinder. For a cylinder which is 8 cm in dia.

$$H_c = 1.0 \times 10^{-4} \cdot V_2^{0.6} \qquad (37)$$

For a cylinder which is 26 cm in dia.

$$H_c = 0.95 \times 10^{-5} V_2^{0.6} \qquad (38)$$

The heat transfer coefficient (in the absence of sweating) for evaporation H_e is

$$H_e = 0.16 \times 10^{-4} \text{ Cal/(cm}^2 \cdot {}^\circ\text{C)}. \qquad (39)$$

Equation (39) was obtained by assuming that the vapor pressure of water changes roughly 2.2 mm Hg per °C, the latent heat of vaporization of water at 30°C is 580 cal/gm., and the rate of heat loss by evaporation is

$$E = 0.16 \times 10^{-4} \left[T_s - \left(T_o - \frac{(1-RH)VP_a}{2.2} \right) \right] \qquad (40)$$

where RH is the relative humidity of ambient air. H_e, in case of completely wetted surface and forced convection, is 4.4 times the coefficient for convection H_c. It has been confirmed experimentally that this also applied to the cooling of human beings [5].

In Wissler's steady state model, the interdependence among the elements is provided through the heart and lung where the six venous streams are mixed, producing an arterial stream at an intermediate temperature. The energy balance for the heart and lung is considered by stating that the rate at which heat is carried into the heart by the venous blood is equal to the rate at which heat is carried away from the heart by arterial blood plus the rate of heat loss through the respiratory system. This relationship can be represented by

$$\sum_{i=1}^{6} \pi a_i^2 L_i (V_i \rho C_p)_i (T_{ha} - T_{vi}) = - Q \qquad (41)$$

where

$$\sum_{i=1}^{6} \pi a_i^2 L_i (V_i \rho C_p)_i T_{ha}$$

is the total heat carried into the heart by the arterial blood and

$$\sum_{i=1}^{6} \pi a_i^2 L_i (V_i \rho C_p)_i T_{vi}$$

is the total heat carried into the heart by venous blood.

The countercurrent heat exchange between the large arteries and veins in an element is approximated by

$$T_{ho} - T_{ai} = \frac{(UA)_i}{wa_i^2 \, L_i \, (V_i \; \rho . S_p)_i} (T_{ho} - T_{vi}) \qquad (42)$$

where T_a is the arterial blood temperature, U is the overall heat transfer coefficient, and A is the effective area of the heat exchanger. In this model all the exchangers in an element are lumped together in a single countercurrent heat exchanger located between the element and the heart. In reality, counter current heat exchange is distributed throughout an element.

D. UNSTEADY STATE MODEL

3.2.2 Wissler's Model (FIRST)

Wissler's first unsteady state model [23] is an extension of Wyndham and Atkins model given by (19) for a single element only. The human body is considered to consist of six elements (Torso, Head, two arms and two legs). Each element is assumed to be a homogeneous cylinder of bone and tissue covered with a layer of fat and skin. Heat is assumed to be generated uniformly by metabolic reactions in each section of the cylinder, but the rates are not necessarily equal. Similarly, the capillary beds of each section are uniformly supplied with arterial blood at a temperature T_{ai}. After neglecting the longitudinal thermal gradient, the transient heat conduction equation takes the following form for the i th element.

$$\rho C_p \frac{\partial T_i}{\partial t} = K\left(\frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r}\frac{\partial T_i}{\partial r}\right) + h_{mi} + (V_i \, \rho C_p)_i (T_{ai} - T_i) \qquad (43)$$

This equation represents the transient counterpart of the steady state heat conduction equation (32). The term on the left hand side is the rate of accumulation of thermal energy. The terms on the right hand side are the rate of heat conduction in a radial direction, the rate of heat generation by metabolic reactions, and the rate of heat transfer by blood circulation. The difference between (43) and (19) is an additional term in (43) representing heat transfer by local blood circulation. This has been recognized for some time as an important factor in thermal physiology. Inclusion of this term contributes greatly to the validity of the mathematical model in predicting thermal response of the human body.

Equation (43) was solved by Wissler subject to the initial and boundary conditions described below. An initial condition specified the initial distribution of the body temperature i.e.

$$T_i\ (r,0) = f(r)$$

The boundary condition indicates that the rate of heat conduction at the surface of the skin from the tissue is equal to the rate of heat transfer from the surface to the environment i.e.

$$- K \left(\frac{\partial T}{\partial r} \right)_{r=ai} = H_i \left[T_i(ai,t) - T_{ai} \right] \qquad (44)$$

Even though (43) represents only the radial heat conduction equation for a single element, the thermal energy balance between each of the elements and the heart is taken into account in this model, as shown below

The relationship which interrelates the elements are the following

$$T_{vi} L_i \int_0^{ai} 2\pi r (V_i \rho C_p)_i \, dr = L_i \int_0^{ai} 2\pi r (V_i \rho C_p)_i T_i \, dr \tag{45}$$

$$T_{ha} - T'_{ai} = T_{hvi} - T_{vi} \tag{46}$$

$$T_{ha} - T_{hvi} = \frac{\pi a_i^2 L_i (V_i \rho C_p)_i (T_{ha} - T_{vi})}{(UA)_i + \pi a_i^2 L_i (V_i \rho C_p)_i} \tag{47}$$

$$T_{ha} - T'_{ai} = \frac{(UA)_i (T_{ha} - T_{hvi})}{\pi a_i^2 L_i (V_i \rho C_p)_i} \tag{48}$$

Equation (45) assumes that the temperature of the venous blood leaving a capillary bed is equal to the temperature of the tissue adjacent to the bed. Equation (46) to (48) are the energy balances among arterial blood, venous blood, and blood in the heart.

3.2.3 Wissler's Second Unsteady State Model

This model considers explicitly the variability of the physiological parameters. The model can be solved by a finite difference technique [24].

In this model, the human body is divided into 15 elements as shown in Fig.6. The elements are connected by vascular system. Metabolic reactions are considered to be the main source of heat. Heat is either stored in the element or conducted away from the axis of the element towards the surface of the skin where it is lost to the environment by convection, conduction, radiation and evaporation. The phenomenon can be mathematically expressed by the heat conduction equations.

$$(\rho \cdot C_p)_i \cdot \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(K_{ir} \frac{\partial T_i}{\partial r} \right) + h_{mi} + Q_{ci} (T_{ai} - T_i)$$

$$+ h_{ai}(T_{ai} - T_i) + h_{vi}(T_{vi} - T_i) \qquad (49)$$

Equation (49) states that the rate of thermal energy accumulated per unit volume is equal to the sum of the rate at which heat is conducted into the unit volume plus the rate at which heat is generated by metabolic reactions plus the rate at which heat is carried into the unit volume by bulk flow of circulating blood plus the rate at which heat is transfered from arterial blood into the unit volume plus the rate at which heat is transferred from the venous blood into the unit volume. The heat conduction in the longitudinal direction is neglected.

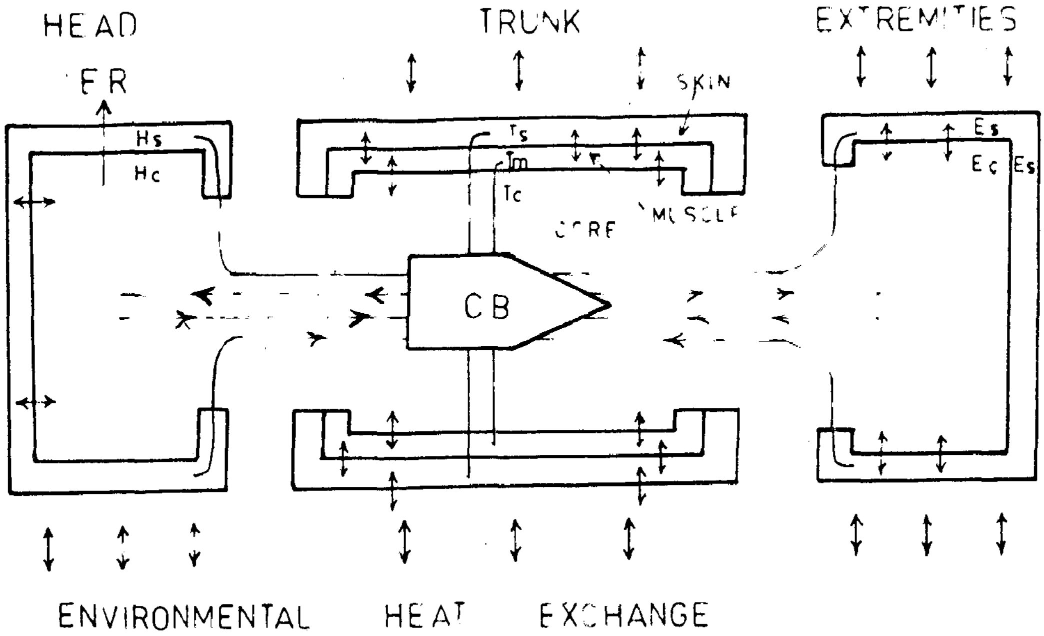
Wissler's second model considered many important factors, such as the variability of the local blood flow rate, the thermal conductivity, the rate of local heat generation by metabolic reactions, the geometry of the human body, heat loss through the respiratory system, sweating etc. These factors had not been considered by previous researchers. However, the physiological thermal regulation mechanism was not considered.

