Experientia 43 (1987), Birkhäuser Verlag, CH-4010 Basel/Switzerland

Effects of climatic stresses on thermoregulatory processes in man

by M. K. Yousef

Desert Biology Research Center, Department of Biological Sciences, University of Nevada, Las Vegas (Nevada 89154, USA)

Key words. Thermal stress; cold environment; heat loss; vasoregulatory responses; brain cooling.

1. Introduction

Although man has been described as a tropical animal, he has been able to live and work successfully in most all of the world's climatic regions. Under extreme natural environmental conditions such as those outlined in figure 1, man has utilized remarkably efficient physiological and behavioral compensatory mechanisms in addition to various technological and sociocultural techniques to insure a flexible but accurate adaptive capacity to meet these climatic challenges. The controls of this adaptive capacity operate in a hierarchy at all levels of biological organization, from molecular to organismic, to preserve or restore the 'milieu interieur', i.e. the constancy state of the internal environment or homeostasis, within fairly narrow limits despite diverse and disruptive external environments. The limits within which the physicochemical characteristics of the 'milieu interieur' vary are a function of the precision of physiological regulation. For example, there is a demonstrable hierarchy of preciseness with which the chemical composition of blood is regulated[42]. Blood Na^+, K^+, and pH are precisely regulated, but levels of glucose, cholesterol, etc. are less closely guarded.

Homeostasis is best exemplified by homeothermy or the body's ability to maintain a relatively constant temperature when a wide range of environmental challenges are encountered. For several decades, physiologists have sought to define and reveal the controlling mechanisms of human thermoregulation. This effort has resulted in major recent conferences and publications wherein voluminous literature was assembled, interpreted and reviewed[15,23,27,28,50]. Due to limited space, I have confined this review to some aspects of human thermoregulation as influenced by heat and cold stress. No attempt has been made to consider all of the excellent papers published recently.

2. Evaluation of the thermal environment

Several meteorological indices have been used to appraise the severity of hot and cold environments thus helping man to set limits beyond which his ability to work and thermoregulate fails, resulting in deleterious consequences. The notable problems of disease in thermoregulations is discussed in this review by Dr Michel Cabanac[8]. Development of available indices began in 1905 with the pioneering work of Haldane[22] who suggested the wet bulb temperature (Twb) as an index of heat stress. This index has been modified to include other meteorological measurements such as dry bulb temperature (Tdb), thermal radiation as measured by the globe thermometer (Tg), and air movement (V).

These meteorological measurements are then assembled using formulas or graphs into a single value rating the stress of the environment. The most commonly used meteorological indices for heat and cold stresses are summarized in table 1. An evaluation of these indices was made by Brief and Confer[4] who revealed that WBGT and WGT are best suited to hot work situations where radiant energy is present. For hot, moist conditions, ET is the preferred index.

3. Physiological regulations in response to thermal stress

The basic thermodynamic processes related to man in hot and cold environments may be estimated from a knowledge of his metabolic rate (M), and of the environmental conditions which establish heat gain or loss by radiation ($\pm$ R), convection ($\pm$ V), conduction ($\pm$ Cd) and evap-

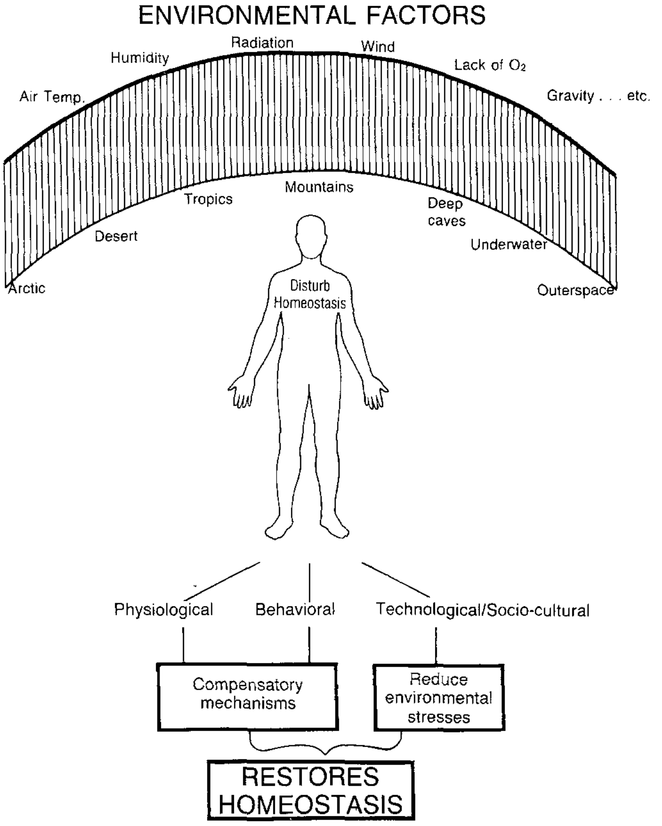

Figure 1. Diagrammatic illustration to show the interrelationships between the external environment and maintenance of homeostasis in man.

