Chapter 2

HUMAN ADAPTATION TO HOT ENVIRONMENTS

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INTRODUCTION

Problems due to heat stress may occur whenever the rate of heat production or heat gain from the environment is sufficiently large in relation to the body's ability to dissipate heat. Thus, sustained high-intensity physical exercise; excessive thermal insulation due to body armor or protective clothing; or thermoregulatory impairment due to fever, drugs, or dehydration may create the conditions for heat-impaired performance or heat illness, even during cool weather.

It is difficult to evaluate the effects of heat stress on the health and performance of troops; thus, the overall impact on military operations is probably much greater than generally appreciated. This is so for several reasons. First, heat illness is probably underreported. Second, in an operational setting, cumulative effects of prolonged heat exposure and combined effects of heat and other stresses are likely to be important, but such effects are difficult and costly to reproduce under controlled experimental conditions. Therefore, they have not been the subject of much experimental study. Third, troops exposed to such conditions may not appreciate the extent to which their abilities and performance are affected.

Most of the earth's hot regions are inhabited, and human physiology permits people to live and work successfully in very hot climates provided they are acclimatized (physiologically adjusted to an environment, in nature) to heat, have access to shade and sufficient supplies of potable water, and can limit their physical activity during the heat of the day. However, military operations in a hot climate must confront problems of heat stress that differ substantially from those ordinarily faced by the local inhabitants. Military operations may involve troops who were not acclimatized to heat before their deployment, and local supplies of fresh water may be insufficient for the requirements of a large military force. Moreover, because of the demands of combat or other mission requirements, troops may have to perform physical exercise during the heat of the day, or at levels that exceed established guidelines for prevention of heat casualties. The accompanying threat to the troops' health and effectiveness may be aggravated by a need to perform such exercise when they are at increased risk of heat illness because they are sleep deprived, or do not have free access to drinking water.

IMPORTANCE OF TISSUE TEMPERATURE

Extreme temperatures injure tissue directly. A protein's biological activity depends on the location of electrical charges in the molecule and on its overall configuration. Many physicochemical processes can alter a protein's configuration and charge distribution, and thus change its activity, without affecting the sequence of amino acids. Such alteration of a protein is called *denaturation*; and by inactivating a cell's proteins, denaturation injures or kills the cell. High temperature can denature proteins, and a familiar illustration of this effect is the coagulation of the albumin in the white of a cooked egg. If living tissue is heated, injury occurs at temperatures higher than about 45°C, which is also the temperature at which heating the skin causes pain. The degree of injury depends on both temperature and duration of the heating.[1]

Cold, like heat, can cause direct injury to tissue, although via different mechanisms. As a water-based solution freezes, crystals of pure ice form. Thus all the dissolved substances are left behind in the liquid that has not yet frozen, which becomes more and more concentrated as more ice forms. Freezing damages cells through two mechanisms. First, ice crystals themselves probably disrupt the cell membranes mechanically. Second, the increase in solute concentration of the cytoplasm as ice forms denatures the proteins by removing their water of hydration, by increasing the ionic strength of the cytoplasm, and by other changes in the physicochemical environment in the cytoplasm.

Mammals, including human beings, are *homeotherms*, or warm-blooded animals, and regulate their internal body temperatures within a narrow band near 37°C (Figure 2-1), despite wide variations in environmental temperature. Tissues and cells can tolerate temperatures from just above freezing to nearly 45°C—a range far wider than the limits within which homeotherms regulate body temperature. What biological advantage do homeotherms gain by maintaining such a stable body temperature?

Temperature is a fundamental physicochemical variable that profoundly affects many biological processes, both through specific effects on such specialized functions as electrical properties and fluidity of cell membranes, and through a general effect on most chemical reaction rates. Most reaction rates vary approximately as an exponential function of temperature within the physiological range, and increasing temperature by 10 Centigrade de-

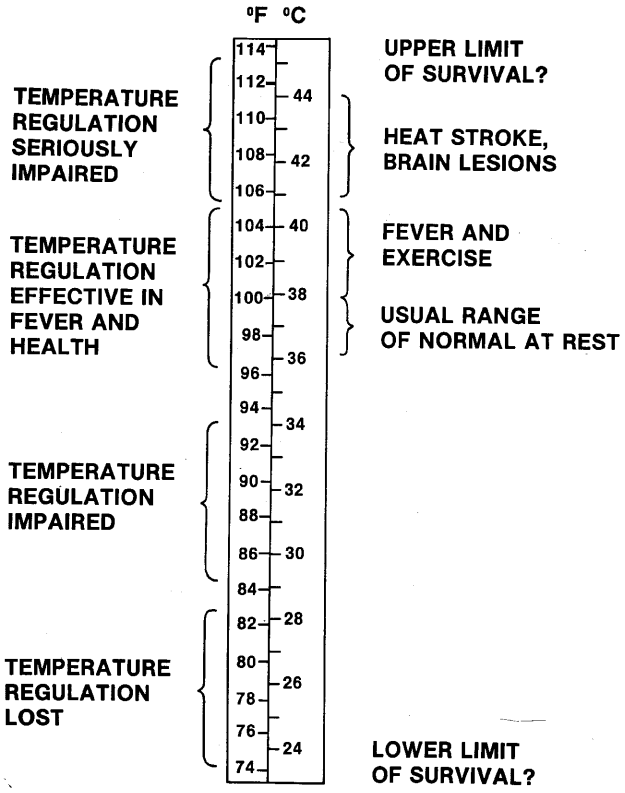

Fig. 2-1. Ranges of rectal temperature found in healthy persons, patients with fever, and persons with impairment or failure of thermoregulation. Reprinted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA. *Medical Physiology.* Boston, Mass: Little, Brown; 1995: 588

grees increases the reaction rate by a factor of 2 to 3. For any reaction, the ratio of the reaction rates at two temperatures 10 Centigrade degrees apart is called the Q_{10} for that reaction, and the effect of temperature on reaction rate is called the Q_{10} *effect*. The concept of Q_{10} is often generalized to apply to a group of reactions that are thought of as comprising a physiological process because they share a measurable overall effect, such as oxygen consumption. The effect of body temperature on metabolic processes is clinically important in caring for patients with high fevers who are receiving fluid and nutrition intravenously, and an often-used rule states that each Centigrade degree of fever increases a patient's fluid and calorie needs by 13%.[2]

BODY TEMPERATURES AND HEAT TRANSFER IN THE BODY

The body is divided into a warm internal *core* and an outer *shell* (Figure 2-2),[3] the temperature of which is strongly influenced by the environment. Although shell temperature is not regulated within narrow limits the way internal body temperature is, thermoregulatory responses do strongly affect the temperature of the shell, and especially its outermost layer, the skin. The shell's thickness depends on the environment and the need to conserve body heat. In a warm environment, the shell may be less than 1 cm thick; but in a subject conserving heat in a cold environment, it may extend several centimeters below the skin. The internal body temperature that is regulated is the temperature of the vital organs inside the head and trunk, which together with a variable amount of other tissue, comprise the warm internal core.

Although heat is produced throughout the body, it is lost only from tissues that are in contact with the environment, mostly skin and respiratory passages. Because heat flows from warmer regions to cooler regions, the greatest heat flows within the body are those from major sites of heat production to the rest of the body, and from core to skin. Within the body, heat is transported by two means: *conduction* through the tissues; and *convection* by the blood, the process by which flowing blood carries heat from warmer tissues to cooler tissues.

Heat flow by conduction is proportional to the thermal conductivity of the tissues, the change of temperature with distance in the direction of heat flow, and the area (perpendicular to the direction of heat flow) through which the heat flows. As Table 2-1 shows, the tissues are rather poor heat conductors.

Heat flow by convection depends on the rate of blood flow and the temperature difference between the tissue and the blood supplying the tissue. Because the capillaries have thin walls and, taken together, a large total surface area, the capillary beds are the sites at which heat exchange between tissue and blood is most efficient. Because the shell lies between the core and the environment, all heat leaving the body via the skin must first pass through the shell. Thus the shell insulates the core from the environment. In a cool subject, skin blood flow is low, so that core-to-skin heat transfer is dominated by conduction; the subcutaneous fat layer adds to the insulation value of the shell, because it adds to the thickness of the shell and because fat has a conductivity only about 0.4 times that of dermis or muscle. In a warm subject, on the other hand, the

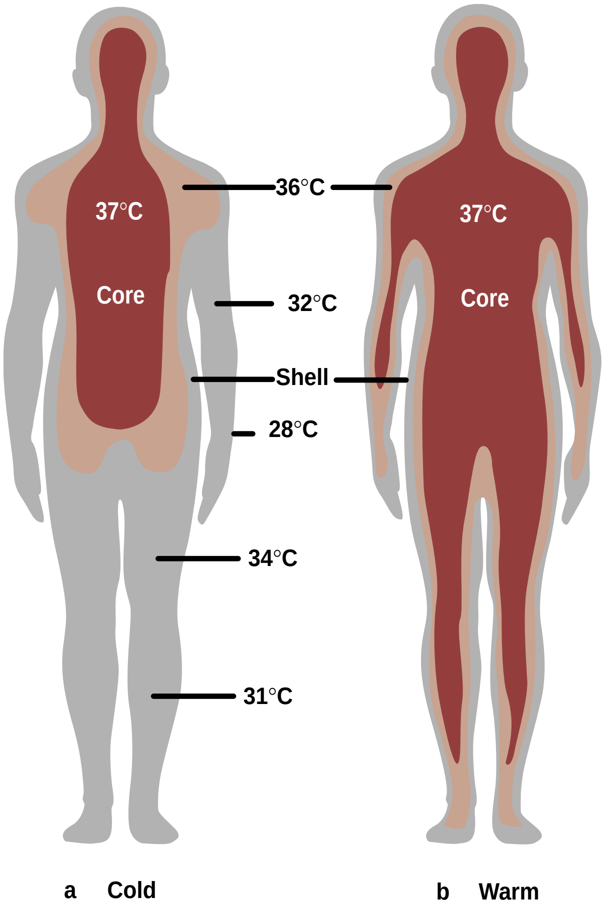

Fig. 2-2. Distribution of temperatures within the body and division of the body into core and shell during exposure to (**a**) cold and (**b**) warm environments. The temperatures of the surface and the thickness of the shell depend on the environmental temperature, so that the shell is thicker in the cold and thinner in the heat. Adapted with permission from Elizondo RS. Regulation of body temperature. In: Rhoades RA, Pflanzer RG, eds. *Human Physiology*. Philadelphia, Pa: Saunders College Publishing; 1989: 823–840.

shell is relatively thin, and thus provides little insulation. Furthermore, a warm subject's skin blood flow is high, so that heat flow from the core to the skin is dominated by convection. In these circumstances the subcutaneous fat layer—which affects conduction but not convection—has little effect on heat flow from core to skin.

Core Temperature

Core temperature varies slightly from one site to another, depending on such local factors as metabolic rate and blood supply and the temperatures of neighboring tissues. However, the notion of a single uniform core temperature is a useful approximation because temperatures at different places in the core are all similar to the temperature of the central blood, and they tend to change together. Sites where core temperature is measured clinically include the mouth, the tympanic membrane, the rectum, and occasionally, the axilla. No site is ideal in every respect, and each has certain disadvantages and limitations (Exhibits 2-1 and 2-2).

The value of 98.6°F that is often given as the normal level of body temperature may suggest that body temperature is regulated so precisely that it is not allowed to deviate even a few tenths of a degree. In fact, 98.6°F is simply the Fahrenheit equivalent of 37°C; and, as Figure 2-1 indicates, body temperature does vary. The effects of heavy exercise and fever, for example, are quite familiar. In addition, variation among individuals and such factors[4] as time of day (Figure 2-3), phase of the menstrual cycle,[5,6] and acclimatization to heat can cause differences of up to about one Centigrade degree in core temperature in healthy subjects at rest. The thermoregulatory system receives information about the level of core temperature provided by temperature-sensitive neurons and nerve endings in the abdominal viscera, great veins, spinal cord, and especially the brain.[7,8] Later in the chapter we

TABLE 2-1

THERMAL CONDUCTIVITIES AND RATES OF HEAT FLOW*

	Conductivity kcal/(s•m•°C)	Rate of Heat Flow kcal/h	Watts
Copper	0.092	33,120	38,474
Epidermis	0.00005	18	21
Dermis	0.00009	32	38
Fat	0.00004	14	17
Muscle	0.00011	40	46
Water	0.00014	51	59
Oak (across grain)	0.00004	14	17
Dry air	0.000006	2.2	2.5
Glass fiber insulation	0.00001	3.6	4.2

*Through slabs of different materials 1 m^2 in area and 1 cm thick, with a difference in temperature of one Centigrade degree between the two faces of the slab

Adapted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA, eds. *Medical Physiology*. Boston, Mass: Little, Brown; 1995: 590.

EXHIBIT 2-1

MEASURING BODY CORE TEMPERATURE

Any measurement that is used as an index of core temperature should not be biased by environmental temperature. Because the tongue is richly supplied with blood, oral temperature under the tongue is usually similar to blood temperature and is 0.3°C to 0.4°C below rectal temperature[1]; but cooling of the face, neck, or mouth can make oral temperature misleadingly low.[2] Oral temperature should not be used to assess a patient with a suspected heat illness because such a patient may hyperventilate, thus cooling the mouth.

In 1959, Benzinger introduced tympanic temperature as an index of internal temperature for research in thermal physiology[3] and later also advocated its use as a clinical tool.[4] As Benzinger demonstrated, tympanic temperature responds more rapidly than rectal temperature to body cooling or heating[5]; and for this reason it has certain advantages over rectal temperature as a research tool. However, Benzinger did not merely say that tympanic temperature responds more rapidly than rectal temperature; he called it "cranial" temperature[5,6] and claimed that it represented hypothalamic temperature. He claimed further that the tympanum and hypothalamus share "a common blood supply … from the internal carotid artery,"[7(p139)] although, in fact, the blood supply of the tympanum is chiefly through branches of the external carotid artery. It would be easy to conclude that Benzinger believed tympanic temperature to be superior to core temperature measured anywhere outside the head (eg, in the esophagus or the heart or great vessels) as a representative of hypothalamic temperature. However, he evidently never claimed that tympanic temperature is superior in this regard to any temperature other than rectal temperature. Nevertheless, later authors[8] have concluded that tympanic temperature does indeed represent hypothalamic temperature better than other internal temperature measurements do—without, however, adducing any intracranial temperature measurements to support their conclusion. (Measurements in a surgical patient, in fact, showed that esophageal temperature followed changes in brain temperature more closely than did tympanic temperature.[9]) As a research tool in thermal physiology, tympanic temperature is now considerably less widely used than esophageal temperature because tympanic temperature is sensitive to skin temperature of the head and neck,[2] and thus may be biased substantially by ambient temperature. Benzinger himself recognized this problem and stressed that in environments cooler than 30°C, the ear should be insulated from the environment—preferably with the palm of the subject's hand.[5] However, his recommendation has frequently been ignored. Moreover, since most of the tympanum's blood supply comes through branches of the external carotid artery, thus following a somewhat superficial course, it is not clear how wide an area should be insulated, and there is no general agreement on this point.