3.2.4 <u>Stolwijk and Hardy's Model</u>

Stolwijk and Hardy [20] proposed a model which is based on a simplified configuration of the human body, but which takes into account mathematically the physiological thermal regulation mechanism. Fig.7 shows that the model divides the body into three cylinders (head, torso, extremities). Each cylinder is then subdivided into two or more concentric layers, such as the head core (HC) and head skin (HS), to characterise the functional differences in their thermo-regulation. It is assumed that the heat flow between the two adjacent layers such as HC and HS is by conduction and that all the layers exchange heat with the central blood compartment (CB) by convection. Heat exchange between the skin and its environment is by conduction, convection, radiation and evaporation. Signals which are proportional to the temperature deviations in the brain and the average skin temperature are supplied to the physiological thermoregulator which then adjusts the values of evaporative heat loss, local blood flow rate, the rates of heat generation by metabolic reaction in appropriate locations of the body.

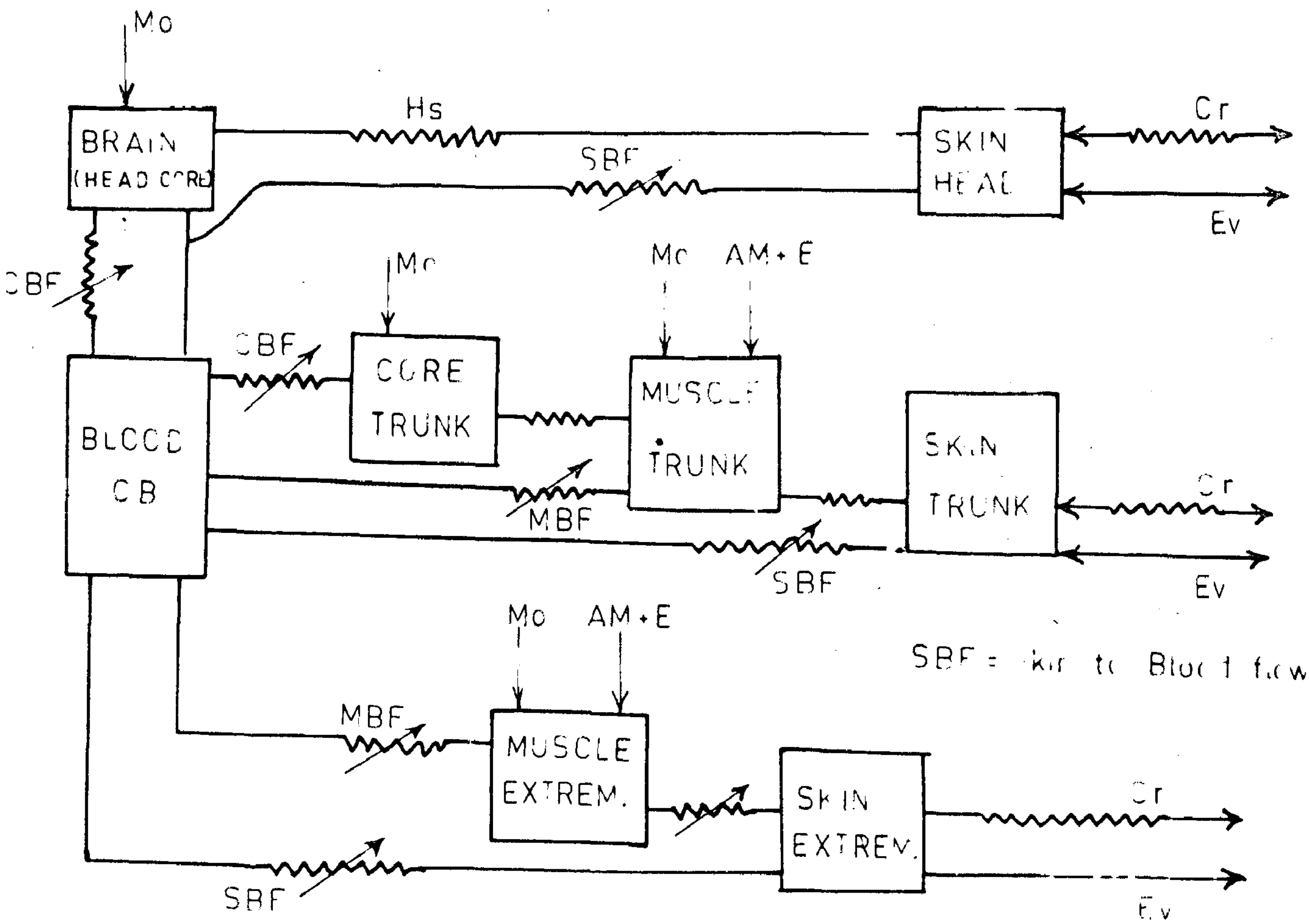
The block diagram of Fig.8 summarises the relationship among the various compartments of the model.

The block representing the head skin (HS) exchanges heat with its environment by convection, conduction, radiation and evaporation. It also exchanges heat with the blood compartment by convection (CBF) and with the brain by conduction. The block representing the head core (brain) exchanges heat with the blood compartment by convection (CBF) while it exchanges heat with head skin (HS) by conduction. A similar phenomenon exists among various blocks of the trunk and extremities.



STOLWIJK AND HARDY'S MODEL

FIG. 7.



BLOCK DIAGRAM OF THERMAL MODEL OF MAN.

FIG. 8.

The heat balance equations of the brain is written as

$$C_{HC} \frac{dT_{HC}}{dt} = c_{HC} \cdot P \cdot C_p \times 40.0(T_{CB} - T_{HC}) + M_{CHC} + 0.04\,CM$$

$$- K_{HCHS}(T_{HC} - T_{HS}) - E_{VR} - E_{V} \qquad (59)$$

where the blood flow to the core of the head is $40.0 \times \frac{l}{h}$ and the fraction of the total shivering metabolism assigned to the core of the head is 0.04 CM. Equation (59) states that the rate of thermal energy accumulation in the core of the head is equal to the rate at which heat is carried away into the core of the head from the blood compartment plus the rate of generation of metabolic heat minus the conduction heat loss to the skin of the head minus the respiratory heat loss.

In the heat balance equation concerning the skin of the head, the heat loss from the skin of the head through convection, conduction and radiation is lumped by the heat transfer coefficient h_o. The equation also includes conductive heat flow from the core to the skin and a convective heat from the blood compartment to the skin. Evaporative heat loss is

$$C_{HS} \frac{dT_{HS}}{dt} = K_{HCHS}(T_{HC} - T_{HS}) + M_{CHS} - 0.09\,E_{VCHS}$$

$$- 0.09\,E_V + c_{HS} \cdot P \cdot C_p \times 0.130\,[illegible](T_{CB} - T_{HS})$$

$$- A_{HS}\, h_o (T_{HS} - T_A) \qquad (60)$$

where $0.09\,E_{VI}$ is the assigned fraction of insensible evaporative heat loss, $0.09\,E_V$ is the assigned fraction of thermal evaporative heat loss and 0.133 SBF is the assigned fraction of the total skin blood flow.

Heat balance equation can also be written for the core of extremities, skin of the extremities, core of the torso, muscle of the torso, skin of the torso and blood compartment.

By using an analog computer, Stolwijk and Hardy simulated the model as well as physiological thermal regulator

3.2.4 Analog Simulation of Thermoregulatory System

We have, the differential equations for core, muscle and skin temperature regulation as seen above. If we take only time variations, and neglect space variations then we get for core

$$M_c \, C_c \frac{d\theta_c}{dt} = M_b - E_{r+ex} - q_{cm} - q_{cs}$$

where

M_b - metabolic heat generation rate

E_{r+ex} - respiratory and exporatory losses

q_{cm} - heat loss from core to muscle

q_{cs} - heat loss from core to skin

q_{ms} - heat loss from muscle to skin

$$q_{cm} = \frac{K.A_{cm} (\theta_c - \theta_m)}{L_{cm}}$$

$$q_{cs} = \frac{K_v. A_{cs} (\theta_c - \theta_s)}{L_{cs}}$$

where L's are equivalent lengths

c,s and m stands for core, skins and muscle.

A's are equivalent areas

θ - temperatures

K - thermal conductivity

K_v - thermal conductivity (variable)