oration (−E) as outlined in figure 2. Heat balance must be maintained as presented by the equation:
$M = E \pm Cv \pm Cd \pm R \pm S$; where S is heat storage.
With the exception of E, all heat loss avenues can also be sources of heat gain as described by the known laws of physics for heat transfer. When heat balance is threatened, physiological compensatory mechanisms are triggered. These mechanisms operate at two levels of communications: fast and slow. The fast regulatory response is related to reactions of the central and peripheral nervous system. The slow regulatory response employs primarily the endocrine system. Both levels of communication are linked resulting in corrective responses in central circulation, body fluids, respiration, metabolism and excretion to prevent breakdown of the thermoregulatory machinery. These responses occur in all healthy individuals irrespective of ethnic origin, sex, or age. However, there are marked quantitative differences between individuals and in the same individual on different occasions. Generally, the intra-individual variability exhibits much less variation than does the inter-individual.

3.1 Physiological regulations of heat loss

Hot environments are encountered by man under natural conditions when living in arid and semi-arid lands, or under artificial conditions found, for example, in certain industries such as mining, metallurgy and glass factories. Under either situation, when faced with an increased environmental heat load, man has two primary avenues by which to prevent an explosive rise in core body temperature: sweating and dilation of peripheral blood flow. The former affects the rate at which the body is able to lose heat to its surroundings by evaporation, and the latter enables the body to regulate the flow of metabolic heat from within the body to the skin surface.

Evaporative heat loss. Sweating results in serious risk of dehydration due to depletion of body water and salt[43]. Efficiency of sweat as a cooling mechanism is optimal only if adequate evaporation is permitted; sweat which drips off is useless, and that which is absorbed by clothing and evaporated at a distance from the skin is less effective. Wallerstrom and Holmer[52] reported that impairment of sweat evaporative efficiency is related to the degree of skin wetness which differs under resting and exercise conditions. Studies under natural desert conditions have revealed that man, even during moderate physical activity (walking at a rate of 80–120 m/min), sweats at a level appropriate to the requirement for thermal balance, i.e. about 1.5% of body weight[15,55,56]. This finding dispells such popularly held beliefs as, 'I sweat very little' or 'I sweat profusely'. On the average, sweat rate (SR)/m^2 is lower in women than in men. However, women with a high degree of physical fitness have similar SR to men walking together at the same rate on a hot desert day. Under natural desert conditions, SR in healthy and heat acclimatized subjects was not influenced by age or race. Also, contrary to the many reports concluding decreased sweating capacity, i.e. 'sweat gland fatigue' with increased duration of heat exposure[10], we observed no evidence of suppressed SR when evaporative capacity of the environment was adequate. Additionally, we found no decrease in whole body SR as a result of dehydration.

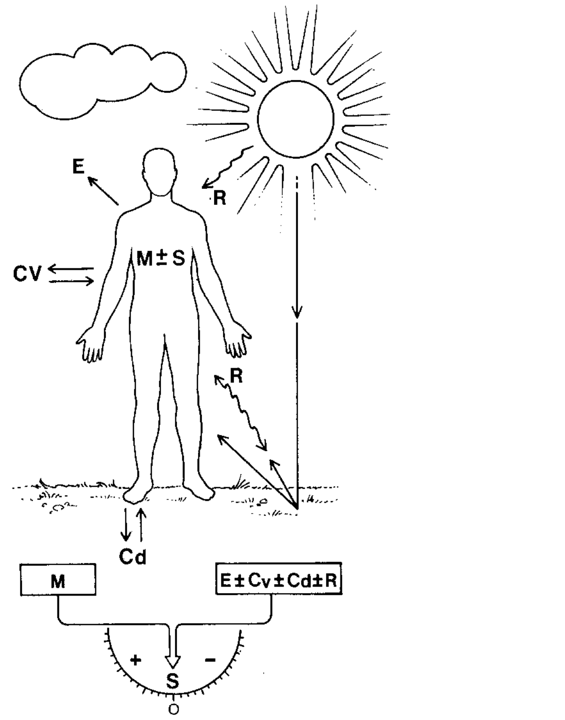

Figure 2. Summary of factors influencing thermal exchange between man and his environment. M, metabolism; S, heat storage; E, evaporative water loss; R, radiation; Cv, convection; Cd, conduction.