Infrared sensing devices for measuring tympanic temperature, which eliminate the need for direct contact with the tympanum, have become available in recent years and have been marketed for clinical use. Tympanic temperature has come to enjoy a fair degree of popularity because these devices give a reading quickly and are easy to use. However, these devices are ordinarily used with no provision for insulating the ear from the ambient air, so tympanic temperature may be seriously biased by ambient temperature and is unsuitable for evaluating a patient suspected of having a heat illness.[10] (For a more extensive critique of tympanic temperature, see Brengelmann.[11])

The rectum is a few tenths of a Centigrade degree warmer than other core sites.[1] The rectum is well insulated from the environment, so rectal temperature is independent of environmental temperature and is the most reliable clinical index of body temperature.

If a patient holds his or her upper arm firmly against the chest so as to close the axilla, its temperature will gradually approach core temperature. Probably the chief advantage of measuring axillary temperature is that disinfecting the thermometer is less critical than when temperature is measured in the mouth or rectum. However, it may take 30 minutes or more for axillary temperature to come reasonably close to core temperature, so axillary temperature may be misleadingly low if insufficient time is allowed or if the patient does not keep his or her arm firmly against the chest. Axillary temperature has all but fallen into disuse.

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(1) Cranston WI, Gerbrandy J, Snell ES. Oral, rectal and oesophageal temperatures and some factors affecting them in man. *J Physiol (Lond)*. 1954;126:347–358. (2) McCaffrey TV, McCook RD, Wurster RD. Effect of head skin temperature on tympanic and oral temperature in man. *J Appl Physiol*. 1975;39:114–118. (3) Benzinger TH. On physical heat regulation and the sense of temperature in man. *Proc Natl Acad Sci U S A*. 1959;45:645–659. (4) Benzinger TH. Clinical temperature. New physiological basis. *JAMA*. 1969;209:1200–1206. (5) Benzinger TH, Taylor GW. Cranial measurements of internal temperature in man. In: Hardy JD, ed. *Temperature, Its Measurement and Control in Science and Industry*. *Vol 3, Part 3, Biology and Medicine*. New York, NY: Reinhold; 1963: 111–120. (6) Benzinger TH, Kitzinger C, Pratt AW. The human thermostat. In: Hardy JD, ed. Part 3. *Biology and Medicine.* In: Herzfeld CM, ed. *Temperature: Its Measurement and Control in Science and Industry.* Vol 3. New York, NY: Reinhold; 1963: 637–665. (7) Benzinger TH. The human thermostat. *Sci Am*. 1961;204:134–147. (8) Cabanac M, Caputa M. Open loop increase in trunk temperature produced by face cooling in working humans. *J Physiol (Lond)*. 1979;289:163–174. (9) Shiraki K, Sagawa S, Tajima F, Yokota A, Hashimoto M, Brengelmann GL. Independence of brain and tympanic temperatures in an unanesthetized human. *J Appl Physiol*. 1988;65:482–486. (10) Roberts WO. Assessing core temperature in collapsed athletes: What's the best method? *The Physician and Sportsmedicine*. 1994;22(8):49–55. (11) Brengelmann GL. Dilemma of body temperature measurement. In: Shiraki K, Yousef MK, eds. *Man in Stressful Environments: Thermal and Work Physiology*. Springfield, Ill: Charles C Thomas; 1987: 5–22.

EXHIBIT 2-2

BRAIN TEMPERATURE

A few investigators believe in the existence in humans of a physiological process called "selective brain cooling" that keeps the brain cooler than the trunk core during hyperthermia.[1,2] A similar process is known to occur in panting animals that possess carotid retes or other specialized vascular structures that provide for heat exchange between carotid arterial blood on its way to the brain, and cool venous blood returning from the respiratory passages, where evaporative cooling takes place. However, panting is not an important heat-loss mechanism in humans, and humans have no such specialized vascular structures for heat exchange. These investigators therefore propose that selective brain cooling in humans depends on venous blood that has been cooled by evaporation of sweat on the skin of the head, and then drains into the cranium[1–3] to exchange heat at several sites, particularly the cavernous sinus.[1,2] The evidence for selective brain cooling in humans is based largely on measurements of tympanic temperature, taken as representing brain temperature. In fact, because fanning to cool the face was found to lower tympanic temperature, fanning the face has been recommended as a way to protect the brains of patients with hyperthermia from thermal injury.[4] However, humans have no known heat-exchange mechanism that can cool the brain's blood supply more than a few hundredths of a Centigrade degree.[5] Interpretation of tympanic temperature as either core temperature or brain temperature is fraught with problems. Moreover, reports that the difference between esophageal and tympanic temperatures can be eliminated by suitable construction and placement of the tympanic temperature probe[6] imply that the notion of significant selective brain cooling in humans rests on a measurement artifact.

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(1) Cabanac M. Keeping a cool head. *News Physiol Sci*. 1986;1:41–44. (2) Cabanac M, Caputa M. Natural selective cooling of the human brain: Evidence of its occurrence and magnitude. *J Physiol (Lond)*. 1979;286:255–264. (3) Cabanac M, Brinnel H. Blood flow in the emissary veins of the human head during hyperthermia. *Eur J Appl Physiol*. 1985;54:172–176. (4) Cabanac M. Face fanning: A possible way to prevent or cure brain hyperthermia. In: Khogali M, Hales JRS, eds. *Heat Stroke and Temperature Regulation*. Sydney, Australia: Academic Press; 1983: 213–221. (5) Wenger CB. More comments on "Keeping a cool head." *News Physiol Sci*. 1987;2:150. (6) Sato KT, Kane NL, Soos G, Gisolfi CV, Kondo N, Sato K. Reexamination of tympanic membrane temperature as a core temperature. *J Appl Physiol*. 1996;80:1233–1239.

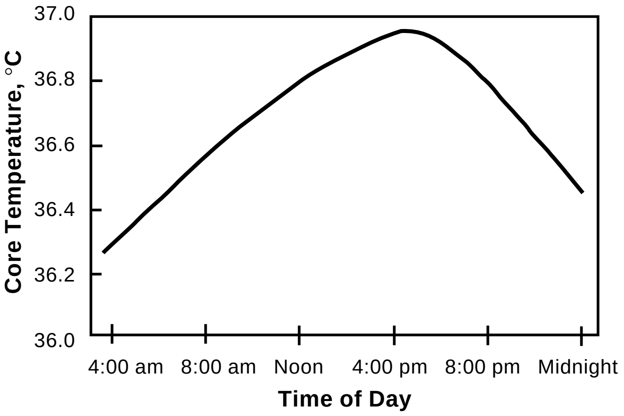

Fig. 2-3. Effect of time of day on internal body temperature of healthy resting subjects. Reprinted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA. *Medical Physiology.* Boston, Mass: Little, Brown; 1995: 591. Original data sources: (1) Mackowiak PA, Wasserman SS, Levine MM. A critical appraisal of 98.6°F, the upper limit of normal body temperature, and other legacies of Carl Reinhold August Wunderlich. *JAMA*. 1992;268:1578–1580. (2) Stephenson LA, Wenger CB, O'Donovan BH, Nadel ER. Circadian rhythm in sweating and cutaneous blood flow. *Am J Physiol.* 1984;246:R321–R324.

discuss how the thermoregulatory system processes this information and uses it to maintain core temperature within a narrow range.

Skin Temperature

Skin temperature is important in heat exchange and thermoregulatory control. Most heat is exchanged between the body and the environment at the skin surface. Skin temperature is much more variable than core temperature and is affected by thermoregulatory responses such as skin blood flow and sweat secretion; by the temperatures of underlying tissues; and by environmental factors such as air temperature, air movement, and thermal radiation. Skin temperature, in turn, is one of the major factors determining heat exchange with the environment. For these reasons, skin temperature provides the thermoregulatory system with important information about the need to conserve or lose body heat. Many bare nerve endings just under the skin are very sensitive to temperature. Depending on the relation of discharge rate to temperature, these nerve endings are classified as either warm or cold receptors[7,9] (Figure 2-4). From the relative densities of cold- and warm-sensitive spots in human skin,[10] cold receptors appear to be roughly 10-fold as nu-

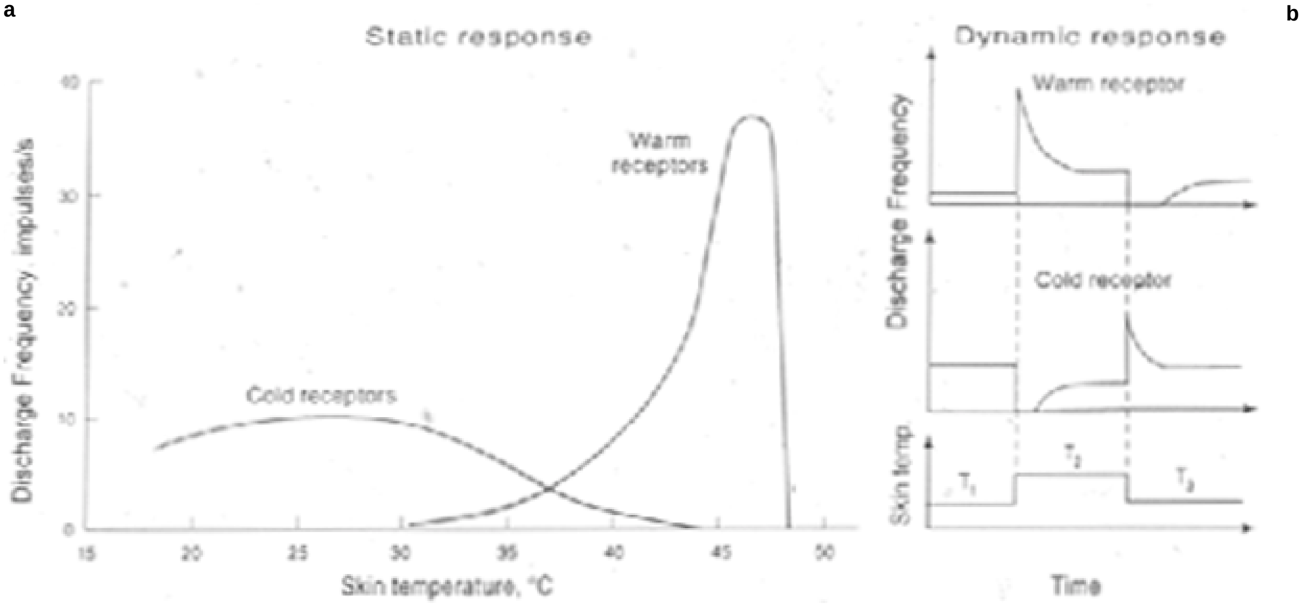

Fig. 2-4. Responses of cold- and warm-sensitive nerve fibers in the skin. Static response (**a**) is the discharge frequency when skin temperature is stable. Dynamic response (**b**) is the discharge frequency following a change in skin temperature. Adapted with permission from Hensel H, Kenshalo DR. Warm receptors in the nasal region of cats. *J Physiol (Lond).* 1969;204:109.

merous as warm receptors because, as a rule, a single cold or warm fiber innervates a single cold- or warm-sensitive spot.[11] With heating of the skin, warm receptors respond with a transient burst of activity, whereas cold receptors respond with a transient suppression; the reverse happens with cooling. These transient responses at the beginning of heating or cooling give the central integrator almost immediate information about changes in skin temperature, and may explain, for example, the intense, brief sensation of being chilled that occurs during a plunge into cold water.

Skin temperature usually is not uniform over the body surface, so a mean skin temperature ($\bar{T}_{sk}$) is frequently calculated from skin temperatures measured at several selected sites, usually weighting the temperature measured at each site according to the fraction of body surface area that it represents. It would be prohibitively invasive and difficult to measure shell temperature directly. Instead, therefore, skin temperature also is commonly used along with core temperature to calculate a mean body temperature and to estimate changes in the amount of heat stored in the body.

BALANCE BETWEEN HEAT PRODUCTION AND HEAT LOSS

All animals exchange energy with the environment. Some energy is exchanged as mechanical work, but most is exchanged as heat—by conduction, convection, and radiation; and as latent heat through evaporation or (rarely) condensation of water (Figure 2-5). If the sum of energy production and energy gain from the environment does not equal energy loss, the extra heat is "stored" in, or lost from, the body. This is summarized in Equation 1, the heat balance equation:

$$(1) \qquad M = E + R + C + K + W + S$$

where *M* is metabolic rate; *E* is rate of heat loss by evaporation; *R* and *C* are rates of heat loss by radiation and convection, respectively; *K* is the rate of heat loss by conduction (only to solid objects in practice, as explained later); *W* is rate of energy loss as mechanical work; and *S* is rate of heat storage in the body, which takes the form of changes in tissue temperatures.[12,13]

The term *M* is always positive, but the other terms in Equation 1 may be either positive or negative. E, R, C, K, and W are positive if they represent energy losses from the body, and negative if they represent

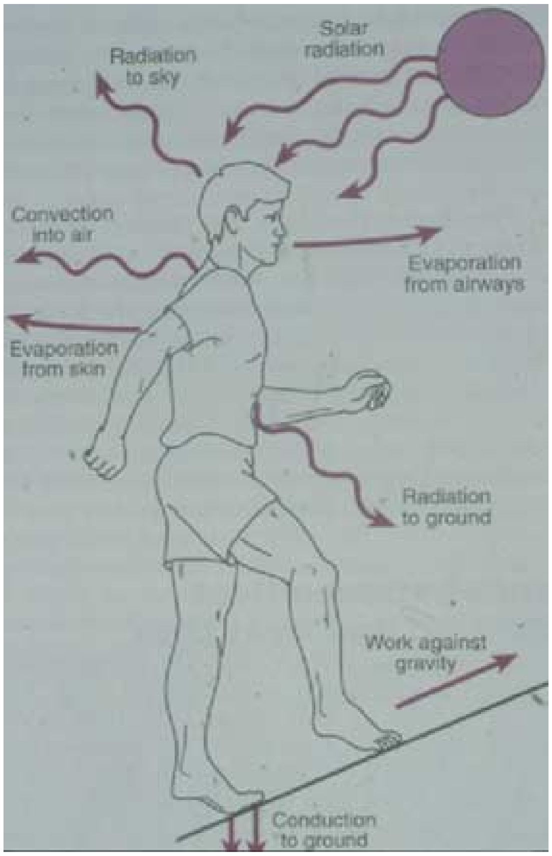

Fig. 2-5. Exchange of energy with the environment. This hiker gains heat from the sun by radiation, and loses heat by conduction to the ground through the soles of his feet, by convection into the air, by radiation to the ground and sky, and by evaporation of water from his skin and respiratory passages. In addition, some of the energy released by his metabolic processes is converted into mechanical work, rather than heat, since he is walking uphill. Reprinted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA, eds. *Medical Physiology*. Boston, Mass: Little, Brown; 1995: 592.

energy gains. When $S = 0$, the body is in heat balance and body temperature neither rises nor falls. When the body is not in heat balance, its mean tissue temperature increases if S is positive, and decreases if S is negative. This commonly occurs on a short-term basis and lasts only until the body responds to changes in its temperature with thermoregulatory responses sufficient to restore balance; but if the thermal stress is too great for the thermoregulatory system to restore balance, the body will continue to gain or lose heat, until either the stress diminishes so that the thermoregulatory system can again restore the balance, or death occurs (Exhibit 2-3).