For Muscle

$$m_m \cdot C_m \frac{d\theta_m}{dt} = H_{ex} + H_s + q_{cm} - q_{ms}$$

where H_{ex} - Heat produced by exercise per unit volume

H_s - Heat produced by shivering per unit volume

For Skin

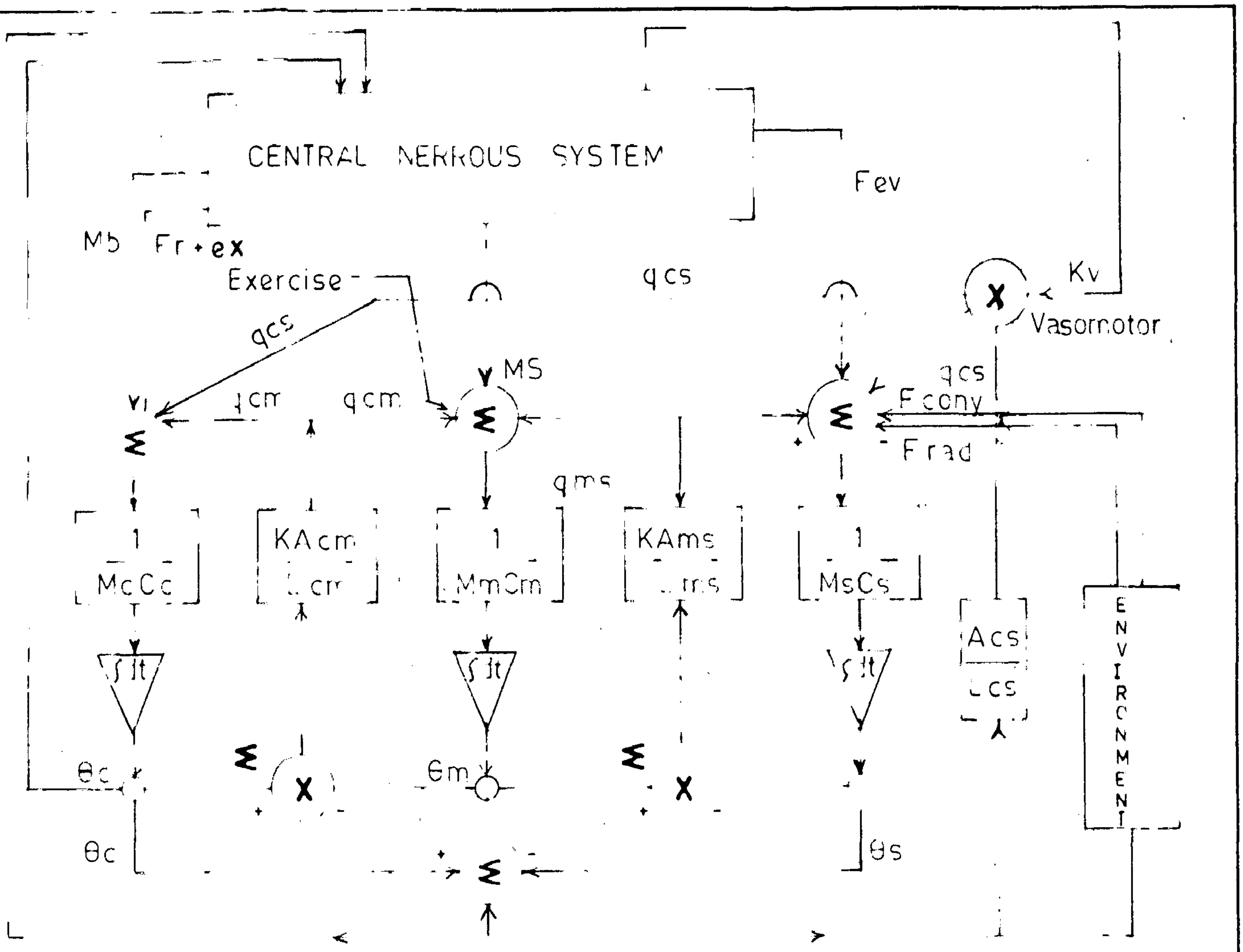
$$m_s \cdot C_s \cdot \frac{d\theta_s}{dt} = q_{cs} + q_{ms} - F_{rad.} - F_{conv.} - F_{ev.}$$

where

Frad, Fconv., Fev. represent heat loss by radiation, convection and evaporation respectively.

3.2.5 Miller and Cosgrove's Model (unsteady state)

Miller and Cosgrove [14] proposed a model consisting of 15 cylinders arranged as shown in Fig.10. Each limb is represented by three cylinders, corresponding to the proximal, medial and distal portions. The head is represented by a single cylinder while the trunk by two cylinders representing the Thorax and Abdomen. Each of these latter three cylinders has three layers viz a core layer representing viscera or brain; a middle layer representing skeletal muscle and bones; and a surface layer, representing skin and subcutaneous fat. The cylinders representing the extremities are each two layered :



ANALOG SIMULATION OF THERMOREGULATORY SYSTEM.

FIG. 9.

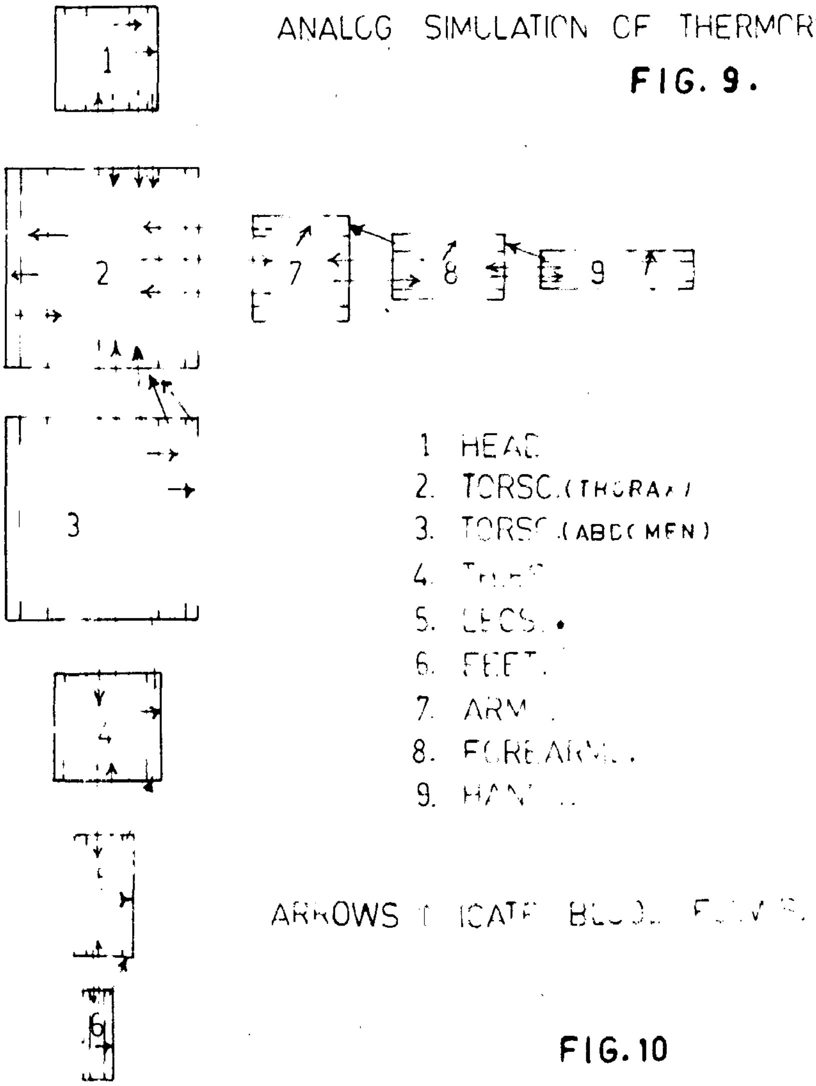


FIG. 10

a central layer of muscle and bone and a surface layer of skin and subcutaneous fat. Thus the core layer refers to the central layer in the three layered cylinders only. The central layer in the extremities refers to the muscle layer.

The core layers are portions where basal, nonvarying metabolic processes occur. Muscle layers are assigned a minimum metabolism, and a variable increased metabolism due to movement of body. Surface layers are assumed to have a small basal metabolism.

Heat transfer between layers in individual cylinders occurs partly by conduction, but largely by convective blood flow. This convective blood flow is also responsible for all the heat transfer between cylinders. In the core regions, blood requirements are assumed constant. The blood flow to muscle region is variable, a minimum constant amount necessary for basal requirements and a varying amount needed to supply nourishment for the working muscle. The skin layers also have a small basal requirements, but they have a widely variable flow for convecting heat from the deeper layers to the surface where it may be lost to environment. Blood supply to the surface layer is independent of muscular requirements. The supply to surface layers in excess of metabolic needs is dependent only on cooling requirements, and varies to a maximum value which is many times the minimum value. This surface supply returns via surface veins from the extremities to the core layers.

It is well known that counter current heat exchange occurs between the arteries and veins in the extremities. The arrangement of large vessels in close proximity allows the body to conserve heat centrally by reducing the losses to the environment by decreased temperature in the extremities. Present model does not explicitly consider counter current exchange between vessels. Blood flow conditions through all sections are assumed to be such that the blood leaving an element is at the same temperature as the element for the non surface layers. This is a much less stringent assumption than that of blood and tissue temperature equality. By dividing two limbs into several sections, features of counter-current exchange are retained without introduction of new artificial parameters to the system.

For the blood going to and from the surface layers, however, it is not reasonable to assume equality between mass average temperature of the surface layer, which includes both skin and subcutaneous fat and blood flowing through the layer, since the superficial vessel lie mostly above the fatty tissue. To allow for blood flow effects, the vessel are assumed to lie at a uniform depth beneath the skin surface and to be at a temperature predicted by a linear temperature gradient near the surface.

MATHEMATICAL DESCRIPTION

System may be described by equation of the first order in time by eliminating the space variables. All the tissues within a layer of cylinder is considered to be at the same temperature, the mass average temperature.

The conductive heat flow through any surface in the cylinder may be represented by

$$Q_r = -2\pi r L K \frac{\partial T}{\partial r}\Big|_r = -2\pi L K \frac{\partial T}{\partial \ln r}\Big|_r \qquad (1)$$

This may be written in finite difference form. If R_i is the geometric average radius of the i th layer, then the flow to i th layer from the i+1 st layer is given by

$$Q_{ri} = -2\pi r_i L K \frac{T_{i+1} - T_i}{R_{i+1} - R_i} \qquad (2)$$

If the thermal conductivity of the layers is not equal, an average may be defined by

$$K_{avg} = \frac{(\text{mass of } 1) \times K_1 + (\text{mass of } 2) \times K_2}{(\text{mass of } 1 + \text{mass of } 2)}$$

Considering the surface temperature used to obtain the heat loss to the environment from the surface layer, a temperature representing the average for the surface layer of a cylinder will not be the same as the temperature at the surface for a layer of finite thickness. Therefore true surface (superficies) temperature is obtained from the average temperature in the surface layer.