Heat acclimation or acclimatization, natural or artificial, is known to increase SR, to initiate sweating at a lower Tb, and to decrease salt loss for a given SR. The many physiological factors involved in heat acclimatization have been summarized by Horvath[25] as shown in table 2. The mechanisms underlying these physiological responses remain open for further investigations. The high SR associated with heat acclimation may be related to decreased sweat output per gland[13], rather than to development of 'new' sweat glands since Kuno[33] reported that the number of sweat glands remains the same during postnatal life. The salt economy during heat acclimatization is perhaps caused by increased Na^+ reabsorption in the sweat gland duct which may be related to the action of aldosterone in response to the renin-angiotensin system[45].

Vasoregulatory responses. Dilation of peripheral blood vessels during rest or exercise in heat results in redistribution of circulatory blood volume to maintain adequate flow to skin and muscles by shunting blood away from other organs that do not require high perfusion. The various changes in compensatory mechanisms of blood volume and the circulatory system have been extensively reviewed recently[5,24,40,44]. Under moderate environmental heat load, adjustments in skin blood flow may increase conductivity of the skin several times, thus preventing hyperthermia. However, as the heat load increases, progressive displacement of blood into cutaneous veins results in reducing of central venous blood pressure, central blood volume, stroke volume, and cutaneous venous compliance and a gradual increase in heart rate. Sufficient compensatory increases in cardiac output, due to increased heart rate, and visceral vasoconstriction oc-

Table 1. Meteorological indices for evaluation of thermal environments

Indices	Meteorological measurements	Remarks	Authors
A) Hot environments			
1. Effective temp. (ET)	Tdb, Twb	Line chart available for calculation[a]	Yaglou[53]
2. Corrected effective temp. (CET)	Tg, Twb, V	Line chart available for calculation[a]	Bedford[2]
3. Wet bulb globe temp. (WBGT)	Tg, Twb, Tdb	WBGT = 0.7 Twb + 0.3 Tg (indoor use) or	Yaglou and Minard[54]
		WBGT = 0.7 Twb + 0.2 Tg + 0.1 Tdb (outdoor use)	Minard et al.[39]
4. Wet globe temp. (WGT)	Wet globe thermometer	A single thermometer[b] to combine: Tdb, Twb, Tg in one reading	Bostford[3]
B) Cold environments			
1. Wind chill factor	Tdb, V	Line chart available for calculation	Sipple and Passel[44]

[a] Heating and Cooling for Man in Industry, 1st edn, chap. 2. Am. Ind. Hyg. Assoc., Southfield, Michigan 1970. [b] A commercial thermometer is available from: Howard Engineering Comp., P.O. Box 3164, Bethlehem, Pennsylvania 18017.

cur so that mean arterial blood pressure tends to be preserved. These circulatory changes are mediated reflexly by autonomic responses and locally by passive release of vasoconstrictor tone and active cholinergic vasodilation.

3.2 Practical methods to reduce heat stress

Brain cooling. Michel Cabanac and his associates have made a notable contribution by demonstrating that man possesses a selective brain cooling mechanism during hyperthermia[9,11,12]. Such a mechanism was first demonstrated anatomically and physiologically in other mammalian species[1]. This mechanism provides a reasonable explanation for the paradox that some mammals, including man, can survive rectal temperature of 46–47 °C although it is known that the highest temperture tolerated by the brain is less than 41 °C. Cabanac[9] found that even during dehydration sweat production was maintained on the face and by evaporation of this sweat, brain (tympanic) temperature (Ttymp) remained below esophageal temperature. Moreover, he demonstrated that fanning the face considerably reduced the initial elevation of Ttymp and decreased it. When face fanning was stopped, Ttymp rose. Therefore, selective brain cooling can be improved by the simple method of face fanning thus providing therapy and preventing brain hyperthermia.