EXHIBIT 2-3

UNITS FOR MEASURING QUANTITY OF HEAT

The International Union of Physiological Sciences endorses the International System of Units (Système Internationale, SI) for expressing physiological quantities. In this system, quantity of heat is expressed in joules, the unit of work, and rate of heat production or heat flow is expressed in watts, the unit of power (1 W = 1 J/s). In traditional physiological usage, however, heat is expressed in kilocalories (kcal), which are still used widely enough that it is useful to be familiar with them. A kilocalorie (1 kcal = 4186 J) is the quantity of heat that will raise the temperature of 1 kg of pure water by one Centigrade degree, and is identical to the calorie (often spelled with a capital C) used to express the energy value of foods. The word "calorie," however, is a potential source of confusion because the same word was used in chemistry and physics to refer to a unit only 0.001 as large (sometimes called a small calorie), which is the quantity of heat that will raise the temperature of 1 g of pure water by one Centigrade degree.

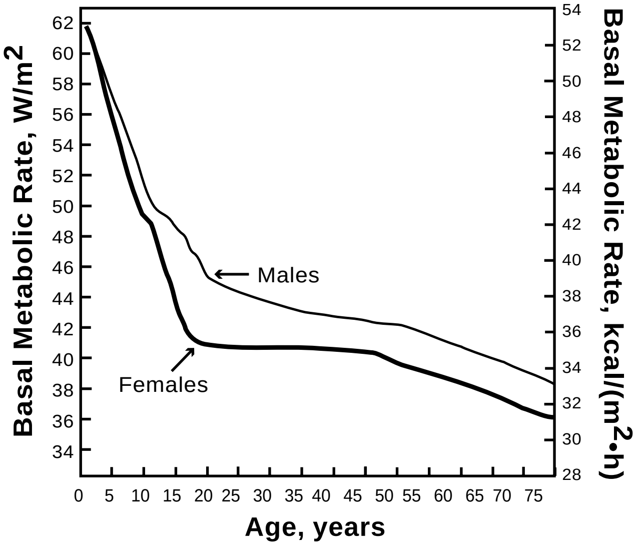

Fig. 2-6. Effects of age and gender on basal metabolic rate of normal subjects, expressed as the ratio of energy consumption to body surface area. Original data source: Fleish PA. La métabolisme basal standard et sa détermination au moyen du "metabocalculator." *Helv Med Acta.* 1951; 18:23–44.

TABLE 2-2

ILLUSTRATIVE VALUES FOR THERMAL PHYSIOLOGY

Measurement	SI[*] Units	Traditional Heat Units
Energy equivalent of oxygen for a mixed diet	20.2 kJ/L	4.83 kcal/L
Heat of evaporation of water	2.43 kJ/g	0.58 kcal/g
For a "Typical," Healthy, Lean, Young Man:		
Mass	70 kg	
Body surface area	1.8 m^2	
Mean specific heat of the body[†]	3.39 kJ/(kg • °C)	0.81 kcal/(kg • °C)
Volume specific heat of blood	3.85 kJ/(L • °C)	0.92 kcal/(L • °C)
Maximum rate of O_2 consumption	3.5 L/min	
Metabolic rate at rest[‡]	45 W/m^2	52.3 kcal/(m^2 • h)
Core-to-skin conductance with minimal skin blood flow[‡]	9 W/(m^2 • °C)	10.5 kcal/(m^2 • °C • h)

[*] Système Internationale (in which heat is expressed in units of work)
[†] Calculated for a body composition of 16% bone, 10% fat, and 74% lean soft tissue (ie, nonfatty tissue, neither bone nor tooth)
[‡] Per square meter of body surface area
Adapted with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA, eds. *Medical Physiology*. Boston, Mass: Little, Brown; 1995: 611.

Heat Production

Metabolic energy is required for active transport via membrane pumps, for muscular work, and for chemical reactions such as formation of glycogen from glucose and proteins from amino acids, whose products contain more energy than the materials that entered into the reaction. Most of the energy used in these processes is transformed into heat within the body. The transformation may be almost immediate, as with energy used in active transport or with heat produced as a by-product of muscular contraction. In other processes the conversion of energy to heat is delayed, as when the energy that was used to form glycogen or protein is released as heat when glycogen is converted back into glucose, or protein back into amino acids.

Metabolic Rate and Sites of Heat Production at Rest

Metabolic rate at rest varies with body size and is approximately proportional to body surface area. In a fasting young man it is about 45 W/m^2 (Figure 2-6) (81 W or 70 kcal/h for 1.8 m^2 body surface area [Table 2-2]), corresponding to an O_2 consumption of about 240 mL/min). At rest the trunk viscera and brain account for about 70% of energy production, even though they comprise only about 36% of body mass (Table 2-3). All the heat required to maintain heat balance at comfortable environmental temperatures is supplied as a by-product of metabolic processes that serve other functions, although in the cold, supplemental heat production may be elicited to maintain heat balance.

Factors other than body size that affect metabolism at rest include gender, age, hormones, and digestion. A nonpregnant woman's metabolic rate is 5% to 10% lower than that of a man of the same age and body surface area, probably because the female

TABLE 2-3

RELATIVE MASSES AND RATES OF METABOLIC HEAT PRODUCTION OF VARIOUS BODY COMPARTMENTS

	Body Mass (%)	Heat Production (%) Rest	Heat Production (%) Severe[*] Exercise
Brain	2	16	1
Trunk Viscera	34	56	8
Muscle and Skin	56	18	90
Other	8	10	1

[*] Intense or heavy
Adapted with permission from Wenger CB, Hardy JD. Temperature regulation and exposure to heat and cold. In: Lehmann JF, ed. *Therapeutic Heat and Cold*. Baltimore, Md: Williams & Wilkins; 1990: 156.

body includes a higher proportion of fat, a tissue with a low metabolic rate. (However, the growing fetus's energy requirements increase a pregnant woman's measured metabolic rate.)

Catecholamines and thyroxine are the hormones with the largest effect on metabolic rate. Catecholamines stimulate many enzyme systems, thus increasing cellular metabolism; and hypermetabolism occurs in some cases of pheochromocytoma, a secreting tumor of the adrenal medulla. Thyroxine magnifies the metabolic response to catecholamines and stimulates oxidation in the mitochondria. Hyperthyroidism may double the metabolic rate in severe cases, although an increase to 45% above normal is more typical; and metabolic rate is typically 25% below normal in hypothyroidism but may be 45% below normal with total lack of thyroxine.

Metabolic rate at rest increases after a meal as a result of the *thermic effect of food* (or "specific dynamic action," the older term). The increase varies according to the composition of the meal and the physiological state, including the level of nutrition, of the subject.[14] In a well-nourished subject the increase is typically 10% to 20%. The effect lasts several hours and appears to be associated with processing the products of digestion by the liver.

Measurement of Metabolic Rate

Heat exchange with the environment can be measured directly with a human calorimeter,[15] a specially constructed insulated chamber that allows heat to leave only in the air ventilating the chamber or, often, in water flowing through a heat exchanger in the chamber. From accurate measurements of the flow of air and water, and their temperatures as they enter and leave the chamber, we can compute the subject's heat loss by conduction, convection, and radiation; and from measurements of the moisture content of air entering and leaving the chamber, we can also determine heat loss by evaporation. *Direct calorimetry,* as this technique is called, is simple in concept but difficult and costly in practice. Therefore metabolic rate is often estimated by *indirect calorimetry*[16] based on measurements of O_2 consumption, because virtually all energy available to the body depends ultimately on reactions that consume O_2.

Consumption of 1 liter of O_2 is associated with release of 21.1 kJ (5.05 kcal) if the fuel is carbohydrate, 19.8 kJ (4.74 kcal) if the fuel is fat, and 18.6 kJ (4.46 kcal) if the fuel is protein. For metabolism of a mixed diet, an average value of 20.2 kJ (4.83 kcal) per liter of O_2 is often used (see Table 2-2). The ratio of CO_2 produced to O_2 consumed in the tissues, called the r*espiratory quotient* (RQ), is 1.0 for oxidation of carbohydrate, 0.71 for oxidation of fat, and 0.80 for oxidation of protein. In a steady state in which CO_2 is exhaled at the same rate that it is produced in the tissues, RQ is equal to the respiratory exchange ratio, R; and the accuracy of indirect calorimetry can be improved by also determining R, and either estimating the amount of protein oxidized—usually small compared with fat and carbohydrate—or calculating it from urinary nitrogen excretion.

Skeletal Muscle Metabolism and Muscular Work

Even during very mild exercise the muscles are the chief source of metabolic heat, and during heavy exercise they (together with the skin) may account for up to 90% of the heat production (see Table 2-3). A healthy but sedentary young man performing moderately intense exercise may increase his metabolic rate to 600 W (in contrast to about 80 W at rest); and a trained athlete performing intense exercise, to 1400 W or more. Exercising muscles may be nearly one Centigrade degree warmer than the core because of their high metabolic rate. Blood is warmed as it perfuses these muscles, and the blood, in turn, warms the rest of the body and raises core temperature. Like engines that burn fossil fuels, muscles convert most of the energy in the fuels that they consume into heat rather than mechanical work.

When adenosine 5'-diphosphate (ADP) is phosphorylated to form adenosine 5'-triphosphate (ATP), 58% of the energy released from the fuel is converted into heat, and only about 42% is captured in the ATP that is formed. Then when ATP is hydrolyzed during a muscle contraction, some of the energy in the ATP is converted into heat rather than into mechanical work. The efficiency of this process varies enormously, and is zero in isometric contraction, in which a muscle's length does not change while it develops tension, so that the muscle does no work even though it consumes metabolic energy. Finally, some mechanical work is converted by friction into heat within the body—as, for example, happens to the mechanical work done by the heart in pumping blood. At best, no more than one quarter of the metabolic energy released during exercise is converted into mechanical work outside the body, and the remaining three quarters or more is converted into heat within the body[17] (Exhibit 2-4).

EXHIBIT 2-4

ENERGY CONSUMPTION AND HEAT PRODUCTION DURING PERFORMANCE OF MILITARY TASKS

Many military tasks require high levels of power output, and are associated with correspondingly high rates of metabolic heat production. Table 3-2 in Chapter 3, Physical Exercise in Hot Climates: Physiology, Performance, and Biomedical Issues lists metabolic rates required by men wearing the battle dress uniform (BDU) to perform 28 military occupational tasks. The added weight and stiffness of special protective clothing increase the energy cost of performing a task, and wearing the full ensemble of nuclear biological chemical protective clothing (including overgarment, boot, gloves, gas mask, and hood) over BDUs increases the rate of oxygen consumption by an average of about 10%.[1]

Of the military tasks with a high energy demand, walking and running—with or without an external load—are probably among those that are most suitable for prediction of energy requirement. For walking speeds of 2.5 km/h or greater, and light-to-moderate loads that are distributed so that their center of gravity is near the body's center of gravity, the following equation[2] predicts the metabolic power requirements for walking as a function of body weight, speed, grade, carried load, and surface:

$$M = \eta\ (W + L)\ \{2.3 + 0.32\ (V - 2.5\ \text{km/h})^{1.65} + G\ [0.2 + 0.7\ (V - 2.5\ \text{km/h})]\}$$

where M represents metabolic rate, kcal/h; η represents the terrain factor, defined as 1 for treadmill walking; W represents body weight in kilograms; L represents external load in kilograms; V represents walking speed in kilometers per hour; and G represents % grade.

Some values of the terrain factor, η, are 1.0 for blacktop surface, 1.1 for dirt road, 1.2 for light brush, 1.5 for heavy brush, 1.8 for swampy bog, and 2.1 for loose sand.[3]

Exhibit Table 1 contains some illustrative predictions for metabolic rates of a 70-kg subject walking at several speeds and grades on blacktop with no external load:

EXHIBIT TABLE 1
PREDICTED METABOLIC RATES OF A 70-KG SOLDIER WALKING AT SELECTED COMBINATIONS OF SPEED AND GRADE

Grade	Speed 4 km/h (2.5 mph)	5 km/h (3.1 mph)	6 km/h (3.7 mph)	7 km/h (4.4 mph)
0%	204 kcal/h	263 kcal/h	338 kcal/h	429 kcal/h
2%	379 kcal/h	536 kcal/h	709 kcal/h	898 kcal/h

Adding an external load, or substituting a less advantageous surface for blacktop, will increase the energy requirements proportionately. The cumulative effect of seemingly small changes in speed, grade, load, and terrain can impose a huge physiological burden on the body's capacity to support physical exercise and dissipate heat.

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(1) Patton JF, Murphy M, Bidwell T, Mello R, Harp M. *Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4.* Natick, Mass: US Army Research Institute of Environmental Medicine; 1995. USARIEM Technical Report T95-9. (2) Givoni B, Goldman RF. Predicting metabolic energy cost. *J Appl Physiol*. 1971;30:429–433. (3) Soule RG, Goldman RF. Terrain coefficients for energy cost prediction. *J Appl Physiol*. 1972;32:706–708.

Heat Exchange With the Environment

Convection, radiation, and evaporation are the dominant means of heat exchange with the environment. Both the skin and the respiratory passages exchange heat with the environment by convection and evaporation, but only the skin exchanges heat by radiation. In some animal species, panting is an important thermoregulatory response, which can produce high rates of heat loss. In humans, however, respiration usually accounts for only a minor fraction of total heat exchange and is not predominantly under thermoregulatory control, although hyperthermic subjects may hyperventilate.

Convection is transfer of heat due to movement of a fluid, either liquid or gas. In thermal physiology the fluid is usually air or water in the environment, or blood inside the body, as discussed earlier. Fluids conduct heat in the same way as solids do, and a perfectly still fluid transfers heat only by conduction. Because air and water are not good conductors of heat, perfectly still air or water are not very effective in heat transfer. Fluids, however, are rarely perfectly still, and even nearly imperceptible movement produces enough convection to cause a large increase in the rate of heat transfer. Thus, although conduction plays a role in heat transfer by a fluid, convection so dominates the overall heat transfer that we refer to the entire process as convection. The conduction term, K, in Equation 1 is therefore restricted to heat flow between the body and other solid objects, and usually represents only a small part of the total heat exchange with the environment.

Convective heat exchange between the skin and the environment is proportional to the difference between skin and ambient air temperatures, as expressed by Equation 2:

$$(2) \qquad C = h_c \bullet A \bullet (\bar{T}_{sk} - T_a)$$

where A is the body surface area, $\bar{T}_{sk}$ and T_a are mean skin and ambient temperatures, respectively, and h_c is the convective heat transfer coefficient.

The term h_c includes the effects of all the factors besides temperature and surface area that affect convective heat exchange. For the whole body, the most important of these factors is air movement, and convective heat exchange (and thus h_c) varies approximately as the square root of the air speed (Figure 2-7) unless air movement is very slight.