Assuming the existence of a thin shell on the surface of the cylinder and allowing this shell to become vanishingly small, a relationship between superficies (outer surface) temperature (T_{os}) and average temperature of the surface T_o can be obtained as follows

$$T_{os} - T_a = \frac{1}{1+\beta} (T_o - T_a) \qquad (4)$$

ere
$$\beta = \frac{1}{1 + (h/K)(r_o - R_o)} \qquad (5)$$

and T_a is the ambient temperature.

The surface heat loss by radiation, conduction and nvection then becomes

$$CCR = -2\pi . r_o . L . h . \beta \, (T_o - T_a) \qquad (6)$$

re h combines the convective heat loss by radiative heat loss.

The convective heat loss by blood flow may be given for e i th layer by

$$CB_i = \sum_j wj \, (\rho . C_p)_b \, (T_i - T_b) \qquad (7)$$

re the summation is over all the j flows which enter the h layer and T_b is the temperature of the layer, the blood in immediately preceding its entrance into the i th layer. is the specific heat in cal/gm/°C.

It is assumed that the temperature profile near the face is linear, and that the blood is at the temperature dicated by a position slightly below the surface, say R_{posit}.

Thus the temperature of the blood in a surface layer given by

$$T_b = T_o + \frac{r_o - R_{posit}}{r_o - R_o}(T_{oo} - T_o) \qquad (8)$$

This temperature must be used to calculate convection the surface layer.

Equations may now be derived for each of the cylinders representing body segments. The equations are quite similar to each other, the main difference being in the convective blood flow pattern.

Considering a three layered cylinder with the layers bounded by r_c, r_m, r_s and each having a geometric centre R_c, R_m, R_s, a heat balance on the core layer gives

$$V_c \cdot \rho \cdot C_p \frac{dT_c}{dt} = 2\pi \cdot r_c \cdot K \cdot L \cdot \frac{T_m - T_c}{R_m - R_c} + \sum_i w_i \, (\rho \cdot C_p)_b \, (T_b - T_c) + V_c(M + \Delta M) \qquad (9)$$

where $\sum_i w_i \, (\rho \cdot C_p)_b \, (T_b - T_c)$, is a general term that considers all blood flow, T_b is the temperature of the section the blood was in last, and ΔM represents the change in metabolic heat generated relative to the steady state value, M. Dividing by $V_c \, \rho \cdot C_p$ gives

$$\frac{dT_c}{dt} = \frac{2}{r_c} \cdot \frac{K}{\rho \cdot C_p} \cdot \frac{T_m - T_c}{R_m - R_c} + \frac{\sum_i w_i (\rho \cdot C_p)_b}{V_c \cdot \rho \cdot C_p} (T_b - T_c) + \frac{M_1 + \Delta M_1}{\rho \cdot C_p} \qquad (10)$$

The first term on the right hand side of (10) represent muscle to core heat flow by conduction, 2nd terms represents heat given by blood and the 3rd terms, metabolic heat generation.

For the middle layer, the same procedure gives

$$\frac{dT_m}{dt} = \frac{2r_c}{r_m^2 - r_c^2} \cdot \frac{K}{\rho \cdot C_p} \cdot \frac{T_c - T_m}{R_m - R_c}$$

$$+ \frac{2r_m}{r_m^2 - r_c^2} \cdot \frac{K}{\rho \cdot C_p} \cdot \frac{T_s - T_m}{R_s - R_m}$$

$$+ \frac{\Sigma v_i}{V_m} \cdot \frac{(\rho \cdot C_p)_b}{\rho \cdot C_p} (T_b - T_m) + \frac{M + \Delta M}{\rho C_p} \qquad (11)$$

For the surface layer, the relation was given by

$$\frac{dT_s}{dt} = \frac{2r_m}{r_s^2 - r_m^2} \cdot \frac{K}{\rho C_p} \cdot \frac{T_m - T_s}{R_m - R_s} + \frac{\Sigma v_i (\rho C_p)_b}{V_s \cdot \rho C_p} (T_b - T_{cb})$$

$$- \frac{2r_s}{r_s^2 - r_m^2} \cdot \frac{hS}{\rho C_p} (T_s - T_a) + \frac{ev}{V_s \cdot \rho C_p} + \frac{M}{\rho C_p} \qquad (12)$$

where ev is heat loss through sweating cal/sec.

This is the general form of equation for the three layered region. Those for the two layered regions are identical except that equation for the central muscle layer is of the same form as the core equation above, and the core equation is absent.

CHAPTER - IV

PROPOSED MODEL

4.1 MATHEMATICAL MODEL OF AN INTEGRATED HUMAN THERMAL SYSTEM

An integrated human thermal system consists of a human thermal system and its external thermal regulation device. A review and systematic classification of the literature on mathematical models of human thermal systems has been carried out by L.T. Fan and F.T. Hsu [4]. Two basic approaches to the modelling of the control system are described in literature. Wissler [24] attempted to deal with the distributed properties of the system allowing for both geometric and time variables in body temperatures. His basic model is in the form of a series of partial differential equations but it does not include physiological temperature regulation. Smith and James [4], Stolwijk and Hardy [21], Huckaba et al. [10] and Stolwijk [18], approximated the distributed parameter system in terms of lumped parameters configuration composed of various numbers and types of simple geometric elements. The model described here is essentially based on Stolwijk (1970) model [18].

The basic difference between the Stolwijk model and the one proposed here is that the head has been taken of cylindorical shape, instead of spherical as assumed by Stolwijk. Following are the assumptions made in the proposed model.

Assumptions

1. Body is assumed to be divided into six anatomical segments viz. head, torso, arms, hands, legs and feet.
2. Every segment is approximated by a cylinder.

3. In case of extremities, single cylinders are used to represent both arms, both hands, both legs and both feet.
4. Each segment is assumed to consist of four concentric layers viz. core, muscle, fat and skin.
5. Heat transfer is assumed to take place from outer to the inner surfaces as well as from inner to outer surfaces.
6. The temperature of the blood flowing in all the segments is taken to be equal to the central blood temperature T_{CB}, except in the case of hands and feet, since the blood, while flowing through the arms and legs segments experiences a fall in temperature. Thus blood temperatures in hands and feet is assumed to be 0.5°C less than central blood temperature.
7. No blood is assumed to be flowing in the core layer of arms, legs, hands and feet. Blood does not flow in the fat.

The geometry of the body considered in the model is shown in Fig.11. The body consists of six anatomical segments. These are : 1. Head, 2. Trunk, 3. arms, 4. hands, 5. legs, and 6. feet. The extremities are represented by single cylinders. Each of these segment is subdivided into four concentric layers, core, muscle, fat and skin. Therefore total layers considered in the body are 24. In addition, a central blood compartment is included, resulting in a total of 25 nodes.

The heat which is produced in a segment by metabolic reactions is stored in the segment, carried away by circulating blood to other parts, or conducted away to the surface where it is generally transferred to the environment. If the environmenta

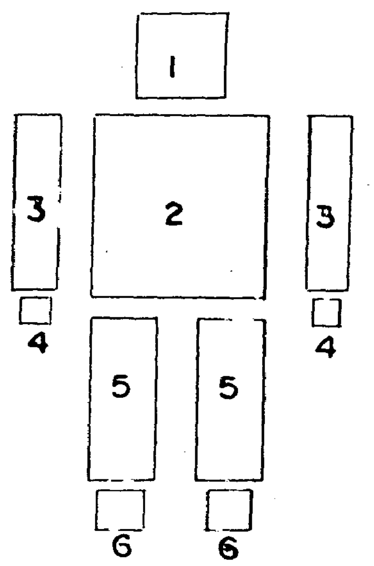


FIG.11 SCHEMATIC DIAGRAM OF THE HUMAN BODY.

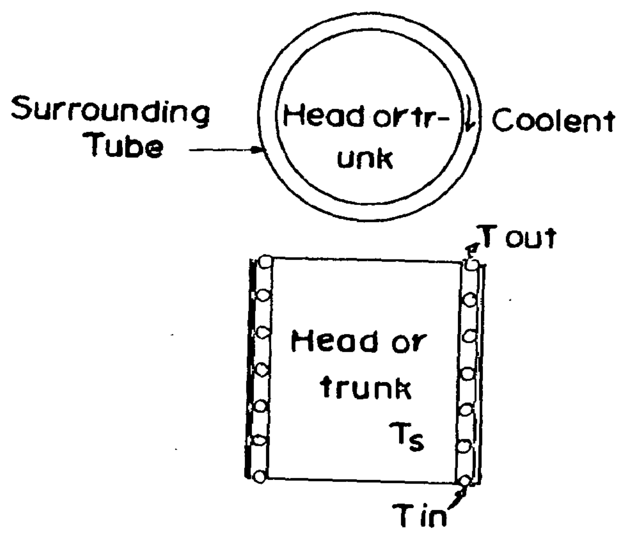


FIG.12 SCHEMATIC DIAGRAM OF CONDUCTION COOLING.

temperature is higher than the skin temperature, the direction of heat loss is reversed and heat flows into the element.

The present model predicting steady state temperature distribution consists of steady state heat balance equations for each of the anatomical segments, such as head, trunk etc., the equation follow the format given in Table I.