Use of garments to optimize evaporative heat loss. Since adding water to the skin surface may result in artifically increasing the body's effective sweat rate, Strethowen et al.[47] found that using an artificially wetted very thin, one-piece, tight-fitting garment, having good wicking characteristics was equivalent to a reduction of Twb of about 1.3 and 4.0 °C when compared to a nude man and to a man wearing conventional clothing, respectively. Although this experiment included only one man, it provided the impetus for further research to consider development of special clothing as an integral part of the strategy aimed at reducing heat stress wherever it is encountered by man. A garment designed to optimize evaporative heat loss could be used to improve safety, increase productivity, and to decrease detrimental effects of heat stress.

Table 2. Changes observed consequent to heat acclimatization (used with permission from Horvath[25])

Heart rate ↓	Subjective discomfort ↓
Cardiac output =	Fatigue ↓
Stroke output ↑	Capacity for work in higher ambients ↑
Core temperature ↓	Coordination ↑
Skin temperature ↓	Mental disturbances ↓
Sweat output ↑	Syncopal responses ↓
Evaporated sweat ↑	Extracellular fluid volume ↑
Onset of sweating ↓	Plasma volume ↑
Wetted surface ↑	Nausea ↓
Skin and core temperature at onset of sweating ↓	Vomiting ↓
NaCl in sweat ↓	Endocrines ↑ ↓ =
Work output ↑	Other systems show variable responses
Endurance ↑	

↑, increase; ↓, decrease; =, no change.

Table 3. Shivering and heat production in men exposed to intense cold (used with permission from Glickman et al.[20])

Time after exposure (h)	Heat production $Cal/m^2 \cdot h$	% Increased over basal level
0	35.4	0.0
1	54.0	52.5
2	72.0	103.4
3	92.0	159.9
4	96.0	171.2

0, pre-exposure.

3.3 Physiological regulations in cold environments

In cold environments, besides low air temperatures, other factors such as wind velocity, radiant heat, duration of exposure, and individual variability must be considered. For example, the chilling power of wind may produce a super cooling effect on exposed skin as is well demonstrated by the windchill index. Man's conquest of cold regions has been achieved by cultural, technological, behavioral, and physiological mechanisms. The importance of these mechanisms is to prevent hypothermia and/or cold tissue injury. Acclimation and acclimatization of man to cold have been recently reviewed[7,18,33], in addition to the excellent volume entitled 'Man in the Cold' by Professor LeBlanc[34]. In general, homeothermy is achieved in a cold environment by increasing heat production and/or decreasing heat loss. These two mechanisms require orchestration of the muscle, nervous, cardiovascular, and circulatory systems.

Heat preservation. Man reduces heat loss by increasing physical and/or physiological insulation. Physical insulation includes both natural, i.e. subcutaneous fat and artificial insulation, i.e., clothing. To measure the influence of clothing on thermal insulation and rate of heat loss, the unit known as clo has been devised. One clo will maintain a resting-sitting man with a metabolic rate of 50 $Cal/m^2 \cdot h$ comfortably in an environment of 21 °C air temperature, relative humidity less than 50%, and wind velocity of 6 m/min[6]. Under these conditions, one clo is equivalent to a business suit or 0.64 Cm clothing[34]. A formula has been derived to provide the number of clos needed for any given environmental temperature:

$$I = \frac{3.1(Tsk\text{-}Ta)}{\ }75\ (M)$$

I = insulation in clo units
Tsk = average skin temperature; Ta = air temperature;
M = metabolism; 50 $Cal/m^2 \cdot h$.

Other factors to be considered in calculating the insulation of clothing are metabolic rate and wind velocity. Line charts are available to permit rapid estimation of the insulative value of clothing under varying conditions[6]. Insulative value of clothing is related to the air trapped between the fibers and between the layers of clothing. Edholm[17] reviewed the effects of clothing in cold and concluded that there is no particular merit in one kind of material as compared with another except in its capacity to trap air. Cotton and wool are as good as down feathers in this respect. The difference in insulative capacity is that under quite moderate pressure cotton and wool become compressed and remain so when pressure is removed. However, down feathers resist compression and rapidly recover their original shape and thickness when pressure is eliminated.

Natural insulation in man is attributed primarily to his layer of subcutaneous fat. Thermal conductivity of fat is much lower than that of muscle. Additionally subcutaneous fat is not well vascularized, consequently its temperature gradient will be affected by Ta[34]. Experimental evidence has shown that subcutaneous fat greatly enhances the effectiveness of the vasomotor adjustments, thus enabling fat individuals to conserve a large portion of metabolic heat and thermoregulate despite considerable cold stress[7,31,38]. From these observations, subcutaneous fat is considered to be an important insulator which may account at least in part for the individual variability in tolerance to cold. Recently Gallow et al.[19] concluded that body morphology could account for differences in heat loss at rest, but during exercise the role of such insulative adaptation decreases and metabolic responses dominate.