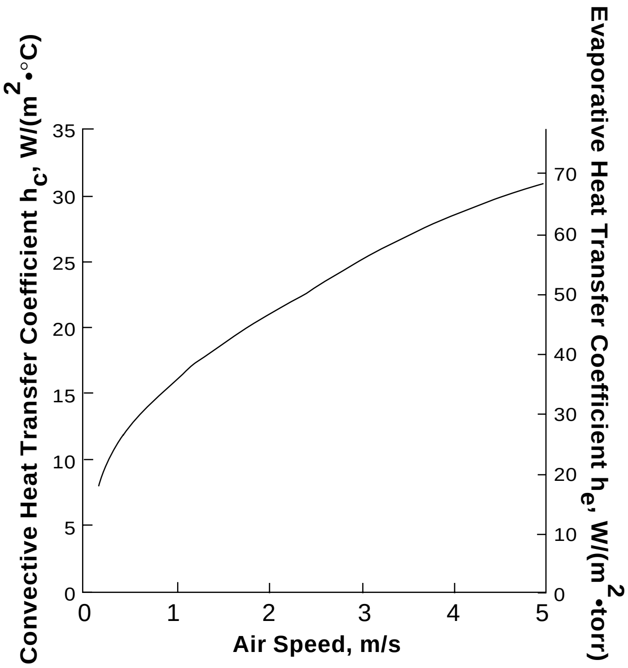

Fig. 2-7. The convective ($h_{c)}$ and evaporative (h_e) heat transfer coefficients for a standing human as a function of air speed. The coefficients h_c and h_e increase with air speed in the same way, and $h_e = h_c \bullet 2.2$°C/mm Hg. Thus with suitable scaling of the vertical axes, as in this figure, the curves for h_c and h_e overlie each other. The horizontal axis can be converted into English units by using the relation 5 m/s = 16.4 ft/s = 11.2 mph.

Every surface emits energy as electromagnetic radiation with a power output that depends on its area, its temperature, and its emissivity (e), a number between 0 and 1 that depends on the nature of the surface and the wavelength of the radiation. (For purposes of this discussion the term "surface" has a broader meaning than usual, so that, for example, a flame and the sky are both surfaces.) The emissivity of any surface is identical to its absorptivity (ie, the fraction of incoming radiant energy that the surface absorbs rather than reflects). Such radiation, called thermal radiation, has a characteristic distribution of energy as a function of wavelength, which depends on the temperature of the surface. For a surface that is not hot enough to glow this radiation is in the infrared part of the spectrum, and at ordinary tissue and environmental temperatures virtually all of the emitted energy is at wavelengths longer than 3 microns. Most surfaces except polished metals have emissivities near 1 in this range, and thus both emit and absorb radiation at nearly the theoretical maximum efficiency. As a surface's temperature increases, however, the average wavelength of its thermal radiation decreases, and most of the energy in solar radiation is in the near infrared and visible range, for which light surfaces have lower absorptivities than dark ones.

If two surfaces exchange heat by thermal radiation, radiation travels in both directions; but because each surface emits radiation with an intensity that depends on its temperature, the net heat flow is from the warmer to the cooler body. Radiative heat exchange between two surfaces is, strictly, proportional to the difference between the fourth powers of the surfaces' absolute temperatures. However, if the difference between $\bar{T}_{sk}$ and the temperature of the radiant environment (T_r) is much smaller than the absolute temperature of the skin, R is nearly proportional to ($\bar{T}_{sk} - T_r$). Some parts of the body surface (eg, inner surfaces of the thighs and arms) exchange heat by radiation with other parts of the body surface, so that the body exchanges heat with the environment as if it had an area smaller than its actual surface area. This smaller area is called the *effective radiating surface area* (A_r), and depends on the posture, being greatest, or closest to the actual surface area, in a "spread eagle" posture, and least in someone who is curled up. Radiative heat exchange can be represented by Equation 3:

$$(3) \qquad R = h_r \bullet e_{sk} \bullet A_r \bullet (\bar{T}_{sk} - T_r)$$

where h_r is the radiant heat transfer coefficient, 6.43 W/(m^2 • °C) at 28°C; and e_{sk} is the emissivity of the skin.

When a gram of water is converted into vapor at 30°C, it absorbs 2,425 J (0.58 kcal; see Table 2-2), the *latent heat of evaporation,* in the process. When the environment is hotter than the skin—as it usually is when the environment is warmer than 36°C—evaporation is the body's only way to lose heat, and must dissipate not only the heat produced by the body's metabolism, but also any heat gained from the environment by R and C (from Equation 1). Most water evaporated in the heat comes from sweat; but even in the cold, water diffuses through the skin and evaporates. Evaporation of this water is called *insensible perspiration,*[9,18] and occurs independently of the sweat glands. E is nearly always positive (representing loss of heat from the body); but it is negative in unusual circumstances, such as in a steam room, where water vapor condensing on the skin gives up heat to the body.

Evaporative heat loss from the skin is proportional to the difference between the water vapor pressure at the skin surface and the water vapor pressure in the ambient air. These relations are summarized in Equation 4:

$$(4) \qquad E = h_e \bullet A \bullet (P_{sk} - P_a)$$

where P_{sk} is the water vapor pressure at the skin surface, P_a is the ambient water vapor pressure, and h_e is the evaporative heat transfer coefficient.

Because water vapor, like heat, is carried away by moving air, air movement and other factors affect E and h_e in just the same way that they affect C and h_c. If the skin surface is completely wet, the water vapor pressure at the skin surface is the saturation water vapor pressure (Figure 2-8) at skin temperature, and evaporative heat loss is E_{max}, the maximum possible for the prevailing skin temperature and environmental conditions. This situation is described in Equation 5:

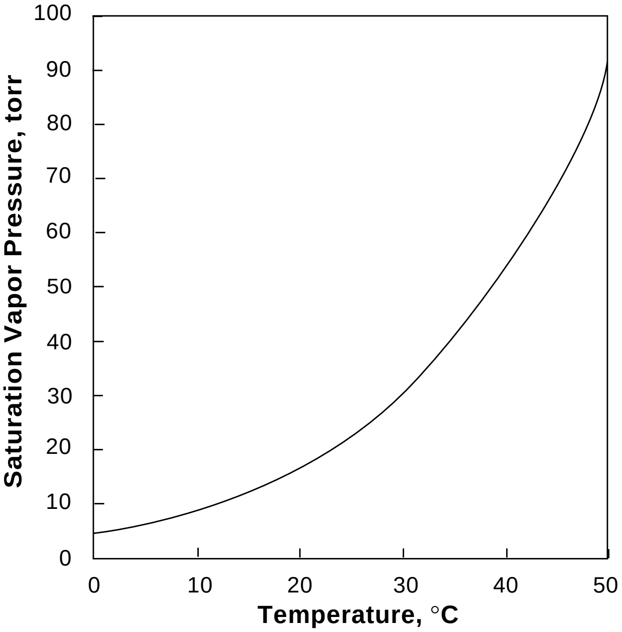

Fig. 2-8. The saturation vapor pressure of water as a function of temperature. For any given temperature, the water vapor pressure is at its saturation value when the air is "saturated" with water vapor (ie, the air holds the maximum amount possible at that temperature, or the relative humidity is 100%).

$$(5) \qquad E_{max} = h_e \bullet A \bullet (P_{sk,sat} - P_a)$$

where $P_{sk,sat}$ is the saturation water vapor pressure at skin temperature, and h_e is the evaporative heat transfer coefficient.

When the skin is not completely wet, it is impractical to measure the actual average water vapor pressure at the skin surface. Therefore a coefficient called skin *wettedness* (w)[19] is defined as the ratio E/E_{max}, with $0 \le w \le 1$. Skin wettedness depends on the hydration of the epidermis and the fraction of the skin surface that is wet. We can now rewrite Equation 4 as Equation 6:

$$(6) \qquad E = h_e \bullet A \bullet w \bullet (P_{sk,sat} - P_a)$$

Wettedness depends on the balance between secretion and evaporation of sweat. If secretion exceeds evaporation, sweat accumulates on the skin and spreads out to wet more of the space between neighboring sweat glands, thus increasing wettedness and E; and if evaporation exceeds secretion, the reverse occurs. If sweat rate exceeds E_{max}, then once wettedness becomes 1, the excess sweat drips from the body because it cannot evaporate.

Note that P_a, on which evaporation from the skin directly depends, is proportional to the actual moisture content in the air. By contrast, the more familiar quantity, relative humidity (rh), is the ratio between the actual moisture content in the air and the maximum moisture content that is possible at the temperature of the air. It is important to recognize that rh is only indirectly related to evaporation from the skin. For example, in a cold environment, P_a will be low enough that sweat can easily evaporate from the skin even if rh = 100%.

Clothing reduces heat exchange between the body and its environment through several mechanisms. By impeding air movement, clothing reduces h_c and h_e at the skin, thereby reducing heat exchange by convection and evaporation. In addition, clothing resists conduction of heat, and is at least a partial barrier to radiative heat exchange and passage of water vapor. For all of these reasons, clothing creates a microenvironment that is closer to skin temperature than is the environment outside the clothing. Furthermore, since the body is a source of water vapor, the air inside the clothing is more humid than outside. The conditions inside this microenvironment—air temperature, water vapor pressure, and temperature of the inner surface of the clothing—are what determine heat gain or heat loss by unexposed skin. These conditions in turn are determined by the conditions outside the clothing, the properties of the clothing, and the rate at which the body releases heat and moisture into this microenvironment. Therefore, the level of physical activity determines both (*a*) the appropriate level of clothing for the environmental conditions and (*b*) the degree of heat *strain* (ie, physiological change produced by a disturbance) that results from wearing clothing that is too warm for the conditions, as protective clothing often is.

Although clothing reduces heat exchange between covered skin and the environment, it has little effect on heat exchange of exposed skin. Therefore—especially when the clothing is heavy and most of the skin is covered—exposed skin may account for a fraction of the body's heat loss that far exceeds the exposed fraction of the body's surface. Thus in the cold, the head may account for half of the heat loss from the body[20]; and in someone exercising while wearing nuclear, biological, and chemical (NBC) protective clothing without gas mask and hood, donning the mask and hood while continuing to exercise may lead to a dramatic increase in heat strain.[21]

Heat Storage

Heat storage is a change in the body's heat content. The rate of heat storage is the difference between heat production/gain and heat loss (see Equation 1), and can be determined from simultaneous measurements of metabolism by indirect calorimetry and heat gain or loss by direct calorimetry. Because heat storage in the tissues changes their temperature, the amount of heat stored is the product of body mass, the body's mean specific heat, and a suitable mean body temperature (T_b). The body's mean specific heat depends on its composition, especially the proportion of fat, and is about 3.39 kJ/(kg • °C) [0.81 kcal/(kg • °C)] (see Table 2-2) for a typical body composition of 16% bone, 10% fat, and 74% lean soft tissue (ie, tissue that is neither bone nor tooth, and is not fatty). Empirical relations of T_b to core temperature (T_c) and $\bar{T}_{sk}$, determined in calorimetric studies, depend on ambient temperature, with T_b varying from $0.67 \bullet T_c + 0.33 \bullet \bar{T}_{sk}$ in the cold to $0.9 \bullet T_c + 0.1 \bullet \bar{T}_{sk}$ in the heat.[19] The shift from cold to heat in the relative weighting of T_c and $\bar{T}_{sk}$ reflects the accompanying change in the thickness of the shell (see Figure 2-2).

HEAT DISSIPATION

Figure 2-9 shows rectal and mean skin temperatures, heat losses, and calculated shell conductances for nude resting men and women at the end of 2-hour exposures in a calorimeter to ambient temperatures from 23°C to 36°C. Shell conductance represents the sum of heat transfer by two parallel modes (ie, conduction through the tissues of the shell, and convection by the blood); it is calculated by dividing heat loss through the skin (HF_{sk})—(ie, total heat loss less heat loss through the respiratory tract)—by the difference between core and mean skin temperatures, as shown in Equation 7:

$$C = HF_{sk}/(T_c - \bar{T}_{sk}) \qquad (7)$$

where C is shell conductance, and T_c and $\bar{T}_{sk}$ are core

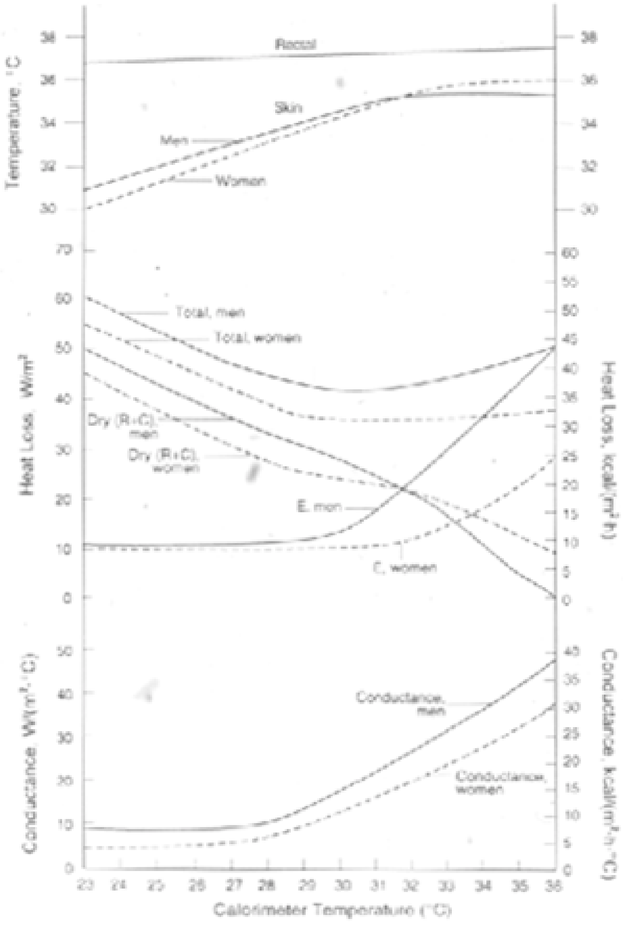

Fig. 2-9. Average values of rectal and mean skin temperatures, heat loss, and core-to-skin thermal conductance for nude resting men and women near steady state after 2 hours at different environmental temperatures in a calorimeter. (All energy-exchange quantities in this figure have been divided by body surface area, to remove the effect of individual body size.) Total heat loss is the sum of dry heat loss (by radiation [R] and convection [C]) and evaporative heat loss (E). Dry heat loss is proportional to the difference between skin temperature and calorimeter temperature, and it decreases with increasing calorimeter temperature. Adapted (data correction) with permission from Wenger CB. The regulation of body temperature. In: Rhoades RA, Tanner GA, eds. *Medical Physiology*. Boston, Mass: Little, Brown; 1995: 596. Data source: Hardy JD, DuBois EF. Differences between men and women in their response to heat and cold. *Proc Natl Acad Sci U S A.* 1940;26:389–398.

and mean skin temperatures, respectively.

At ambient temperatures below 28°C, these subjects' conductance is minimal because their skin blood flow is quite low. Because the minimum attainable level of conductance depends chiefly on the subcutaneous fat layer, the women's thicker layer allows them to attain a lower conductance than men. At about 28°C, conductance begins to increase, and above 30°C, conductance continues to increase and sweating begins. For these nude subjects, the range 28°C to 30°C is the zone of *thermoneutrality;* that is, the range of comfortable environmental temperatures in which thermal balance is maintained without either shivering or sweating.[12] In this zone, heat loss is matched to heat production by controlling conductance, and thus $\overline{T}_{sk}$, R, and C.