Table - I Steady State Heat Balance Equations Applying to each Anatomical Segment

	INPUT				OUTPUT		
	METABOLIC HEAT PRODUCTION	+	HEAT TRANSFER THROUGH INNER SURFACE	=	HEAT TRANSFER THROUGH OUTER SURFACE	+ HEAT EXCHANGE WITH BLOOD	
Core	M_c	+	0	=	$KC(T_c-T_m)+$ [illegible]	+ $CBF \cdot C_B(T_c-T_o)$	(1)
Muscle	M_m+H_B	+	$K_c(T_c-T_m)$	=	$K_m(T_m-T_f)$	+ $MBF \cdot C_B(T_m-T_o)$	(2)
Fat	M_f	+	$K_m(T_m-T_f)$	=	$K_f(T_f-T_s)$	+ $FBF \cdot C_B(T_f-T_o)$	(3)
Skin	M_s	+	$K_f(T_f-T_s)$	=	$E_S+H_S A_S(T_S-T_A)$	+ $SBF \cdot C_B(T_S-T_O)$	(4)

For six anatomical segments we have 6 x 4 = 24 equations.

Also,

$$T_{CB} = \sum_{i=1}^{24} [(BF_i)(T_i)]/(\text{Total blood flow in all the segments}) \quad (25)$$

H_B - Applies only to arms and legs and represent heat lost by blood flowing through those segments (assumed transferred to muscle layer).

Where,

M - Metabolic heat production cal/hr

K - Thermal conductance, cal/hr/°C

CBF - Core blood flow rate, ml/hr

FBF - Fat blood flow rate, ml/hr

MBF - Muscle blood flow rate ml/hr

SBF - Skin blood flow rate ml/hr.

C_B - Specific heat of blood cal/ml/°C

A_S - Skin surface area cm^2

H_E - Environmental heat transfer coefficient cal/cm^2/hr/°C

E_R - Respiratory evaporative heat loss cal/hr

E_S - Evaporative heat loss from skin cal/hr

H_B - Heat lost by blood (going to feet and hands) to legs and arms. cal/hr

T_A - Temperature of the coolant in the external device at the surface of segment °C

T_{in} - Inlet temperature of coolant °C

T_{out} - Outlet temperature in external device °C

q - Heat removed by external thermal regulating device

m - Coolant mass flow rate.

Subscripts

c - Core

f - Fat

m - Muscle

s - Skin

The term for heat transferred through the inner surface of a cylinderical section is by conduction. As the core is the inner most surface, it has no term corresponding to this category. Heat transfer through the outer surface occurs also by means of conduction, except for skin, which loses heat by evaporation, convection and radiation. The heat lost by convection and radiation is accounted through the environmental heat transfer coefficient H_C. Heat exchange with the blood is proportional to the change in temperature of the blood as it flows through a given section.

In case of heat core, an additional term is added to the output side to account for respiratory evaporative heat loss, H_1.

The term H_3 in muscle layer equation is used to account for the heat loss to the surrounding tissues from the blood flowing along the arms and legs on the way to hands and feet. Thus

$$(H_3)_{arms} = (MBF)_{hands} (T_B - T_0) C_B$$

and

$$(H_3)_{legs} = (MBF)_{feet} (T_B - T_0) C_B$$

The inlet blood temperature T_0 is assumed equal to the central blood temperature T_{CB}, except in the case of hands and feet, since the blood, in flowing through the arm and leg segments experiences a fall in temperature, where it is taken to be 0.5°C below T_{CB}.

In addition to 24 steady-state heat balance equations, there is another equation used to calculate the mixed blood temperature as it flows back into the central blood compartment from the various anatomical segments. The parameters to be used for the solution of above 25 equations are given in table - II and table III. The model gives rise to the temperature distribution of human body which is exposed to a specific environmental condition.

<u>Table - II</u> <u>Anatomical and Physiological Parameters</u>

A. Dimensions of Anatomical Segments

Body Segment	Volume lit.	Area m^2	Length cm
Head	6.5	0.157	30.0
Trunk	51.9	0.685	72.0
Arms	8.1	0.330	107.0
Hands	0.9	0.073	47.2
Legs	16.6	0.546	143.0
Foot	2.0	0.110	48.0

B. Blood Flow Distribution ml/min.

Body Segment	Skin	Fat	Muscles	Core
Head	62	0	20	900
Trunk	240	0	1092	3120
Arms	14	0	123	0
Hands	57	0	6	0
Legs	29	0	262	0
Foot	63	0	7	0

C. Percentage Distribution of Metabolism

Body Segment	Skin	Fat	Muscle	Core
Head	0.18	0.17	0.27	16.52
Trunk	0.70	2.46	10.15	59.55
Arms	0.23	0.30	1.72	0.70
Hands	0.10	0.05	0.05	0.10
Legs	0.40	0.52	3.66	1.53
Feet	0.20	0.13	0.07	0.24

Table - III Numerical Values of Constants used in the System

A. Thermal Conductivity

K_c = 0.00120 K cal/sec/°C = 4320 cal/hr/°C

K_m = 0.00126 K cal/sec/°C = 4540 cal/hr/°C

K_f = 0.00055 K cal/sec/°C = 1980 cal/hr/°C

B. Metabolic Heat Generation Rate for Head

Layer of Head	For Total Metabolic Rate of (Btu/hr)		
	1800	2400	3000
Core (M_c)	74935 cal/hr	10^5 cal/hr	1.25×10^5 cal/hr
Muscle(M_m)	1225 cal/hr	1630 cal/hr	2040 cal/hr
Fat (M_f)	771 cal/hr	1028 cal/hr	1285 cal/hr
Skin(M_s)	816.5 cal/hr	1089 cal/hr	1361 cal/hr

C. Blood Flow Rates in Head

An average cardiac output of 6.1 litres/minute can be used [10]

The average blood flow figures for head are as follows :

CBF = 54000 ml/hr

MBF = 1200 ml/hr

FBF = 0

SBF = 3720 ml/hr.

D. Other Parameters

i) Specific heat of blood $C_B = 0.87$ cal/ml/$^{\circ}$C

ii) Environmental heat transfer coefficient $H_S = 0.0576$ cal/cm^2/hr

iii) Skin area A_S (Head) = 1570 cm^2.

iv) Evaporative heat loss from skin (Head) = 1099 cal/hr.

v) Total evaporation heat loss from body = 13.3 K cal/hr.

vi) Respiratory evaporative heat loss, $E_R = 2.22$ cal/sec. = 7992 cal/hr.

(This value of E_R [14] is for a steady respiration rate of 30/min under relative humidity of 50 per cent and ambient temperature of 30°C)

4.2 The Model of Internal Temperature Regulation Device

For a man working in heat stress environment, there are situations in which it is not possible to cool the environment. The alternative is to ignore the environment and to cool the man i.e. individual cooling. Individual cooling can be done by conduction, convection or evaporation of water (generally sweat). Cooling by evaporation of sweats and convection is done by blowing air over the man. The increased velocity of the ambient air improves evaporation, thus reducing the heat load.

External thermal regulating device for the entire human body have been developed and tested. Kons, Duncan and Morales[16] examined the effectiveness of the regulation device on the head. In this work, external thermal regulation device on head and trunk is considered. It is based on the principle used by Buchberg and Harrah [2].

The cooling system consists of a network of tubes held in contact with the surface of the skin of the head and trunk, with a liquid coolant flowing inside the tubes. The tubes are assumed to be perfectly insulated from the outside environment. The external thermal regulation device can be considered as a substitutive thermoregulatory device, because if the device has sufficient capability and is properly controlled, the human body can be maintained in a state of thermoneutrality. The main purpose of the device is to minimize the natural thermoregulatory mechanisms of shivering and sweating by varying the skin temperature as a function of metabolic heat and to maintain the human body in thermal comfort.

The schematic diagram of the external thermal regulation device (Fig.12) shows the head or torso surrounded by a network of tubes, insulated from its outside environment and held in contact with the surface of skin. The liquid coolant enters the tube from one end and flows from the other end. It is assumed that the spacing of the tubes is so small that the skin temperature is uniform throughout the segment.

The function of the external device is to remove the heat from the surface of the skin. The device is assumed to regulate the micro-environmental temperature, T_A in equation (4) for head and trunk, which can be approximated by the arithmatic mean of the inlet coolant temperature, T_{in} and outlet coolant temperature. T_{out} as

$$T_A = \frac{1}{2}(T_{in} + T_{out}) \tag{26}$$

The heat removed, q, by the device is given by

$$q = m\, C_p\, (T_{out} - T_{in})$$

Rearranging

$$T_{out} = T_{in} + \frac{q}{mC_p}$$

Substituting T_{out} in (26)

$$T_A = T_{in} + \frac{q}{2\, m\, C_p} \tag{27}$$

Equation (27) determines the environmental temperature for any given inlet coolant temperature , amount of heat to be removed and coolant mass flow rate.

The set of simultaneous equations summarised in table-I alongwith eqn.(26) and (27) approximately represent the integrated human thermal system. The unknown variables are T_c, T_m, T_f and T_s for different segments of the body. The simulation takes into account the parameters of external thermal regulation system.

The temperature profiles in various elements of the body can be obtained for a given metabolic rate, inlet coolant temperature and coolant mass flow rate.

4.3 RESULTS AND DISCUSSIONS

Following results are obtained

I. Steady state temperature distribution in man for different values of metabolic heat generation rates.

II. Relationship between coolant mass flow and deep body temperatures for various values of Metabolic heat generation rates and inlet coolant temperatures.