Physiological insulation refers to the vasoregulatory mechanisms in response to cold. Peripheral vasoconstriction results in lowering Tsk due to reduced blood flow, decreasing the gradient Tsk-Ta. Consequently heat loss to the environment diminishes. Accompanying peripheral vasoconstriction, blood flow to the viscera is augmented resulting in increased heart rate, cardiac output and blood pressure.

Peripheral vasoconstriction of a finger upon immersion into cold water was observed to alternate with vasodilation[37]. This cold-induced vasodilation known as the Lewis 'hunting' phenomenon was found to be associated with increased blood flow to the finger due to sudden opening of the arteriovenous anastomoses[21]. These observations were confirmed on other regions of the periphery and the differences in the vascular 'hunting' reaction to cold as related to sex, season, and environmental temperatures have been reported[48,49]. The vasoregulatory responses to immersing the hand in cold water or to cold air blowing on the face are characterized by different responses of both branches of the autonomic nervous system[33]. Immersion of the hand in cold water causes in activation of the sympathetic branch as evidenced by increased blood pressure and heart rate. On the other hand, cold wind blown on the face produces a rise in blood pressure but at the same time causes a reflex bradycardia of vagal origin. Activity of the sympathetic branch is decreased with adaptation by intermittant exposure to severe cold, whereas activity of the parasympathetic branch seems to increase[35]. Also, the decreased sympathetic activity in adapted subjects was found to parallel a decrease in the subjective pain caused by cold stimulation. If heat preservation via insulative means is not adequate to offset heat flux to a cold environment, metabolic responses are evoked to insure maintenance of heat balance.

Metabolic responses. Two different types of metabolic responses known to increase heat production (HP) in cold environment have been described in man: shivering and non-shivering thermogenesis. For a naked man, an increase in HP usually occurs when air temperature decreases below 25 °C. The most rapid way to increase HP is either by shivering or active physical exercise. Shivering can raise HP two to threefold and this increase is progressive throughout the cold stress as shown in table 3[20]. From an energy viewpoint, efficiency of the shivering mechanism is relatively low, approximately 10%. Also, shivering is mentally disturbing, and although it is usually periodic in character men have been observed shivering for periods up to 10 days[26].

Increased HP through active exercise is limited by man's capacity to maintain high levels of activity for prolonged periods of time. Man may be able to maintain an HP level equal to 5 times that of the basal level for about 8 h a day for several days[26]. Can man maintain such high levels of HP if continuously exposed to cold? This is doubtful; however, quantitative evidence is lacking.

In contrast to the many animal studies on cold acclimation, there is little evidence that in man shivering is replaced by non-shivering thermogenesis, i.e., increased HP in the absence of visible or electromyographically detectable muscle activity. Non-shivering thermogenesis in animals is mediated by hormonal responses especially norepinephrine. The basic problem in human studies is the difficulty in finding people who are habitually exposed to cold or individuals who will accept the necessary experimental protocol of continuous exposure to cold long enough to follow the sources of metabolic responses. Davis[14] published the first experimental evidence for a decrease in shivering and an increase in non-shivering thermogenesis in men exposed for 4 weeks for daily 8-h-periods to temperatures of 5-11 °C. Further evidence for non-shivering thermogenesis was demonstrated by the increased sensitivity to norepinephrine in men after repeated exposure to cold[30] and in the Ainu of Japan who are considered to be well-adapted to cold[29]. Contrary to this evidence, a review of studies on native populations of cold regions, i.e. Alacalufe Indians, Athapascan Indians, Australian aborigines, Eskimos, Kalahari Bushmen, Korean Ama, Norwegian Lapps and Peruvian Quechuas provided no concrete evidence for non-shivering thermogenesis[17,18,33]. These populations have developed a high degree of adjustment to cold stress, but they differ in the manner of attaining the adaptation. Some populations

(Australian aborigines and Kalahari Bushmen) are adapted by utilizing a degree of hypothermia or as termed by LeBlanc[33] 'overnight torpor' to reduce HL, thus decreasing shivering allowing for a comfortable sleep. The suppression of shivering was accompanied by a decrease rather than an increase in HP; thus non-shivering thermogenesis may not exist. However, the Alacalufe Indians had high metabolic rates throughout a cold night without visible shivering and maintained their body temperature. The question to ask is whether or not these people have developed non-shivering thermogenesis. Edholm[17] speculated in a teleological way on the difference between the adaptive mechanisms of the Australian aborigines and the Alacalufe Indians. He stated that the Australian aborigines can afford hypothermia during the night, as they will quickly rewarm in the morning sun, and by cooling down they conserve heat and water which are valuable commodities in their environment. However, the Alacalufe Indians, who live in a cloudy, rainy, and moist environment cannot, without great risk, cool down their body as rewarming would be difficult. In such an environment, an individual with high HP would have an advantage, and if this were an inheritable trait it would, in time, become a general attribute.