Evaporation

As we saw in Figure 2-9, evaporative heat loss is nearly independent of ambient temperature below 30°C, and is 9 to 10 W/m^2. This corresponds to evaporation of about 13 to 15 g/(m^2 • h), of which about half is lost through breathing and half as insensible perspiration. This heat loss is not under thermoregulatory control. To achieve heat balance at higher ambient temperatures, the subjects in Figure 2-9 depend more and more on evaporation of sweat, which in humans can dissipate large amounts of heat.

There are two histological types of sweat glands, *eccrine* and *apocrine*. In humans, apocrine glands are found mostly in the axilla, inguinal region, perianal skin, and mammary areolae, and less consistently on other parts of the trunk and the face.[22] Eccrine sweat is essentially a dilute electrolyte solution, but apocrine sweat also contains fatty material. Eccrine sweat glands are widely distributed and are the more important type in human thermoregulation, and functionally active eccrine glands number about 2 to 3 million.[23] They are controlled through postganglionic sympathetic nerves, which release acetylcholine[23] rather than norepinephrine. A healthy man unacclimatized to heat can secrete up to 1.5 liters of sweat per hour. Although the number of functional sweat glands is fixed before the age of 3 years,[23] the secretory capacity of individual glands can change, especially with endurance exercise training and heat acclimatization; and a man who is well acclimatized to heat can secrete more than 2.5 L/h.[24,25] Such rates cannot be maintained, however, and the maximum daily sweat output is probably about 15 L.[26]

Sodium concentration of eccrine sweat ranges from less than 5 to 60 mEq/L[27] (vs 135–145 mEq/L in plasma); but even at 60 mEq/L, sweat is one of the most dilute body fluids. To produce sweat that is hypotonic to plasma, the glands reabsorb sodium from the sweat duct by active transport. As sweat rate increases, the rate at which the glands reabsorb sodium increases more slowly, so that sodium concentration in the sweat increases.

Skin Circulation and Dry (Convective and Radiative) Heat Exchange

Heat produced within the body must be delivered to the skin surface to be eliminated. When skin blood flow is minimal, core-to-skin thermal conductance (ie, the conductance of the shell) is typically 5 to 9 W per Centigrade degree per square meter of body surface (see Figure 2-9). A lean resting subject with a surface area of 1.8 m^2, minimal whole-body conductance of 16 W/°C [ie, 8.9 $W/(°C \bullet m^2)$ x (1.8 m^2)] and a metabolic heat production of 80 W, requires a temperature difference between core and skin of five Centigrade degrees (ie, 80 W ÷ 16 W/°C) to allow the heat produced inside the body to be conducted to the surface. In a cool environment, T_{sk} may easily be low enough for this to occur. However, in an ambient temperature of 33°C, $\overline{T}_{sk}$ is typically about 35°C; and without an increase in conductance, core temperature would need to rise to 40°C—a high although not yet dangerous level—for the heat to be conducted to the skin. But if the rate of heat production were increased to 480 W by moderate exercise, the temperature difference between core and skin would have to rise to 30°C—and core temperature to well beyond lethal levels—to allow all the heat produced to be conducted to the skin. In such circumstances a large increase in conductance is needed for the body to reestablish thermal balance and continue to regulate its temperature; and this is accomplished by increasing skin blood flow.

Role of Skin Blood Flow in Heat Transfer

If we assume that blood on its way to the skin remains at core temperature until it reaches the skin, comes to skin temperature as it passes through the skin, and then stays at skin temperature until it returns to the core, we can compute the rate of heat flow (HF_b) due to convection by the blood as seen in Equation 8:

$$(8) \quad HF_b = SkBF \bullet (T_c - T_{sk}) \bullet 3.85\ kJ/(L \bullet °C)$$

where *SkBF,* the rate of skin blood flow, is expressed in L/s rather than the more usual L/min, to simplify computing HF in W (ie, J/s); and *3.85 kJ/(L • °C) [0.92 kcal/(L • °C)]* = volume specific heat of blood[28] (see Table 2-2).

Conductance due to convection by the blood (C_b) is calculated as seen in Equation 9:

$$(9) \quad C_b = HF_b/(T_c - T_{sk}) = SkBF \bullet 3.85\ kJ/(L \bullet °C)$$

Of course, heat continues to flow by conduction through the tissues of the shell, so that total conductance is the sum of conductance due to convection by the blood plus that due to conduction through the tissues; and total heat flow is given by Equation 10:

$$(10) \quad HF = (C_b + C_0) \bullet (T_c - T_{sk})$$

in which C_0 is thermal conductance of the tissues when skin blood flow is minimal, and thus is due predominantly to conduction through the tissues.

The assumptions on which Equation 8 depend represent the conditions for maximum efficiency of heat transfer by the blood, and are somewhat artificial. In practice, blood also exchanges heat with the tissues through which it passes going to and from the skin. Heat is exchanged with these other tissues most easily when skin blood flow is low, and in such cases heat flow to the skin may be much less than that predicted by Equation 8. However, Equation 8 is a reasonable approximation in a warm subject with moderate-to-high skin blood flow. It is not possible to measure whole-body skin blood flow directly, but it is estimated to reach nearly 8 L/min during maximal cutaneous vasodilation.[29,30] Maximal cutaneous vasodilation does not occur during heavy exercise,[31] but skin blood flow still may reach several liters per minute during heavy exercise in the heat.[29] If SkBF = 1.89 L/min (0.0315 L/s), then, according to Equation 9, skin blood flow contributes about 121 W/°C to the conductance of the shell. If conduction through the tissues contributes 16 W/°C, total shell conductance is 137 W/°C; and if T_c = 38.5°C and T_{sk} = 35°C, then this will produce a core-to-skin heat transfer of 480 W, the heat production in our earlier example of moderate exercise. Thus even a moderate rate of skin blood flow can have a dramatic effect on heat transfer.

In a person who is not sweating, raising skin blood flow brings skin temperature nearer to blood temperature, and lowering skin blood flow brings skin temperature nearer to ambient temperature. In these conditions the body controls dry (convective and radiative) heat loss by varying skin blood flow and thus skin temperature. Once sweating begins, skin blood flow continues to increase as the person becomes warmer, but now the tendency of an increase in skin blood flow to warm the skin is approximately balanced by the tendency of an increase in sweating to cool the skin. Therefore, after sweating has begun, further increases in skin blood flow usually cause little change in skin temperature or dry heat exchange, and serve primarily to deliver to the skin the heat that is being removed by evaporation of sweat. Skin blood flow and sweating thus work in tandem to dissipate heat under such conditions.

Sympathetic Control of Skin Circulation

Blood flow in human skin is under dual vasomotor control.[8,30,32] In most of the skin the vasodilation that occurs during heat exposure depends on sympathetic nervous signals that cause the blood vessels to dilate, and this vasodilation can be prevented or reversed by regional nerve block.[33] Because it depends on the action of nervous signals, such vasodilation is sometimes referred to as active vasodilation. Active vasodilation occurs in almost all the skin except in the so-called acral regions—hands, feet, lips, ears, and nose.[34] In the skin areas where active vasodilation occurs, vasoconstrictor activity is minimal at thermoneutral temperatures; and as the body is warmed, active vasodilation does not begin until close to the onset of sweating.[30,35] Thus skin blood flow in these areas is not much affected by small temperature changes within the thermoneutral range.[34] The neurotransmitter or other vasoactive substance responsible for active vasodilation in human skin has not been identified.[36] However, because sweating and vasodilation operate in tandem in the heat, some investigators[30,37] have proposed that the mechanism for active vasodilation is somehow linked to the action of sweat glands.

Reflex vasoconstriction, which occurs in response to cold and also as part of certain nonthermal reflexes such as baroreflexes, is mediated primarily through adrenergic sympathetic fibers, which are distributed widely over most of the skin.[36] Reducing the flow of impulses in these nerve fibers allows the blood vessels to dilate. In the acral regions[30,36] and in the superficial veins,[30] vasoconstrictor fibers are the predominant vasomotor innervation, and the vasodilation that occurs during heat exposure is largely a result of the withdrawal of vasoconstrictor activity.[34] Blood flow in these skin regions is sensitive to small temperature changes even in the thermoneutral range, and may be responsible for "fine tuning" heat loss to maintain heat balance in this range.

THERMOREGULATORY CONTROL

In control theory, the words *regulation* and *regulate* have meanings distinct from those of *control*. A control system acts to minimize changes in the *regulated* variable (eg, core temperature) that are produced by disturbances from outside the system (eg, exercise or changes in the environment) by making changes in certain other variables (eg, sweating rate, skin blood flow, metabolic rate, and thermoregulatory behavior), which are called *controlled* variables. Human beings have two distinct subsystems to regulate body temperature: behavioral thermoregulation and physiological thermoregulation. Physiological thermoregulation is capable of fairly precise adjustments of heat balance but is effective only within a relatively narrow range of environmental temperatures. On the other hand, behavioral thermoregulation, through the use of shelter and space heating and clothing, enables humans to live in the most extreme climates on earth, but it does not provide fine control of body heat balance.

Behavioral Thermoregulation

Behavioral thermoregulation is governed by thermal sensation and comfort. Sensory information about body temperatures is an essential part of both behavioral and physiological thermoregulation. The distinguishing feature of behavioral thermoregulation is the direction of conscious effort to reduce discomfort. Warmth and cold on the skin are felt as either comfortable or uncomfortable, depending on whether they decrease or increase the physiological strain.[38] Thus a shower temperature that feels pleasant after strenuous exercise may be uncomfortably cold on a chilly morning. Because of the relation between discomfort and physiological strain, behavioral thermoregulation, by reducing discomfort, also acts to minimize the physiological burden imposed by a stressful thermal environment. For this reason the zone of thermoneutrality is characterized by thermal comfort as well as by the absence of shivering and sweating.

The processing of thermal information in behavioral thermoregulation is not as well understood as it is in physiological thermoregulation. However, perceptions of thermal sensation and comfort respond much more quickly than either core temperature or physiological thermoregulatory responses to changes in environmental temperature,[39,40] and thus appear to anticipate changes in the body's thermal state. Such an anticipatory feature presumably reduces the need for frequent small behavioral adjustments.

Physiological Thermoregulation

Physiological thermoregulation operates through graded control of heat-production and heat-loss responses. Familiar nonliving control systems, such as most refrigerators and heating and air-conditioning systems, operate at only two levels because they act by turning a device on or off. In contrast, most physiological control systems produce a response that is graded according to the disturbance in the regulated variable. In many physiological systems, changes in the controlled variables are proportional to displacements of the regulated variable from some threshold value, and such control systems are called *proportional control* systems.

The control of heat-dissipating responses is an example of a proportional control system.[9] Figure 2-10 shows how reflex control of sweating and skin blood flow depends on body core and skin temperatures. Each response has a core temperature threshold, a temperature at which the response starts to increase; and these thresholds depend on mean skin temperature. Thus at any given skin temperature, the change in each response is proportional to the change in core temperature; and increasing the skin temperature lowers the threshold level of core temperature and increases the response at any given core temperature. In humans, a change of one Centigrade degree in core temperature elicits about nine times as great a thermoregulatory response as a change in mean skin temperature of one Centigrade degree.[8] (Besides its effect on the reflex signals, skin temperature has a local effect that modifies the blood vessel and sweat gland responses, as discussed later.)

Integration of Thermal Information

The central nervous system integrates thermal information from core and skin. Receptors in the body core and the skin transmit information about their temperatures through afferent nerves to the brainstem, and especially the hypothalamus, where much of the integration of temperature information occurs.[41] The sensitivity of the thermoregulatory responses to core temperature allows the thermoregulatory system to adjust heat production and heat loss to resist disturbances in core temperature. Their sensitivity to mean skin temperature allows the system to respond appropriately to mild heat or cold exposure with little change in body core temperature, so that environmentally induced changes in body heat content occur al-

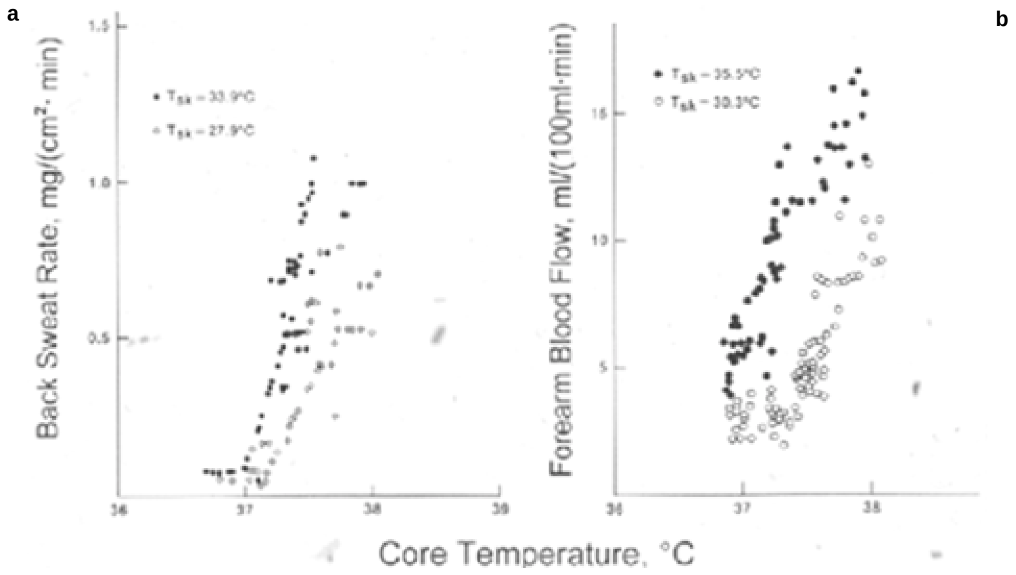

Fig. 2-10. The relations of (**a**) back (scapular) sweat rate and (**b**) forearm blood flow to core temperature and mean skin temperature ($\bar{T}_{sk}$). In the experiments shown, core temperature was increased by exercise. Adapted with permission from Sawka MN, Wenger CB. Physiological responses to acute exercise–heat stress. In: Pandolf KB, Sawka MN, Gonzalez RR, eds. *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes.* Indianapolis, Ind: Benchmark Press (now Cooper Publishing Group, Carmel, Ind); 1988: 101.

most entirely in the peripheral tissues (see Figure 2-2). For example, when someone enters a hot environment, his or her skin temperature rises and may elicit sweating even if there is no change in core temperature. On the other hand, an increase in heat production due to exercise elicits the appropriate heat-dissipating responses through a rise in core temperature.