III. Relationship between deep body temperature and metabolic heat generation rates for various values of coolant mass flows and for particular values of inlet coolant temperatures.

IV. Relationship between the deep body temperature and the metabolic heat generation rate without using the external thermal regulation device.

I. STEADY STATE TEMPERATURE DISTRIBUTION

The temperature in different parts of head i.e. core, muscle, fat and skin have been calculated for three different values of metabolic heat generation rates viz., M = 1800 Btu/hr, M = 2400 Btu/hr and M = 3000 Btu/hr. Such results are calculated to see how the skin temperature is affected by the variation of temperature. It is seen that a difference of maxm. 3°C occurs between core temperature and skin temperature.

M = 1800 lbm/hr

T_G °F(°C)	T_D °C	T_f °C	T_o °C	$T_o - T_{CB}$ °C
80(26.66)	26.05	25.60	24.82	25.24
85(29.44)	28.74	28.19	27.61	28.02
90(32.22)	30.33	30.79	30.1	30.8
95(35.00)	33.89	32.90	31.50	33.60
100(37.77)	36.91	36.22	35.90	36.35
105(40.55)	39.02	38.03	37.76	37.11
110(43.33)	42.37	41.65	41.80	41.9

M = 2400 lbm/hr

T_G °F(°C)	T_D °C	T_f °C	T_o °C	$T_o - T_{CB}$ °C
80(26.66)	25.68	24.5	24.1	24.80
85(29.44)	28.72	28.17	27.43	27.49
90(32.22)	31.5	31.01	30.47	31.26
95(35.00)	34.03	33.56	32.41	33.05
100(37.77)	36.87	36.80	35.33	35.82
105(40.55)	39.67	39.28	38.30	38.59
110(43.33)	42.35	41.62	40.84	41.37

M = 3000 Btu/hr

T_a °F(°C)	T_b °C	T_f °C	T_s °C	T_o °C
80(26.66)	25.9	25.7	24.6	24.2
85(29.44)	28.30	28.20	26.11	27.00
90(32.22)	31.54	31.13	29.89	29.77
95(35.00)	33.74	33.70	31.80	32.55
100(37.77)	36.20	35.90	34.5	35.35
105(40.55)	39.55	38.72	37.85	38.07
110(43.33)	42.76	42.30	40.35	40.88

The above results of steady state temperature distribution in various segments of head show that the mean blood temperature in the body T_b decreases with the increase in metabolic heat rate. This can be explained physiologically as below.

Due to increase in metabolic rate, the temperature inside the body increases. This will increase the heat transfer from the inner to the outer layers of the body and ultimately to atmosphere. In the steady state condition, the ultimate temperature of blood will decrease.

The distribution of temperature in human body (say head or any segment of body) is useful in designing the external thermo-regulatory systems.

II. COOLANT MASS FLOW Vs. BODY TEMPERATURE CURVES

The relationship for various values of inlet coolant temperatures (viz. T_{in} = 32°F, 40°F, 50°F and 60°F) have been plotted between coolant mass flow rate and deep body temperature. These curves are for the different values of M, i.e.

M = 1800 Btu/hr

M = 2400 Btu/hr

and, M = 3000 Btu/hr

It is very clear from the curves that as the inlet temperature increases, the curve becomes more and more flat. i.e. mass flow rate increases with the increase in the inlet coolant. An inlet coolant temperature of 60°F and coolant mass flow rate of 67.5 lb/hr can be employed to obtain head core temperature of 98°F for metabolic rate of 1800 Btu/hr. Similarly, the inlet coolant temperature of 60°F and 50°F and mass flow rates of 87.5 lb/hr and 43 lb/hr can be employed to get the head core temperature of 98°F for metabolic rate of 2400 Btu/hr. The corresponding figures for 3000 Btu/hr metabolic rate are 93.5 lb/hr and 50 lb/hr. Thus it is clear that the coolant mass flow increases with the increase in metabolic heat production rates.

III. EFFECT OF MASS FLOW RATE ON HUMAN BODY COOLING

Figs. 15A and 15B show the temperature of the head core for different mass flow rates and metabolic rates. The results show that inlet coolant temperature of 60°F and coolant mass flow rate of 10 lb/hr can be used to maintain the head core

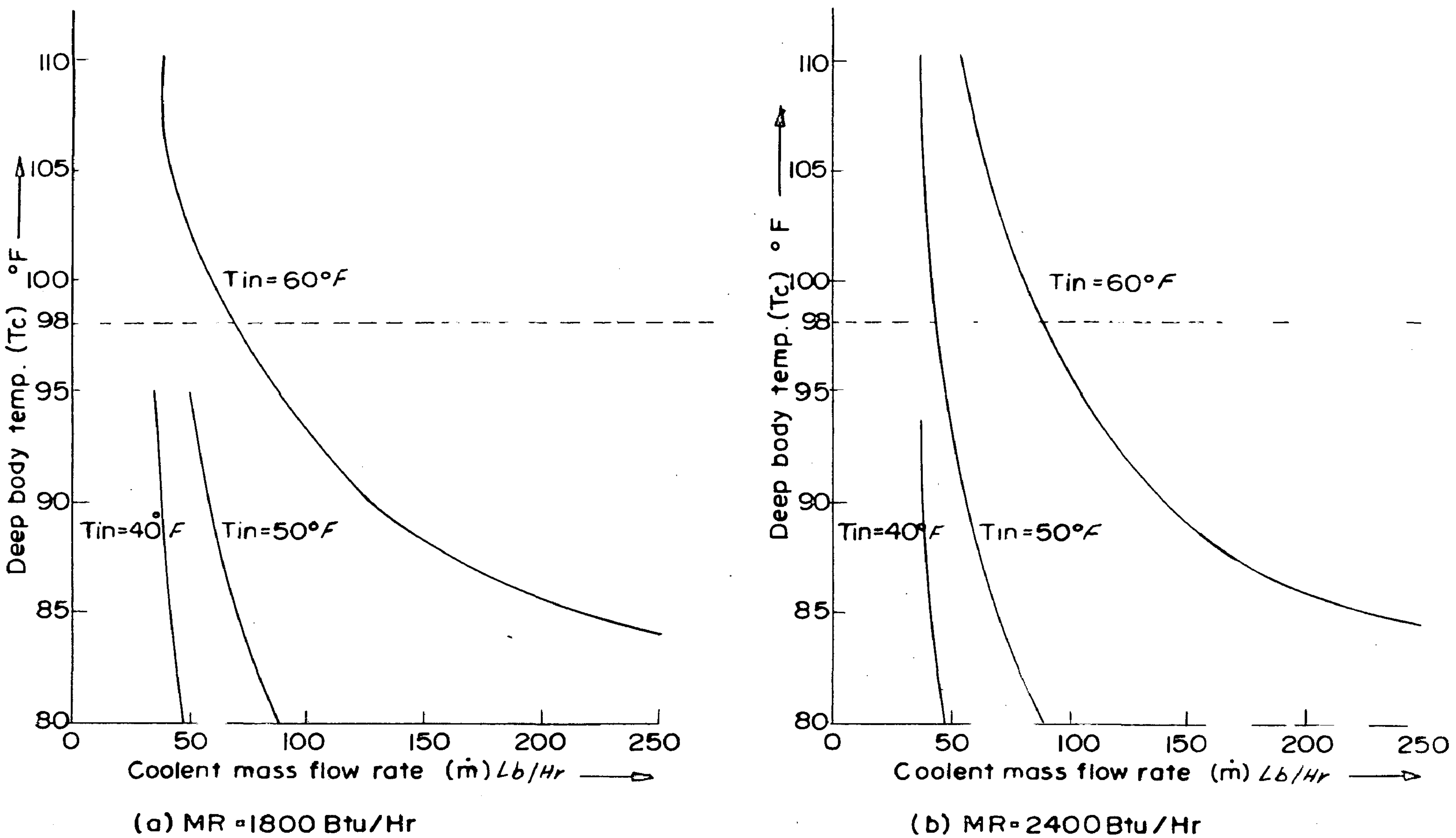


FIG.13 EFFECT OF COOLENT TEMP. AND MASS FLOW RATE ON HUMAN BODY COOLING.