Individual variability: a fundamental problem. One of the very first concerns in thermogenic responses of man to thermal stress is the rather wide inter and intra-individual variability. This variability in a cold environment is ascribed to many factors including body morphology, sex, physical fitness, and age. The role of body morphology was discussed under physical insulation. McArdle et al.[38] found that the insulatory benefits of body fat, per se, may vary in comparison of thermoregulatory responses between the sexes. Women did not maintain core temperature at rest in cold water as effectively as men of the same body fat content. The relatively greater cooling at rest of women was partly explained by a generally larger surface area to mass ratio.

The effect of physical training on physiological responses to cold and the tolerance of cold has not been critically evaluated. In view of the ambiguity in findings and lack of research in this area, any conclusion is open to question. Eagan[16] reported no relationship between physical fitnesss and resistance to finger cooling. On the other hand, other investigators found a relatively reduced HP with physical conditioning (when exposed to cold) in conjunction with reduced skin and core temperatures and a further lowering of the body temperature threshold for an elevation in HP[32,33]. These studies demonstrate that physiological responses and/or tolerance to cold are not uniform among individuals and this varibility, at least in part, may be related to the level of physical fitness.

Few studies have been devoted to the effects of age on tolerance or responses to cold. Available evidence indicates that old individuals have a less effective response to cold stress than young ones[34,46]. The younger individuals reacted rapidly to cold (16–17°C) by increasing HP and decreasing HL by cutaneous vasoconstriction, whereas older men did not increase HP to the same extent and were less able to maintain body heat stores by cutaneous vasoconstriction[51]. The mechanisms reflecting the inability of older men to thermoregulate as effectively as the young men in a cold environment remain open to investigation. Only very few of the individuals studied in these experiments were above 65 years of age. The effects of age on cold responses need to be studied with many more subjects before valid conclusions can be drawn for the entire aged population. The need for such studies has become more urgent with the shortage of energy to maintain proper heating in homes for the elderly combined with their reduced ablity to thermoregulate, resulting in devastating effects on the aged.

4. *Concluding remarks*

In reviewing the effects of thermal stresses, specifically, heat and cold on man's immediate physiological responses and adaptive processes, it becomes quite apparent that much more research is needed. Only two of the many unsolved questions are stressed here. First, most of our knowledge of human thermal physiology is based on data obtained using primarily young men and women. Little emphasis has been given to the study of aging individuals, especially those above 65 years of age. The available, though scanty, data indicate that many functions and responses are affected by age. As population growth and control in developed countries become more successful, the aged population will rise at an unprecedented rate in the near future. Thus, it is the obligation of biometeorologists to provide a better understanding of the thermal limits of comfort for aging men and women.

Other unanswered questions relate to individual variability in responses to thermal stress. It has been shown in several reports that some individuals react differently from the average of the group studied. Individual differences must be emphasized and additional experiments should be designed to reveal the mechanisms underlying individual variability.