Core temperature receptors involved in the control of thermoregulatory responses are concentrated especially in the hypothalamus,[42] but temperature receptors in other core sites, including the spinal cord and medulla, also participate.[42] The anterior preoptic area of the hypothalamus contains many neurons that increase their firing rate either in response to warming or in response to cooling, and temperature changes in this area of only a few tenths of a Centigrade degree elicit changes in the thermoregulatory effector responses of experimental mammals. Thermal receptors have been reported elsewhere in the core, including the heart, pulmonary vessels, and spinal cord; but the thermoregulatory role of core thermal receptors outside the central nervous system is not known.[8]

Let us consider what happens when a disturbance—say, an increase in metabolic heat production due to exercise—upsets the thermal balance. Heat is stored in the body, and core temperature rises. The thermoregulatory controller receives information about these changes from the thermal receptors, and responds by calling forth appropriate heat-dissipating responses. Core temperature continues to rise, and these responses continue to increase until they are sufficient to dissipate heat as fast as it is being produced, thus restoring heat balance and preventing further increases in body temperatures. The rise in core temperature that elicits heat-dissipating responses sufficient to reestablish thermal balance during exercise is an example of a *load error*[9]; a load error is characteristic of any proportional control system that is resisting the effect of some imposed disturbance or "load." Although the disturbance in this example was exercise, parallel arguments apply if the disturbance is a change in the environment, except that most of the temperature change will be in the skin and shell rather than in the core.

Relation of Effector Signals to Thermoregulatory Set Point

Both sweating and skin blood flow depend on core and skin temperatures in the same way, and changes in the threshold for sweating are accompanied by similar changes in the threshold for vasodilation.[4] We may therefore think of the central integrator (Figure 2-11) as generating one thermal command signal for the control of both sweating and skin blood flow. This signal is based on the information about core and skin temperatures that the integrator receives, and on the thermoregulatory *set point*.[4] We may think of the set point as the target level of core temperature, or the setting of the body's "thermostat." In the operation of the thermoregulatory system, it is a reference point that determines the thresholds of all the thermoregulatory responses.

Nonthermal Influences on Thermoregulatory Responses

Each thermoregulatory response may be affected by other inputs besides body temperatures and factors that affect the thermoregulatory set point. Nonthermal factors may produce a burst of sweating at the beginning of exercise,[43,44] and the involvement of sweating and skin blood flow in emotional responses is familiar to everyone.

Of the thermoregulatory responses that are important during heat stress, skin blood flow is most affected by nonthermal factors because of its involvement in reflexes that function to maintain cardiac output, blood pressure, and tissue oxygen delivery during heat stress, postural changes, and hemorrhage, and sometimes during exercise, especially in the heat.

Physiological and Pathological Changes to the Thermoregulatory Set Point

Several physiological and pathological influences change the thermoregulatory set point. Fever elevates core temperature at rest, heat acclimatization decreases it, and time of day and phase of the menstrual cycle change it in a cyclical fashion.[4–6] Core temperature at rest varies with time of day in an approximately sinusoidal fashion, reaching a minimum at night, several hours before awaking, and a maximum—which is one half to one Centigrade degree higher—in the late afternoon or evening (see Figure 2-3). Although this pattern coincides with patterns of activity and eating, it is independent of them, occurring even during bed rest and fasting. This pattern is an example of a *circadian* rhythm (ie, a rhythmic pattern in a physiological function with a period of about 1 day). During the menstrual cycle, core temperature is at its lowest point just before ovulation; over the next few days it rises one-half to one Centi-

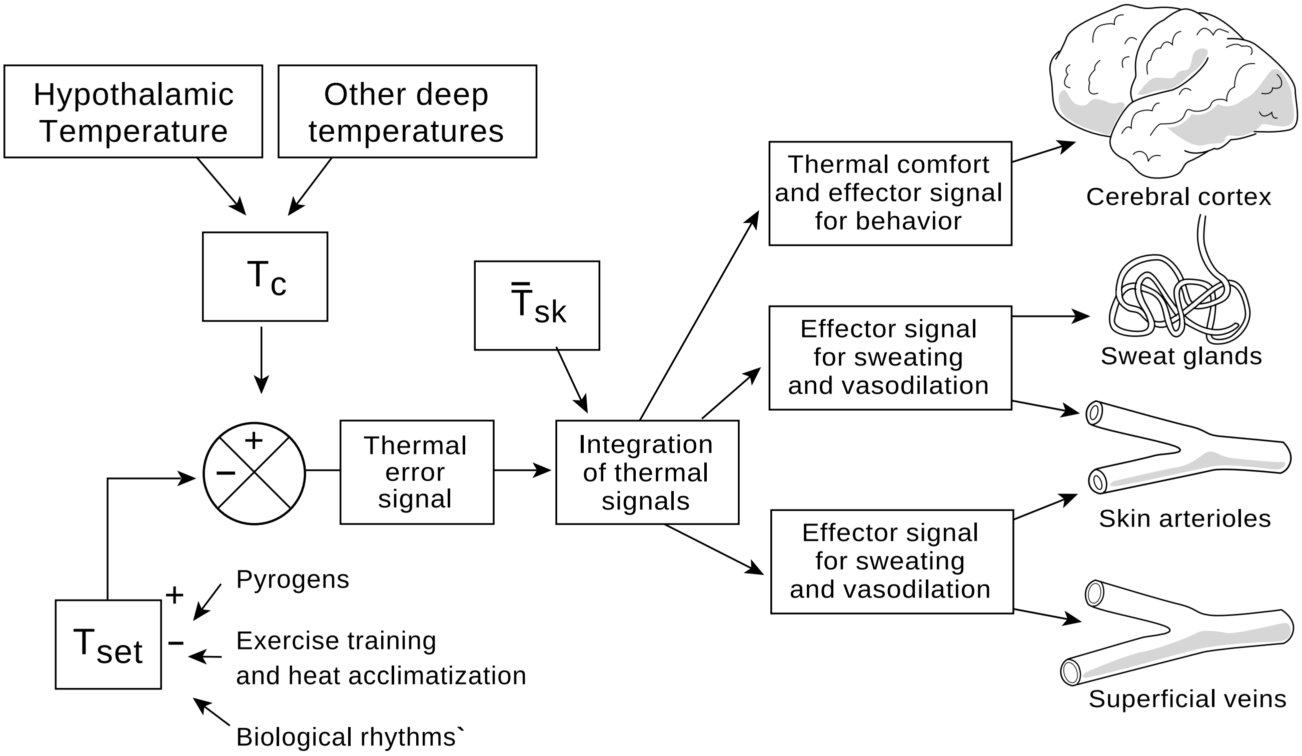

Fig. 2-11. Schematic diagram of the control of human thermoregulatory responses. The signs by the inputs to T_{set} indicate that pyrogens raise the set point, and heat acclimation lowers it. Core temperature, T_c, is compared with the set point, T_{set}, to generate an error signal, which is integrated with thermal input from the skin to produce effector signals for the thermoregulatory responses. Adapted with permission from Sawka MN, Wenger CB. Physiological responses to acute exercise-heat stress. In: Pandolf KB, Sawka MN, Gonzalez RR, eds. *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*. Indianapolis, Ind: Benchmark Press (now Traverse City, Mich: Cooper Publishing Group); 1988: 97–151.

grade degree and remains elevated for most of the luteal phase. Each of these factors—fever, heat acclimatization, the circadian rhythm, and the menstrual cycle—affects core temperature at rest by changing the thermoregulatory set point, thus producing corresponding changes in the thresholds for all the thermoregulatory responses.

Peripheral Modification of Skin Vascular and Sweat Gland Responses

The skin is the organ most directly affected by environmental temperature, and skin temperature affects heat loss responses not only through the reflex actions shown in Figure 2-10 but also through direct effects on the effectors themselves. Local temperature changes act on skin blood vessels in at least two ways. First, local cooling potentiates (and heating weakens) the constriction of blood vessels in response to nervous signals and vasoconstrictor substances.[36] Second, in skin regions where active vasodilation occurs, local heating dilates the blood vessels (and local cooling constricts them) through a direct action that is independent of nervous signals.[45,46] This effect is especially strong at skin temperatures above 35°C[46]; and when the skin is warmer than the blood, increased blood flow helps to cool the skin and protect it from heat injury.

The effects of local temperature on sweat glands parallel those on blood vessels, so that local heating magnifies (and local cooling reduces) the sweating response to reflex stimulation or to acetylcholine,[37] and intense local heating provokes sweating directly, even in sympathectomized skin.[47] During prolonged (several hours) heat exposure with high sweat output, sweat rates gradually diminish, and the sweat glands' response to locally applied cholinergic drugs is reduced also. The reduction of sweat gland responsiveness is sometimes called *sweat gland "fatigue."* Wetting the skin makes the stratum corneum swell, mechanically obstructing the sweat duct and causing a reduction in sweat secretion, an effect called *hidromeiosis*.[48] The glands' responsiveness can be at least partly restored if the skin is allowed to dry (eg, by increasing air movement[49]), but prolonged sweating also causes histological changes, including depletion of glycogen, in the sweat glands.[50]

THERMOREGULATORY RESPONSES DURING EXERCISE

Vigorous exercise can increase oxygen consumption and heat production within the body 10-fold or more, depending on the individual's aerobic fitness. Unless exercise is very brief, it is soon accompanied by increases in the heat-dissipating responses—skin blood flow and sweating—to counter the increase in heat production. Although hot environments also elicit heat-dissipating responses, exercise ordinarily accounts for the greatest demands on the thermoregulatory system for heat dissipation, and exercise provides an important example of how the thermoregulatory system responds to a disturbance in heat balance.

Exercise and thermoregulation impose competing demands on the circulatory system. Exercise requires large increases in blood flow to exercising muscle, and the thermoregulatory responses to exercise require increases in skin blood flow. Muscle blood flow is several times as great as skin blood flow during exercise, but the increase in skin blood flow involves disproportionately large demands on the cardiovascular system, as discussed below. Moreover, if the water and electrolytes lost through sweating are not replaced, the resulting reduction in plasma volume will eventually create a further challenge to cardiovascular homeostasis.

Restoration of Heat Balance During Exercise

Exercise increases heat production so that it exceeds heat loss and causes core temperature to rise. The increase in core temperature, in turn, elicits heat-loss responses, but core temperature continues to rise until heat loss has increased enough to match heat production, so that heat balance is restored and core temperature and the heat-loss responses reach new steady state levels. Because the heat-loss responses are proportional to the increase in core temperature, the increase in core temperature at steady state is proportional to the rate of heat production, and thus to the metabolic rate.

A change in ambient temperature changes the levels of sweating and skin blood flow that are needed to maintain any given rate of heat dissipation. However, the change in ambient temperature is accompanied by a skin temperature change that elicits, via both direct and reflex effects, much of the required change in these responses. For any given rate of heat production, there is a range of environmental conditions (sometimes called the "prescriptive zone"; see Chapter 3, Physical Exercise in Hot Climates: Physiology, Performance, and Biomedical Issues) within which ambient temperature changes elicit the necessary changes in heat-dissipating responses almost entirely through the effects of skin temperature changes, with virtually no effect on core temperature at steady state.[51] (The limits of this range of conditions depend on the rate of heat production, and on such individual factors as skin surface area and state of heat acclimatization.) Within this range, core temperature reached during exercise is nearly independent of ambient temperature; and for this reason it was once believed that the increase in core temperature during exercise is caused by an increase in the thermoregulatory set point,[52] just as during fever. As stated previously, however, the increase in core temperature with exercise is an example of a load error rather than an increase in set point. Note the following differences between fever and exercise (Figure 2-12):

- First, although heat production may increase substantially (through shivering) when core temperature is rising early during fever, it does not need to stay high to maintain the fever, but in fact returns nearly to prefebrile levels once the fever is established. During exercise, however, an increase in heat production not only causes the elevation in core temperature but is necessary to sustain it.
- Second, while core temperature is rising during fever, rate of heat loss is, if anything, lower than before the fever began; but during exercise, the heat-dissipating responses and the rate of heat loss start to increase early and continue increasing as core temperature rises. (Although in this chapter the term "fever" is used to mean specifically an elevation in core temperature due to pyrogens and occurring in connection with infection or other inflammatory process, some authors use "fever" more loosely to mean any significant elevation of core temperature.)

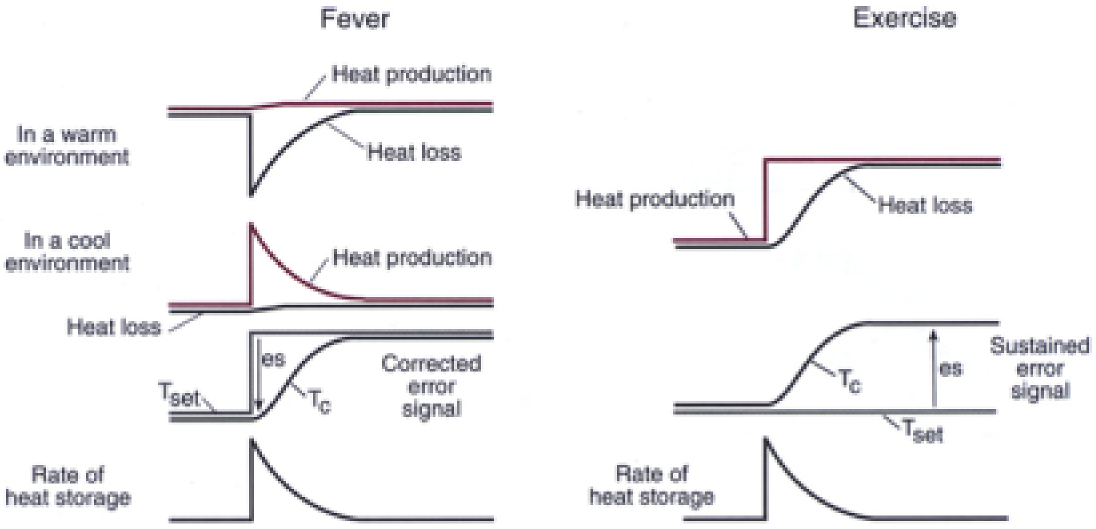

Fig. 2-12. Thermal events during the development of fever (left) and the increase in core temperature (T_c) during exercise (right). The error signal, es, is the difference between T_c and the set point, T_{set}. At the start of a fever, T_{set} has risen, so that T_{set} is higher than T_c, and es is negative. At steady state, T_c has risen to equal the new level of T_{set} and es is corrected (ie, it returns to zero). At the start of exercise, $T_c = T_{set}$ so that es = 0. At steady state, T_{set} has not changed but T_c has increased and is greater than T_{set}, producing a sustained error signal, which is equal to the load error. The error signal (or load error) is here represented with an arrow pointing down for $T_c < T_{set}$, and with an arrow pointing up for $T_c > T_{set}$. Adapted with permission from Stitt JT. Fever versus hyperthermia. *Fed Proc.* 1979;38:43.

Challenge of Exercise in the Heat to Cardiovascular Homeostasis

As pointed out earlier, skin blood flow increases during exercise in order to carry all of the heat that is produced to the skin. In a warm environment, where the temperature difference between core and skin is relatively small, the necessary increase in skin blood flow may be several liters per minute.

Impairment of Cardiac Filling

Whereas the work of supplying the skin blood flow required for thermoregulation in the heat may represent a heavy burden for a patient with cardiovascular disease,[53] in healthy subjects the primary cardiovascular burden of heat stress results from impairment of venous return.[29,30,54] As skin blood flow increases, blood pools in the large, dilated cutaneous vascular bed, thus reducing central blood volume and cardiac filling (Figure 2-13). Because stroke volume is decreased, a higher heart rate is required to maintain cardiac output. These effects are aggravated by a decrease in plasma volume if the large amounts of salt and water lost in the sweat are not replaced. Because the main cation in sweat is sodium, disproportionately much of the body water lost in sweat is at the expense of extracellular fluid, including plasma, although this effect is mitigated if the sweat is dilute.