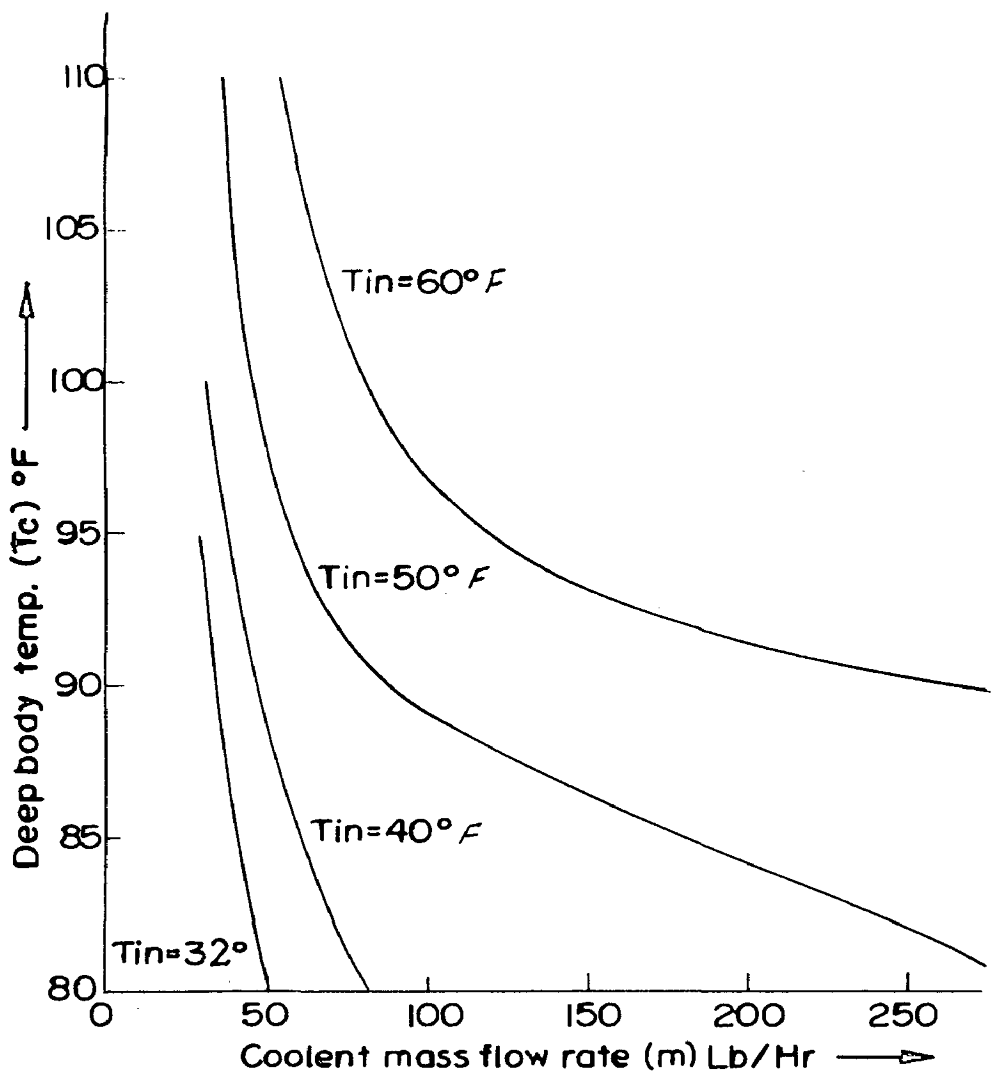


FIG.13(c) EFFECT OF COOLENT MASS FLOW RATE AND TEMP. ON HUMAN BODY COOLING.

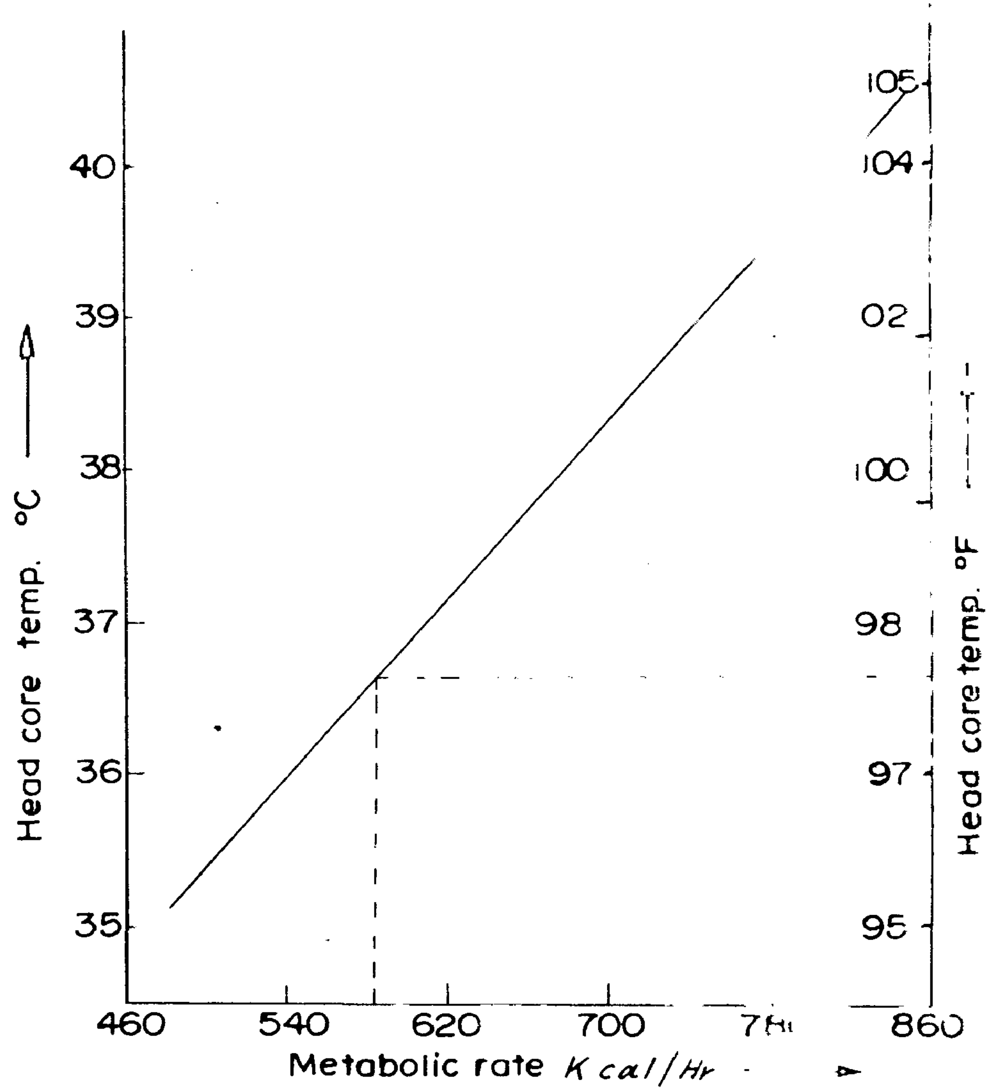


FIG.14 EFFECT OF METABOLIC RATE ON LEP BODY TEPERATURE.

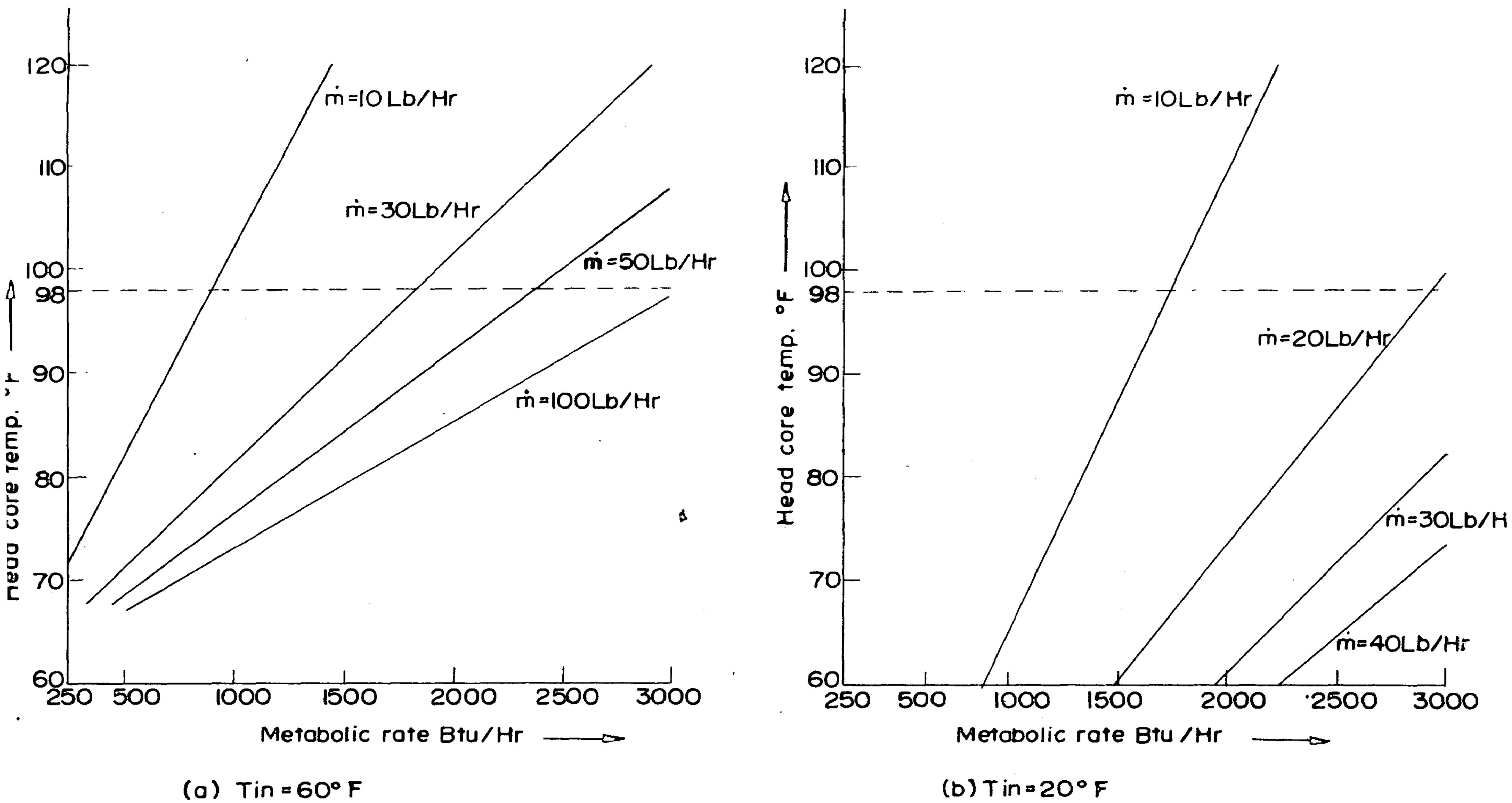


FIG.15 EFFECT OF MASS FLOW RATE ON HUMAN BODY COOLING.

at 98°F even at metabolic rate of 1750 Btu/hr. The corresponding values of metabolic rates for coolant mass flow rate of 30 lb/hr, 50 lb/hr and 100 lb/hr were 1840 Btu/hr, 2375 Btu/hr and more than 3000 Btu/hr for a coolant temperature of 60°F. Whereas a mass flow rate of 30 lb/hr and 40 lb/hr will be too much to maintain a core temperature of 98°F when the coolant temperature is 20°F.