1 Baker, M.A., Brain cooling in endotherms in heat and exercise. A. Rev. Physiol. *44* (1982) 85–96.
2 Bedford, T., Environmental warmth and its measurement. Medical Research Council, War Memorandum No. 17, H.M. Stationary Office, 1946.
3 Botsford, J.H., A wet globe thermometer for environmental heat measurement. Am. Indian Hyg. Assoc. J. *32* (1971) 1–10.
4 Brengelmann, G.L., Circulatory adjustments to exercise and heat stress. A. Rev. Physiol. *45* (1983) 191–212.
5 Brief, R.S., and Confer, R.G., Comparison of heat stress indices. Am. Indian Hyg. Assoc. J. *32* (1971) 11–16.
6 Burton, A.C., and Edholm, O.G., Man in a Cold Environment. Edward Arnold, London 1955.
7 Buskirk, E.R., Cold stress: A selective review, in: Environmental Stress, pp. 249–266. Eds L.J. Folinsbee et al. Academic Press, New York 1978.
8 Cabanac, M., Disease in temperature regulation. Experientia *43* (1987) 19–27.
9 Cabanac, M., Face fanning: A possible way to prevent or cure brain hyperthermia, in: Heat Stroke and Temperature Regulation, pp. 213–221. Eds M. Khogali and J.R.S. Hales. Academic Press, Sydney 1983.
10 Cabanac, M., Temperature regulation. A. Rev. Physiol. *37* (1975) 415-439.
11 Cabanac, M., and Caputa, M., Natural selective cooling of the human brain: Evidence for its occurrence and magnitude. J. Physiol., London *286* (1979a) 255–264.
12 Cabanac, M., and Caputa, M., Open loop increase in trunk temperature produced face cooling in working humans. J. Physiol., London *289* (1979b) 163-174.
13 Chen, W.Y., and Elizzondo, R.S., Peripheral modification of thermoregulatory function during heat acclimation. J. appl. Physiol. *37* (1974) 367–373.