Compensatory Cardiovascular Responses

Several reflex adjustments help to maintain cardiac filling, cardiac output, and arterial pressure during exercise and heat stress. The cutaneous veins constrict during exercise; and because most of the vascular volume is in the veins, constriction makes the cutaneous vascular bed less compliant and reduces peripheral pooling. Splanchnic and renal blood flow are reduced in proportion to the intensity of the exercise or heat stress. This reduction of blood flow has two effects. First, it allows a corresponding diversion of cardiac output to skin and exercising muscle. Second, because the splanchnic vascular beds are very compliant, a decrease in their blood flow reduces the amount of blood pooled in them[29,30] (see Figure 2-13), helping to compensate for decreases in central blood volume caused by reduced plasma volume and blood pooling in the skin. Because of the essential thermoregulatory function of skin blood flow during exercise and heat stress, the body preferentially compromises splanchnic and renal flow to maintain cardiovascular homeostasis.[55] Above a certain level of cardiovascular strain, however, skin blood flow, too, is compromised.

Despite these compensatory responses, heat stress markedly increases the thermal and cardiovascular strain that exercise produces in subjects

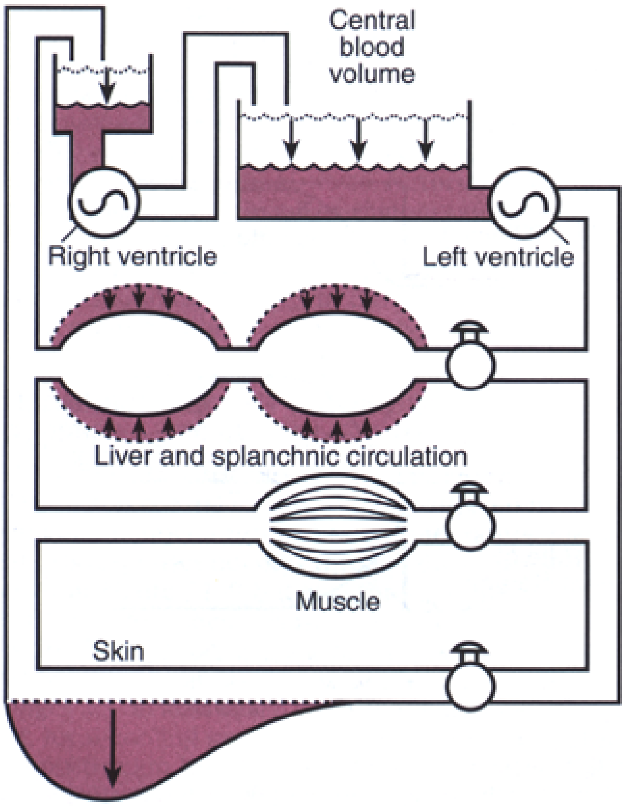

Fig. 2-13. Schematic diagram of the effects of skin vasodilation on peripheral pooling of blood and the thoracic reservoirs from which the ventricles are filled, and also the effects of compensatory vasomotor adjustments in the splanchnic circulation. The valves drawn at the right sides of liver/splanchnic, muscle, and skin vascular beds represent the resistance vessels that control blood flow through those beds. Arrows show the direction of the changes during heat stress. Adapted with permission from Rowell LB. Cardiovascular aspects of human thermoregulation. *Circulation Res*. 1983;52:367–379.

who are unacclimatized to heat. A comparison of responses on the first day of exercise on hot days with those on cool days shows some effects of unaccustomed environmental heat stress on the responses to exercise (Figure 2-14[56]). On the first day in the heat, heart rate during exercise reached a level about 40 beats per minute higher than in the cool environment, to help compensate for the effects of impaired cardiac filling and to maintain cardiac output; and rectal temperature during exercise rose one Centigrade degree higher than in the cool environment. Other effects of exercise–heat stress may include headache, nausea and vomiting secondary to splanchnic vasoconstriction, dizziness, cramps, shortness of breath, dependent edema, and orthostatic hypotension.

During prolonged exercise there is a gradual "drift" in several cardiovascular and thermoregulatory responses. This may include a continuous rise in heart rate, accompanied by a fall in stroke volume and reductions in aortic, pulmonary arterial, and right ventricular end-diastolic pressures.[57] Rowell named these changes "cardiovascular drift," and thought of them as appearing as early as after 15 minutes of exercise.[57] He and Johnson[57,58] empha-

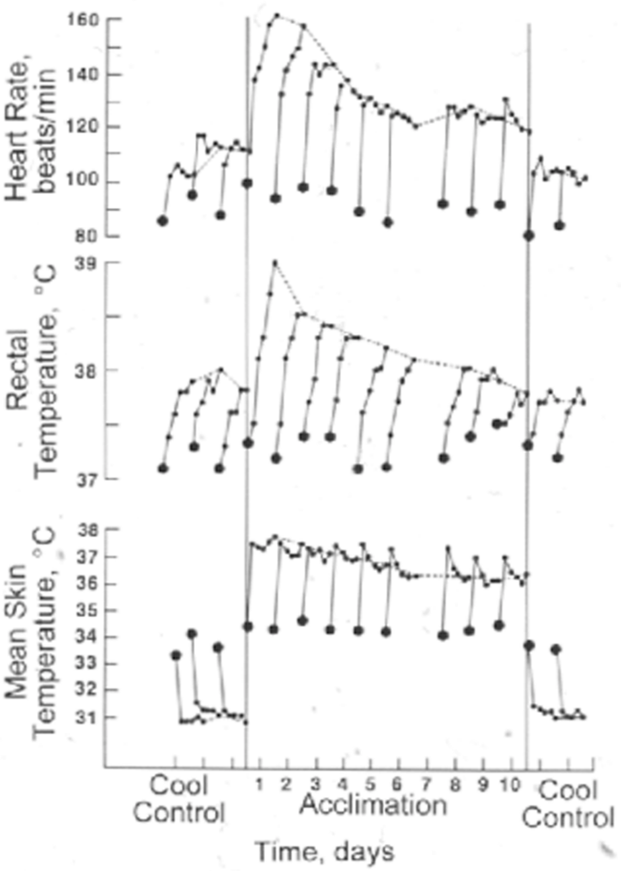

Fig. 2-14. Change in the responses of heart rate, rectal temperature, and mean skin temperature during exercise in a 10-day program of acclimation to dry heat (50.5°C, 15% relative humidity [rh]), together with responses during exercise in a cool environment before and after acclimatization. (The "cool control" conditions were 25.5°C, 39% rh.) Each day's exercise consisted of five 10-minute treadmill walks at 2.5 mph (1.12 m/s) up a 2.5% grade. Successive walks were separated by 2-minute rest periods. Large circles show values before the start of the first exercise period each day, small circles show values at the ends of successive exercise periods, and dotted lines connect final values each day. Adapted with permission from Eichna LW, Park CR, Nelson N, Horvath SM, Palmes ED. Thermal regulation during acclimatization in a hot, dry (desert type) environment. *Am J Physiol.* 1950;163:588.

sized the role of thermoregulatory increases in skin blood flow in producing cardiovascular drift. However, later authors[59–61] have described, as part of the picture of cardiovascular drift, an upward creep in core temperature, which may begin only after a period of apparent thermal steady state (eg, after 30–60 min of exercise). In some of these studies, most but not all of the changes in cardiovascular and thermoregulatory responses could be prevented by replacing fluid lost in sweat, suggesting that these changes were mostly secondary to changes in plasma volume and osmolality due to sweating. Other factors that may affect cardiovascular and thermoregulatory function during prolonged exercise include changes in myocardial function, changes in baroreceptor sensitivity or peripheral α-adrenergic receptor responsiveness (see Tibbits[62] and Raven and Stevens[63] for a discussion of these effects), or an upward adjustment of the thermoregulatory set point,[64] presumably due to some sort of inflammatory response and perhaps elicited by products of muscle injury. These effects have not been investigated extensively, and little is known about the underlying physiological or pathological mechanisms. Some of these effects have been reported only after several hours of exercise or near exhaustion, and little is known about the conditions of exercise duration and intensity required to produce them and their persistence after the end of exercise. Although their functional significance is, as yet, only poorly understood, these changes may be important in limiting performance during prolonged strenuous activity, such as forced marches.

FACTORS THAT ALTER HEAT TOLERANCE

Heat Acclimatization

Prolonged or repeated exposure to stressful environmental conditions elicits significant physiological changes, called *acclimatization,* which reduce the physiological strain that such conditions produce. (The nearly synonymous term, *acclimation,* is often applied to such changes produced in a controlled experimental setting.[12]) Figure 2-14 illustrates the development of these changes during a 10-day program of daily treadmill walks in the heat. Over the 10 days, heart rate during exercise decreased by about 40 beats per minute, and rectal and mean skin temperatures during exercise decreased more than 1°C. Because skin temperature is lower after heat acclimatization than before, dry (nonevaporative) heat loss is less (or, if the environment is warmer than the skin, dry heat gain is greater). To compensate for the changes in dry heat exchange, evaporative heat loss—and thus sweating—increases. The three classic signs of heat acclimatization are

- lower heart rate,
- lower core temperature, and
- higher sweat rate during exercise–heat stress.

Other changes include

- an increased ability to sustain sweat production during prolonged exercise-heat stress, which is essential to increasing tolerance time;
- decreased solute concentrations in sweat;
- redistribution of sweating from trunk to limbs;
- increases in total body water and changes in its distribution;
- metabolic and endocrine changes; and
- other poorly understood changes that protect against heat illness.

The overall effect of heat acclimatization on performance can be quite dramatic, so that acclimatized subjects can easily complete exercise in the heat, which previously was difficult or impossible. Figure 3-22 in Chapter 3, Physical Exercise in Hot Climates: Physiology, Performance, and Biomedical Issues, in this textbook graphically shows the day-to-day improvement in performance during a 7-day program of heat acclimation.

At any given air temperature, increasing the humidity impedes evaporation of sweat (see Equation 6). To allow sweat to evaporate rapidly enough to maintain heat balance, the wetted area of skin must increase. The distribution of sweating may change to allow more of the skin surface area to be wetted, but wetter skin also favors development of hidromeiosis, limiting tolerance time by hampering maintenance of high sweat rates. Although heat acclimatization in a dry environment confers a substantial advantage in humid heat,[65,66] acclimatization in humid heat produces somewhat different physiological adaptations, corresponding to the characteristic physiological and biophysical challenges of humid heat.

Acquisition and Loss

A degree of heat acclimatization is produced either by heat exposure alone or by regular strenuous exercise, which raises core temperature and provokes heat-loss responses. Indeed, the first summer heat wave produces enough heat acclimatization that after a few days most people notice an improvement in their feelings of energy and general well-being. However, the acclimatization response is greater if heat exposure and exercise are combined, causing a greater rise of internal temperature and more profuse sweating. Up to a point, the degree of acclimatization acquired is proportional to the daily heat stress and the amount of sweat secreted during acclimatization,[67] but full development of exercise–heat acclimatization does not require continuous heat exposure.

Continuous, daily 100-minute periods of heat exposure with exercise are widely considered sufficient to produce an optimal heat acclimatization response in dry heat. However, this notion is based chiefly on one study,[68] in which subjects' responses were evaluated only during 100-minute heat exposures, which provide little information about their ability to sustain heat-loss responses over time. An adequate assessment of heat tolerance may, in fact, require an exposure lasting several hours. For example, Strydom and Williams[69] compared responses of two groups of subjects during 4 hours of exercise in humid heat. Although the groups' responses were indistinguishable during the first hour, the responses of the more heat-tolerant group were clearly different from those of the less heat-tolerant group during the third and fourth hours.

Several factors affect the speed of development of heat acclimatization. However, most of the improvement in heart rate, skin and core temperatures, and sweat rate typically is achieved during the first week of daily exercise in a hot environment, although there is no sharp end to the improvement.[70] Heart rate shows the most rapid reduction,[71–73] most of which occurs in 4 to 5 days.[71] After 7 days, the reduction in heart rate is virtually complete and most of the improvement in skin and core temperatures has also occurred[72,74]; and the thermoregulatory improvements are generally believed to be complete after 10 to 14 days of exposure.[75] The improved sweating response[71,74] and ease of walking[72,74] reported during heat acclimatization may take 1 month to develop fully, and resistance to heatstroke may take up to 8 weeks.[76] Experimental heat acclimation (physiological adjustment to an environment, in a controlled setting) develops more quickly in warm weather,[66] probably because subjects are already partly acclimatized.

High aerobic fitness hastens development of acclimatization.[72,77] Aerobic exercise elevates core temperature and elicits sweating even in a temperate environment, and aerobic training programs involving exercise at 70% of maximal oxygen uptake ($\dot{V}O_2max$) or more[78,79] produce changes in the control of sweating similar to those produced by heat acclimatization. There has, however, been much disagreement as to whether or not aerobic training in a temperate environment induces true heat acclimatization. In a critical review of the evidence and arguments on both sides of the issue, Gisolfi and Cohen[80] concluded that exercise training programs lasting 2 months or more in a temperate environment produce substantial improvement in exercise heat tolerance. However, exercise training alone has not been shown to produce a maximal state of exercise–heat tolerance.

The benefits of acclimatization are lessened or undone by sleep loss, infection, and alcohol abuse[71,81]; salt depletion[71]; and dehydration.[71,82,83] Heat acclimatization gradually disappears without periodic heat exposure, although partial losses due to a few days' lapse are easily made up.[81] The improvement in heart rate, which develops more rapidly, also is lost more rapidly than are the thermoregulatory improvements.[68,77,84,85] However, there is much variability in how long acclimatization persists. In one study, for example, acclimatization almost completely disappeared after 17 days without heat exposure[86]; but in another study, approximately three quarters of the improvement in heart rate and rectal temperature was retained after 18 days without heat exposure.[77] Physically fit subjects retain heat acclimatization longer[65,66]; and warm weather may[66] or may not[85] favor persistence of acclimatization, although intermittent exposure to cold seems not to hasten the loss of heat acclimatization.[87]

Changes in Thermoregulatory Responses

After acclimatization, sweating during exercise starts earlier and the core temperature threshold for sweating is lowered. Acclimatization also increases the sweat glands' response to a given increment in core temperature and also their maximum sweating capacity. These latter changes reflect changes in the individual glands rather than in the nervous systems signals to the glands, because after acclimatization the glands also produce more sweat when stimulated with methacholine,[88,89] which mimics the effect of acetylcholine.