Relationships II and III have been established to see that there may be a number of combinations for regulating the body temperature at 98°F employing different coolant temperatures, and different coolant mass flow rates (for different metabolic heat production rates). These relations will be helpful in evolving some optimum values of coolant temperature and mass flow rate to regulate the body temperatures.

IV. EFFECT OF METABOLIC RATE ON HEAD CORE TEMPERATURE

Using the simultaneous equations given in table - I, the metabolic heat rates were calculated for various values of head core temperatures. Following results were obtained,

Head Core Temperature T_c	Metabolic Rate	
(°C)	K cal/hr	Btu/hr
35	488	193.5
36	549	218
37	611	243
38	673	267
39	733	291
40	796	316
41	897	356

The head core temperature is plotted against the metabolic rate. By graph, the metabolic rate at 98°F (normal rectal temperature) is 584K cal/hr and at 105°F (maximum temperature in case of Typhoid) is 852 K cal/hr. Thus the value of metabolic rate has increased by45.9 per cent with the rectal temperature increase of 7°F. Therefore there is an increase of 6.56 per cent of metabolic rate for every °F increase in core temperature. This result is quite near to the established figure of approximately 7 percent increase in metabolic rate per °F increase in body temperature [26]. Ambiguity between the results may be due to some error in the parameters taken in the proposed model.

The model suggested here is better than the other previous models in the following respects,

1. Here each segment is assumed to be divided in four layers viz. core, muscle, fat and skin. The previous models have either three or two layers in each segment. Therefore in the present model the temperature distribution is more reasonable.

2. The temperature of blood flowing in various segments seems to be better represented because the areas of all the layers of all the segments as well as their temperature have been taken into account while calculating mean temperature of blood.

3. Heat lost by the blood going to hands and feet (via arms and legs respectively), to the arms and legs has been taken into account (In other segments the blood directly goes from the central blood compartment).

4. Due to the heat lost by the blood going to hands and feet (as mentioned in 3), the temperature of the blood in these segments is taken to be 0.5°C lesser than the central blood temperature.

5. Heat lost in the lungs is taken into account.

The error in the results may be due to improper values of the parameters taken in the calculation. The parameters taken here are not standard values mentioned anywhere, but are the values used in their models by certain workers. Our values are mainly the ones used by M/s Miller and Seagrave [14] and M/s Huckaba [10]. The results may further be modified by obtaining new appropriate values of the constants.

APPENDICES AND REFERENCES

APPENDIX - X

RESPIRATORY QUOTIENT

The respiratory quotient (R.Q.) is the ratio of the volume of CO_2 evolved from the lungs over the volume of O_2 absorbed from the lungs in one minute.

METABOLIC RATE

From the knowledge of the respiratory exchanges, the metabolic rate i.e. the energy produced in the body can be indirectly determined. It may be assumed that all the energy is derived from varying proportions of carbohydrate and fat.

If different proportions of carbohydrate and fat are burned in a calorimeter with 1 litre of oxygen, it is found that pure carbohydrate (R.Q = 1) yield about 5 K cal; pure fat (RQ = 0.7) yields about 4.8 K cal, and various mixtures of carbohydrate and fat (R.Q. between 0.7 and 1.0) gives between 4.8 and 5 K cal.

The R.Q. being known, the heat value of 1 litre of oxygen is deduced from a table; if the oxygen consumption is also known the heat production can be determined. Thus if R.Q. = 0.8 (calorific value per litre O_2 = 4.875) and O_2 consumption per minute is 0.25 litre, then the heat production per minute is 0.25 x 4.875 = 1.22 K cal.

Clinically the metabolic rate under conditions of complete rest and fasting (bacal metabolic rate) is calculated from the oxygen consumption alone.

APPENDIX - II

BASAL METABOLIC RATE
(BASAL METABOLISM)

By this is meant the energy output of an individual under standardised resting conditions, i.e. at complete bodily and physical rest, 12-18 hours after a meal (post-absorptive period) and an equable environmental temperature.

The basal metabolism is not the lowest possible level to which the metabolism can fall in a subject; it may be lowered further, for ex, by starvation or thyroid deficiency, it is simply stated as the metabolism under standard resting conditions.

Clinically B.M.R. is expressed as a percentage above or below the accepted normal standard for the individual. Thus the B.M.R. of +50 means one which is 50 per cent above the normal average for that person.

The normal range of metabolism in people of identical physical status may vary commonly by ± 10 per cent and rarely even by as much as ± 20 per cent.

Factors Influencing Metabolic Rate

1. SURFACE AREA : The basal metabolism is most closely related to the surface area and is less directly related to height or weight. The surface area can be calculated from the following formula, if the height and weight are known.

$$A = W^{0.425} \times H^{0.725} \times 71.84.$$

A = surface area cm^2

W = weight in Kg.

H = height in cm.

In the male 40 K cal. and in female adult 37 K cal. are given off every hour per sq.m. of body surface (the surface area of an average adult is about 1.8 cm^2); or expressed in terms of body weight, the basal metabolism amounts to about 1 K cal/kg/hr. The values quoted for metabolic rate average normal values.

2. AGE : The basal metabolism is considerably greater per sq. meter of surface in children than in adults; there is a further gradual fall in the metabolism during adult life as age advances. These facts are shown in the table below.

Age in years	BMR in K cal. per sq. meter per hr.	
	Male	Female
2	57.0	52.5
6	53.0	50.6
8	51.8	47.0
10	48.5	45.9
16	45.7	38.8
20	41.4	36.1
30	39.3	35.7
40	38.0	35.7
50	36.7	34.0
60	35.5	32.6

3. STARVATION : or prolonged undernutrition damps down the metabolic rate. For example, in a man who has fasted 31 days, the daily basal metabolism diminished from 930 to 737 K cal/m^2 of surface area, a fall of over 20 percent. In poorly nourished patients the reduced body weight can finally be maintained on considerably less than the standard basal caloric requirements.

4. BODY TEMPERATURE : For every rise of 1^oF in the internal temperature of body, the basal metabolism increased by 7 per cent. The chemical reactions of the body, like those occuring in a test tube, are speeded up by a rise of temperature. Thus a patient suffering from pneumonia with a temperature of 105^oF (about 7^oF above normal) would have an increase of 50 per cent in his metabolism (and in his pulmonary ventilation) because of fever alone.

5. EXTERNAL TEMPERATURE : Exposure to cold increases the metabolism, there is consequently increased heat production which helps to maintain the normal body temperature. Exposure to external heat of brief duration has little effect on metabolism, as compensation is effected mainly by increasing heat loss, if the exposure is prolonged, a gradual fall in the metabolic rate takes place.

6. DUCTLESS GLANDS

(i) The active principle of the thyroid gland - thyroxine- acts as a general catalyst, speeding up the metabolic activities of the tissues.

Thus in thyrotoxicosis, in which there is increased secretion of the active principle of the gland, the basal metabolism may increase in a severe case upto double the normal (i.e. the B.M.R. is upto + 100). In myxoedema, in which there is lessened secretion of thyroxinal , metabolic activity may be depressed to 60 per cent or 70 per cent of the normal.

(ii) Adrenaline increases the metabolic rate, but to a less extent than thyroxine.

(iii) The anterior pituitary influences the metabolic rate indirectly through its thyrotrophic harmone.

7. In certain other conditions there is an increased metabolic rate for no very clear reason.

8. The taking of food stimulates metabolism. This effect is not equally marked with all classes of food stuffs, being least with carbohydrates and fat, and greatest with protein. If 125 gm. of protein in the form of meat are eaten at one meal, the metabolism rises to reach a maximum after 3 to 5 hours and then slowly declines; the peak percentage increase is 10-35 per cent; the total increase in metabolism may average 20 per cent.

9. Lastly, and most important, there is an increase in the metabolism with muscular work. During every violent exercise the oxygen consumption per minute may rise from 250 ml to 4 litres, or even more i.e. the metabolism may increase over 16 times.

APPENDIX - III

Estimates of Energy Metabolism (M) of Various Types of Activity

(Values apply for a 154 lb man, and do not include rest pause)

Activity	M Btu/hr.
Light work	
Sleeping	250
Sitting quietly	400
Sitting, moderate arm and trunk movements (e.g. desk work typing)	450-550
Sitting, moderate arm and leg movements (e.g. playing organ, driving car in traffic)	550-650
Standing, light work at machine or bench, mostly arms	550-650
Moderate work	
Sitting, heavy arm and leg movements,	650-800
Standing, light work at machine or bench, some walking about.	650-750
Standing, moderate work at machine or bench, some walking about	750-1000
Walking about with moderate lifting or pushing	1000-1400
Heavy work	
Intermittent heavy lifting, pushing or pulling (e.g. pick and shovel work)	1500-2000
Hardest sustained work	2000-2400

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