14 Davis, T. R. A., Chamber cold acclimatization in man. J. appl. Physiol. *16* (1961) 1011–1015.
15 Dill, D. B., The Hot Life of Man and Beast. Charles C. Thomas, Springfield, Ill 1985.
16 Eagen, C. J., Resistance to finger cooling related to physical fitness. Nature *200* (1963) 851–852.
17 Edholm, O. G., Man – Hot and Cold. Edward Arnold, London 1978.
18 Frisancho, A. R., Human Adaptation. C. V. Mosby, St. Louis, MO 1979.
19 Gallow, D., Graham, T. E., and Pfeiffer, S., Comparative thermoregulatory responses to acute cold in women of Asian and European descent. Hum. Biol. *56* (1984) 19–34.
20 Glickman, N., Mitchell, H., Keeton, R., and Lambert, E., Shivering and heat production in men exposed to intense cold. J. appl. Physiol. *22* (1967) 1–8.
21 Grant, R. T., and Bland, E. F., Observations on arterio-venous anastomoses in human skin and in bird's foot with special reference to reaction to cold. Heart *15* (1931) 385–407.
22 Haldane, J. S., The influence of high air temperatures (No. 1). J. Hyg. Cambridge *5* (1905) 494–513.
23 Hales, H. R. S., Thermal Physiology. Raven Press, New York 1984.
24 Harrison, M.H., Effects of thermal stress and exercise on blood volume in human. Physiol. Rev. *65* (1985) 149–209.
25 Horvath, S. M., Man in cold environments. Am. Soc. mech. Engng Paper No. 60-WA-240, 1960.
26 Horvath, S. M., Historical perspectives of adaptation to heat, in: Environmental Physiology: Aging, Heat and Altitude. pp. 11–25. Eds S. M. Horvath and M. K. Yousef. Elsevier/North Holland, New York 1981.
27 Horvath, S. M., and Yousef, M. K., Environmental Physiology: Aging, Heat and Altitude. Elsevier/North Holland, New York 1981.
28 Houdas, Y., and Ring, E. F. J., Human Body Temperature. Its Measurement and Regulation. Plenum Press, New York 1982.
29 Itoh, S., Doi, K., and Kuroshima, R., Enhanced sensitivity to noradrenaline of the Ainu. Int. J. Biomet. *14* (1970) 195–200.
30 Joy, R. J. T., Responses of cold-acclimatized men to infused norepinephrine. J. appl. Physiol. *18* (1963) 1209–1212.
31 Keatinge, W. R., Body fat and cooling rates in relation to age, in: Environmental Stress, pp. 299–302. Eds L. J. Folinsbee et al. Academic Press, New York 1978.
32 Kollias, J., Boileau, R., and Buskirk, E. R., Effects of physical conditioning in man on thermal responses to cold air. Int. J. Biomet. *16* (1972) 389–402.
33 Kuno, Y., Human Perspiration. C. C. Thomas, Springfield, Ill. 1956.
34 LeBlanc, J., Man in the Cold. C. C. Thomas, Springfield, Ill. 1975.
35 LeBlanc, J., Adaptation of man to cold, in: Strategies in Cold: Natural Torpidity and Thermogenesis, pp. 695–715. Eds L. C. H. Wang and J. W. Hudson. Academic Press, New York 1978.
36 LeBlanc, J., Blais, B., Barabe, B., and Cote, J., Effects of temperature and wind on facial temperature, heart rate and sensation. J. appl. Physiol. *40* (1976) 127–131.
37 Lewis, T., Vasodilation in response to strong cooling. Heart *15* (1930) 177–181.
38 McArdle, W. J., Magel, J. R., Gergley, T. J., Spina, R. J., and Toner, M. M., Thermal adjustment to cold-water exposure in resting men and women. J. appl. Physiol. Respir. Envir. Exercise Physiol. *56* (1984) 1561–1571.
39 Minard, D., Belding, H. S., and Kingston, J. R., Prevention of heat casualties. J. Am. med. Assoc. *165* (1957) 1813-1818.
40 Nadel, E. R., Body fluid and electrolyte balance during exercise: Competing demands with temperature regulation, in: Thermal Physiology, pp. 365–376. Ed. J. R. S. Hales. Raven Press, New York 1984.
41 Rowell, L. B., Cardiovascular aspects of thermoregulation. Circ. Res. *52* (1983) 367–379.
42 Sargent, F., II. Introduction to human biometeorology: its concepts and problems, in: Seminar on Human Biometeorology. U.S. Public Health Service Pub. No. 999-AP-25, 1967.
43 Senay, L. C. Jr, Temperature regulation and hypohydration: a singular view. J. appl. Physiol. *47* (1979) 1–7.
44 Siple, P. A., and Passel, C. F., Measurements of dry atmospheric cooling in subfreezing temperatures. Proc. Am. Phil. Soc. *89* (1945) 177–199.
45 Smiles, K. A., and Robinson, S., Sodium ion conservation during acclimatization of men to work in the heat. J. appl. Physiol. *31* (1971) 63–69.
46 Spurr, G. B., Hutt, B. K., and Horvath, S. M., The effects of age on finger temperature responses to local cooling. Am. Heart J. *50* (1955) 551–555.
47 Strethowen, S. J., and Murray-Smith, A. I., Evaluation of an artificially wetted garment as a method of reducing heat stress in mines. Res. Rpt. No. 40/83, Chamber of Mines of South Africa Research Organization 1983.
48 Tanaka, M., Experimental studies on human reaction to cold – Differences in the vascular hunting reaction to cold according to sex, season, and environmental temperature. Bull. Toleyo med. dent. Univ. *18* (1971) 269–280.
49 Tanaka, M., Harimura, Y., Tochihara, Y., Yamazaki, S., Ohnaka, T., Matsui, J., and Yoshida, K., Effects of season on peripheral resistance to localised cold stress. Int. J. Biomet. *28* (1984) 39–45.
50 Tromp, S. W., and Bouma, J. J., Biometeorological Survey, vol. 1, 1973–1978, Part A: Human Biometeorology. Heyden, London 1979.
51 Wagner, J. A., Robinson, S., and Marino, R. P., Age and temperature regulation of humans in neutral and cold environments. J. appl. Physiol *37* (1974) 562–565.
52 Wallerstrom, B., and Holmer, I., Efficiency of sweat evaporation during exercise in the heat, in: Thermal Physiology, pp. 433–436. Ed. J. R. S. Hales. Raven Press, New York 1984.
53 Yagiou, C. P., The thermal index of atmospheric conditions and its application to sedentary and industrial life. J. Indian Hyg. *8* (1926) 5-19.
54 Yaglou, C. P., and Minard, D., Control of heat casualties at military training centers. Archs Indian Hlth *16* (1957) 302–316.
55 Yousef, M. K., Responses of men and women to desert heat. Int. J. Biomet., suppl. *24* (1980) 29–41.
56 Yousef, M. K., Dill, D. B., Vitez, T. S., Hillyard, S. D., and Goldman, A. S., Thermoregulatory responses to desert heat: age, race and sex. J. Geront. *39* (1984) 406–414.

0014-4754/87/010014-06$1.50 + 0.20/0

The pathology of human temperature regulation: Thermiatrics

by M. Cabanac and H. Brinnel

Laboratoire de Physiologie, Faculté de Médecine Lyon-Sud, Chemin du Petit Revoyet, B.P. 12, F-69921 Oullins Cedex (France), and Intensive Care Department, Hôpital Saint Joseph, 9 Rue du Professor Grignard, F-69365 Lyon Cedex (France)

Key words. Temperature regulation; pathology; human; nosography.

Comparative physiology shows that most animal species regulate their body temperature (T_b). The bigger species generally regulate their body temperature at values lower than of the smaller species. The range of tolerated body temperature narrows with the advancement of the phylogenic evolution of the species. The question arises as to