In an unacclimatized person, sweating is most profuse on the trunk; but during acclimatization in humid heat, the fraction of sweat secreted on the limbs increases,[90–93] enabling an acclimatized person to make better use of the skin surface for evaporation and achieve higher rates of evaporative heat loss. During a heat stress lasting several hours, sweat rates that were initially high tend gradually to decline as the heat stress continues. Although several mechanisms may contribute to the decline, much of the decline is due to hidromeiosis, associated with wetness of the skin, and the decline is most pronounced in humid heat. After acclimatization to humid heat, this decline of sweat rate occurs more slowly[67] (Figure 2-15), so that higher sweat rates can be sustained and tolerance time is prolonged. This effect of acclimatization appears to act directly on the sweat glands themselves, and during acclimatization to dry heat it can be produced selectively on one arm by keeping that arm in a humid microclimate (eg, inside a plastic bag).[94]

Because heat acclimatization is an example of a set-point change,[4,95] thresholds for sweating and cutaneous vasodilation both are reduced in such a way that vasodilation and the onset of sweating accompany each other after acclimatization in the same way as before,[96] and heat transfer from core to skin is maintained at the lower levels of core and skin temperature that prevail after acclimatization. These changes by themselves say nothing about the effect of acclimatization on the levels of skin blood flow reached during exercise–heat stress. In many studies[56,97] (especially those using dry heat), heat acclimatization was found to widen the core-to-skin temperature gradient, presumably allowing heat balance to be reached with a lower level of skin blood flow and a lesser cardiovascular strain. Even in relatively dry heat, however, acclimatization to heat does not always widen the core-to-skin temperature gradient.[72]

Nonthermoregulatory Changes

On the first day of exercise in the heat, heart rate reaches much higher levels than in temperate conditions (see Figure 2-14), and stroke volume is lower. Thereafter, heart rate decreases and stroke volume usually, but not always, increases. Orthostatic tolerance also improves with heat acclimatization.[95] Several mechanisms participate in these changes, but their relative contributions are not known and probably vary. Plasma volume at rest expands during the first week of acclimatization and contributes to the reduction in heart rate and circulatory strain; however, if acclimatization continues, plasma volume at rest returns toward control levels after 1 or 2 weeks,[74,98–100] whereas the improvements in cardiovascular function persist. In addition, it is likely that a decrease in peripheral pooling of blood helps to support cardiovascular function in acclimatized subjects. When a decrease in skin blood flow (which is allowed by a widened core-to-skin temperature gradient) occurs, it presumably decreases peripheral pooling of blood. In addition, an increase in venous tone might substantially decrease pooling of blood, since venoconstriction can mobilize up to 25% of the blood volume.[98] The information available about such changes,[101–103] however, is very limited and far from conclusive.

Heat acclimatization increases total body water, but there is much variability both in the total increase and in its distribution among the various fluid compartments.[95] Much of the increase is accounted for by an expansion of plasma volume at rest, which develops rapidly at first and continues more slowly for about a week. The resulting increase in blood volume ranges from 12% to 27%.[104] The mechanisms responsible for this expansion are unclear, but may include an increase in extracellular fluid—ranging from 6% to 16%[104]—due to salt

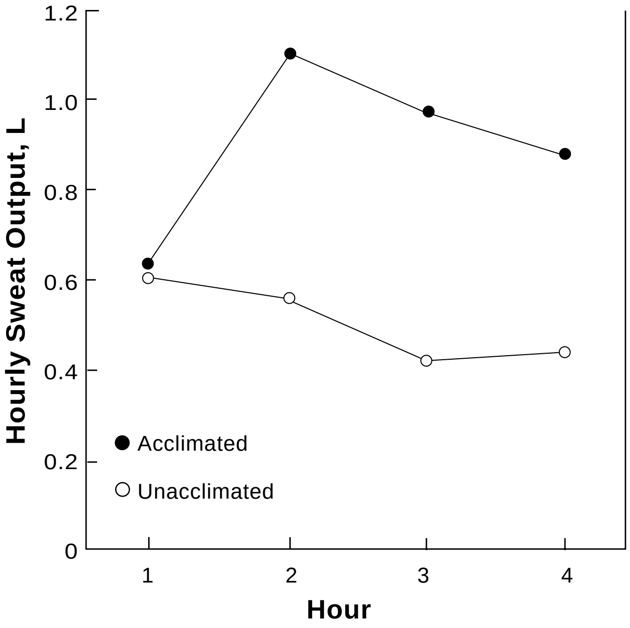

Fig. 2-15. Sweat rates during 4 hours' exercise (bench stepping, 35-W mechanical power) in humid heat (33.9°C dry bulb, 89% relative humidity, 35 mm Hg ambient vapor pressure) on the first and last days of a 2-week program of acclimatization to humid heat. Adapted with permission from Wyndham CH, Strydom NB, Morrison JF, et al. Heat reactions of Caucasians and Bantu in South Africa. *J Appl Physiol.* 1964;19:601.

retention, and a net fluid shift from interstitial space to plasma due to an increase in the mass of protein in the plasma.[105,106]

At the start of acclimatization, secretion of adrenocorticotropic hormone (ACTH) increases in response to the circulatory strain caused by heat stress. The adrenal cortex responds to ACTH by increasing secretion of cortisol and aldosterone. If salt intake is insufficient to replace losses in sweat, the resulting sodium depletion also acts via the renin–angiotensin system to increase aldosterone secretion. Cortisol and aldosterone both contribute to sodium retention: by the kidneys within a few hours, and by the sweat glands after 1 to 2 days. Exercise and heat stress also elicit secretion of aldosterone[107,108] through the renin–angiotensin system. Within a few days the sodium-conserving effects of aldosterone secreted via this pathway are sufficient to restore and maintain sodium balance, and ACTH secretion returns to normal. Depending on sodium intake, the kidneys may eventually "escape" the effects of aldosterone and excrete as much sodium as needed to maintain sodium balance. The sweat glands, however, do not escape but continue to conserve sodium as long as acclimatization persists.

An unacclimatized person may secrete sweat with a sodium concentration as high as 60 mEq/L, corresponding to 3.5 grams of NaCl per liter, and can lose large amounts of salt in the sweat (Figure 2-16). With acclimatization, the sweat glands conserve sodium by secreting sweat with a sodium concentration as low as 5 mEq/L.[27] Acclimatized men in whom sodium conservation is maximally developed can sweat up to 9 L/d and stay in salt balance on 5 grams of NaCl per day.[109,110] Maximal development of sodium-conserving capacity was accomplished with a program that combined gradual reduction of dietary sodium intake with daily exercise in the heat. However, most whites who are not secreting large volumes of sweat and are in salt balance with an intake of 10 grams of NaCl per day (a typical intake for a western diet) have high concentrations of sodium in the sweat.[111] If suddenly required to secrete large volumes of sweat, they may undergo a substantial net loss of sodium before their mechanisms for sodium conservation become fully active. Therefore, subjects who are exercising in a hot environment and are either unacclimatized or not consuming a normal diet should receive 10 grams of supplemental salt per day unless water is in short supply.[111] However, salt supplements are not recommended for acclimatized subjects performing heavy exercise in the heat if they are eating a normal diet and are not salt depleted.

Fig. 2-16. Salt deposited on a soldier's uniform by evaporation of sweat. Photograph: Courtesy of Robert E. Burr, MD, Natick, Massachusetts.

The mineralocorticoids, aldosterone and desoxycorticosterone, have been administered to subjects just before or during heat acclimatization programs.[98,104,112,113] Mineralocorticoid administration produced some responses characteristic of heat acclimatization, but neither produced a state equivalent to what the subjects attained as a result of undergoing heat acclimatization nor reduced the time necessary to reach that state. However, because of the way these studies were designed, their results do not support definite conclusions about the role of endogenous aldosterone in heat acclimatization.[95]

Effects on Heat Disorders

The harmful effects of heat stress operate through cardiovascular strain, fluid and electrolyte loss, and, especially in heatstroke, tissue injury whose mechanism is not well understood but evidently involves more than just high tissue temperatures. The topic is also discussed in Hubbard[114] and in Chapter 5, Pathophysiology of Heatstroke, in this textbook.

Heat syncope is a temporary circulatory failure due to pooling of blood in the peripheral veins and the resulting decrease in diastolic filling of the heart. Although a large increase in thermoregulatory skin blood flow is the direct cause of the peripheral pooling, an inadequate baroreflex response is probably an important contributing factor. Heat acclimatization rapidly reduces susceptibility to heat syncope, as expected from the improvement in orthostatic tolerance,[101,115,116] noted earlier.

Like heat syncope, heat exhaustion is believed to result from a decrease in diastolic filling. However, dehydration with resulting hypovolemia has a major role in the development of heat exhaustion; the baroreflex responses usually are strong enough to prevent syncope, and also account for much of the symptomatology. Little is known about the effect of acclimatization on susceptibility to heat exhaustion.

Heatstroke is the most severe heat disorder; and without prompt, appropriate treatment, mortality may be high. Typical victims of the exertional form, in which a high rate of metabolic heat production is a primary pathogenic factor, are athletes or military personnel—especially recruits. During World War II, the incidence of fatal heatstroke was low after 8 weeks of training,[76] by which time the recruits were well acclimatized. Much of the protective effect of acclimatization is presumably owing to thermoregulatory improvement, but acclimatization and physical conditioning may also protect in ways that are poorly understood, since rectal temperatures above 41°C have been measured in runners competing in marathons with no apparent ill effect.[117,118]

A small proportion of apparently healthy individuals cannot acclimatize to heat.[119,120] In South African gold-mining recruits (the population studied most extensively in this regard) individuals who do not acclimatize are, on average, smaller, older, and less aerobically fit than those who do.[120]

Physical Fitness, Gender, and Age

Individuals with low physical fitness tend to have reduced heat tolerance and less sensitive sweating responses. Obesity also is associated with reduced heat tolerance. To a large extent, the effect of obesity is explained by its relation to physical fitness, but other factors contribute as well.[121]

Women as a group are less tolerant to exercise–heat stress than men. However, the gender difference largely disappears when subjects are matched according to size, acclimatization, and $\dot{V}O_2max$.[121] The exertional form of heatstroke is often said to be quite rare in women,[122] and perhaps women enjoy a degree of protection against exertional heatstroke for either physiological or behavioral reasons. Women are susceptible to exertional heatstroke, however, and in active-duty soldiers (a population in which most heatstroke is of the exertional type), annual incidence rates of heatstroke in women are at least half of those in men.[123] Although the thermoregulatory set point changes with the phase of the menstrual cycle, as discussed earlier, the phase of the menstrual cycle has not been shown to affect tolerance or performance during exercise in the heat (for a review, see Stephenson and Kolka[124]). It may be, however, that studies of exercise at different phases of the menstrual cycle have not used exercise of sufficient intensity or duration to demonstrate an effect. In fact, Pivarnik and associates,[125] studying women's responses during exercise in a temperate environment (22°C), found that after 60 minutes of exercise heart rate was 10 beats per minute higher in the luteal phase than in the follicular; and that rectal temperature increased 1.2 Centigrade degrees in the luteal phase and was still rising, while it increased 0.9 Centigrade degrees in the follicular phase and was near steady state. Although they examined only one set of experimental conditions, their data, when extrapolated to warmer environments, suggest a decline in tolerance to exercise–heat stress during the luteal phase. Advancing age also is associated with a decline in heat tolerance. Most of the decline disappears, however, if effects of chronic disease, adiposity, and reduced physical fitness are eliminated.[126]

Drugs and Disease

Many drugs inhibit sweating, most prominently those used for their anticholinergic effects, such as atropine and scopolamine. Intramuscular injection of 2 mg atropine (the dose in one autoinjector for acute treatment of exposure to nerve agent) inhibits sweating sufficiently to cause a noticeable impairment of thermoregulation during walking in dry heat.[127] Some drugs used for other purposes, such as glutethimide (a sleep medicine), tricyclic antidepressants, and phenothiazines (tranquilizers and antipsychotic drugs) also have some anticholinergic action; and all of these, plus several others, have been associated with heatstroke.[128,129] A 30-mg oral dose of pyridostigmine bromide (the dose given thrice daily for pretreatment against nerve agent) reduced thermoregulatory vasodilation during moderate exercise in a warm environment,[130] and may potentially impair thermoregulation under more severe heat-stress conditions.

Both chronic and acute disorders may reduce heat tolerance. Untreated hypertension impairs the circulatory responses to heat stress. The effect of treated hypertension on heat tolerance is not known, but there are theoretical reasons for suspecting that some drugs used to treat hypertension may impair heat tolerance.[121] Congestive heart failure substantially impairs both sweating and the circulatory responses to heat stress, and moderate heat exposure worsens the signs and symptoms of congestive heart failure.[53] Neurological diseases involving the thermoregulatory structures in the brainstem can impair thermoregulation. Although hypothermia may result, hyperthermia is more usual and typically is accompanied by loss of sweating and the circadian rhythm. Several skin diseases impair sweating sufficiently that heat exposure, especially combined with exercise, may produce dangerously high body temperatures. Ichthyosis and anhidrotic ectodermal dysplasia can profoundly limit the ability to thermoregulate in the heat. In addition, heat rash (miliaria rubra)[131] and even mild sunburn[132] impair sweating and may reduce tolerance to exercise in the heat. The thermoregulatory effects of heat rash may persist for a week or longer after the appearance of the skin has returned to normal.[131]

SUMMARY

The body may be divided into an internal core, which includes the vital organs, and a superficial shell. Tissue temperature is fairly uniform throughout the core. Core temperature is regulated by the thermoregulatory system and is relatively unaffected by changes in environmental conditions. The temperature of the shell is not uniform, and varies both from point to point within the shell and with changes in environmental conditions. Most heat exchange between the body and the environment occurs at the skin surface, by convection, radiation, and evaporation. These three modes of heat exchange depend on the temperature and degree of wetness of the skin, and on environmental conditions including air movement, the temperature and moisture content of the air, and the temperatures of radiating surfaces in the environment.

The body controls heat flow between core and skin by controlling skin blood flow. Changes in skin blood flow affect skin temperature, and thus controlling skin blood flow provides a means of influencing heat exchange with the environment by convection and radiation. However, the effect of skin blood flow on heat exchange with the environment is limited in the heat, and the body cannot dissipate heat by convection and radiation if the environment is warmer than the skin. Secretion of sweat wets the skin, and sweating increases evaporative heat loss, as long as the environmental conditions allow the sweat to evaporate. Large amounts of heat can be dissipated by evaporation of sweat: sweat rates of 1L/h (corresponding to a rate of heat loss of about 675 W) can be sustained for many hours, and higher rates can be achieved for shorter periods.

Sweating and skin blood flow are controlled via the sympathetic nervous system, and these responses are graded according to elevations in core and skin temperatures. The operation of the thermoregulatory system is governed by the thermoregulatory set point, which we may think of as the setting of the body's "thermostat." The set point varies in a cyclical fashion, with an amplitude of 0.5 to 1.0 Centigrade degrees, according to time of day and, in women, the phase of the menstrual cycle, and it is elevated during fever.

Vigorous exercise can increase heat production within the body 10-fold or more. Because of the levels of skin blood flow needed for high rates of heat dissipation in a hot environment, exercise and heat dissipation make competing demands on the cardiovascular system. Moreover, if water and electrolytes lost as sweat are not replaced, plasma volume eventually is depleted. For these reasons, heavy exercise in the heat may seriously challenge cardiovascular homeostasis.

Heat tolerance is increased by aerobic exercise training and by acclimatization to heat. Acclimatization to heat develops quickly: the effectiveness of the heat-dissipating arm of the thermoregulatory system and exercise performance in the heat show pronounced improvements within a week. Conversely, poor physical fitness and certain disease states and drugs are associated with impairment of the thermoregulatory responses.

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