THERMOREGULATION AND ACCLIMATIZATION

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Thermal Regulation in the Human Organism

Ecology is the branch of biology that deals with the relations between living organisms and their environments. Today, it is widely recognized that an organism is at the center of an *ecosystem.* As such, it is influenced by a multitude of physical and biological environmental factors. It is the essence of living things to be part of an ecosystem and yet to be capable of resisting, to some extent, the impact of the environment (Prosser, 1964).

Organisms progress in complexity from a clump of cells that must closely conform to the conditions of their environment to more highly organized accumulations of soft tissues and organs that are capable of independent action. No organism's internal composition is exactly similar to its environment. Regulating organisms are capable of maintaining a relatively constant internal condition *(homeostasis)* despite widely fluctuating environmental conditions. The internal conditions of conforming organisms, on the other hand, are more closely restricted to the conditions of the surrounding environment.

The human is an excellent example of a regulating organism that is able to maintain a relatively constant internal temperature when exposed to a wide range of environmental conditions. Because of this ability, the human is referred to as a *homeotherm,* or warm-blooded animal, rather than as a *poikilotherm,* or cold-blooded animal. Regulating organisms are generally capable of living in more widely divergent environments (ecosystems) than organisms that conform to their environments. The limits of survival for the organism are defined in terms of its environment. Because the organism conforms closely to its environment, it cannot survive extreme variations in that environment. In general, the *range of internal variation* tolerable to a conforming organism is somewhat greater than for a regulating organism (Prosser, 1964). Regulating organisms do not conform to its environment but instead is capable of regulating its internal environment. As such, the regulating organism, which has a narrower internal variation, is able to survive in a wider environmental range.

The temperature of the human body oscillates in a more or less regular pattern around an average value of 37 °C/98.6 °F. Deep internal organs that are highly active metabolically-such as the heart, brain, liver, and kidney-have much higher temperatures than peripheral tissues. With strenuous muscular exertion, muscle temperatures rise, blood flow patterns change, and excess metabolic heat is distributed more extensively throughout the body. Body surface temperatures vary widely depending on such factors as metabolic heat load, subcutaneous blood flow patterns, ambient temperature, radiant heat load, secretion of sweat, convective air currents about the body, and relative humidity of the air. All these variables play a role in regulating body core temperature within a rather narrow range. A deep body core temperature of 41 °C (106 °F) is often fatal, but 42 °C (107.6 °F) has been tolerated for a few hours (Folk, 1974, p. 218). Heavy physical exercise has been known to elevate body core temperatures to about 40 °C (104 °F). The lowest core temperature recorded was 17.7 °C (64 °F), with a respiration rate of three breaths per minute (Folk, 1974, p. 135).

Mechanisms of Temperature Regulation

In humans, thermal regulation is apparently under the control of the hypothalamus. Sometimes referred to as the human thermostat, this organ is located just superior to the optic nerve at the base of the brain stem. The hypothalamus is thought of as the master gland of the body. In the case of temperature regulation , it acts as a thermal sensor, an integrator of information from other locations in the body, and as a controller of various effector mechanisms, which are always ready to either increase or decrease the body's ability to conserve or dissipate heat. The hypothalamus senses the temperature of the blood flowing through it and possible receives information from other parts of the body.

The exact role of extrahypothalamic thermal receptor organs is controversial. Deep core receptors have been postulated but not verified in humans. Warm and cold receptors have been located in skin tissue, but there is no agreement as to their role in thermoregulation. It is possible that these receptors send information to the conscious areas of the brain to tell us about our skin temperatures but that they play a relatively unimportant role in thermoregulation. There may also be peripheral temperature receptors in the deep veins that drain the musculature.

The integrative function of the hypothalamus is thought to compare sensed information with set-point temperature like an electrical thermostat. If this integrated information reveals that the body temperature is above the set-point, then neural discharge from the anterior area of the hypothalamus is increased and effector mechanisms that help dissipated heat from the tissues such as vasodilation and sweating are initiated.

The principle question about this theoretical model is: What sets the set-point? The answer is enigmatic. Fever disrupts the normal set-point as a pyrogen (viral or bacterial agent) affects the hypothalamus such that the set-point is elevated above its usual range. Antipyrogenic agents such as aspirin restore the normal set-point by destroying or inhibiting the pyrogen.

The hypothalamic set-point is not an absolute constant; it may change under many physiological and environmental conditions. For example, diurnal (day to night) and menstrual (follicular to luteal phase) variations are observed. A prominent pattern I s a low early morning and high late afternoon pattern. This corresponds to the usual light-dark cycle and the usual patterns of metabolic activity. Women have a slightly higher core temperature during the second half of the monthly menstrual cycle. This elevation in temperature may be due to the anabolic effects of progesterone, but the exact mechanism, is unknown.

Before examining the physiological role of the effector mechanisms in body temperature regulation, we will discuss the physical avenues of heat exchange. These are the physical processes by which heat can be transferred or transported from one tissue to another, from one space to another, from the environment to the body, or conversely, from the body to the environment.

Avenues of Heat Exchange

Thermal balance can best be understood by the law of conservation of energy. Simply, this law states that for a system to be in thermal balance, all avenues of heat gain or loss must quantitatively balance to zero.

$M \pm S - E \pm C_o \pm C_v \pm R \pm W = 0$ or thermal balance

Sources of heat loss or gain:

- M= metabolic heat production
- S = thermal state of body (storage)
- E = evaporative heat loss
- C_o = conduction (loss or gain)
- C_v = convection
- R = radiation
- W = work

When balanced, all should equal zero

Metabolic Heat Production

Metabolic heat production (M) is the body's only means of heat production and as such is really not an avenue of heat exchange. It is the total energy released by all anaerobic and aerobic processes and is most often determined by measuring oxygen uptake, calculating the respiratory exchange ratio, and multiplying by the appropriate kilocalorie factor for consumed oxygen. Metabolic heat production can be elevated voluntarily by exercise and involuntarily by shivering. Some persons can lower their metabolic heat production by entering a deep meditative state, but most of us have not developed our capacity to do so.

Radiation

Radiation (R) is the exchange of electromagnetic energy waves emitted from one object and absorbed by another. The solar heat gain on a clear summer day is the most obvious example of radiant heat exchange. Another example is the loss of heat from the earth on a clear cool night. Globe temperature is often used to measure radiant temperature. A 6-in diameter copper sphere painted flat black is suspended with a thermometer sealed inside so that the sensory section is located exactly in the center. The black globe represents an "ideal black body," which is an object that absorbs all the radiation that falls on it. The emittance of a black body is by definition equal to 1 in all temperatures. The emittance of a non-black body varies with temperature. The human body is very close to an ideal black body, because it absorbs nearly all the radiation that falls on it. For that reason it is a good idea to be lightly but fully clothed when directly exposed to sunlight. Clothed individuals sitting in the sun gain only about half as much: heat as unclothed persons. Desert clothing has traditionally been white, which reflects *more* heat and absorbs *less* heat than does the skin or dark-colored clothing. Skin color has been reported to affect the amount of solar radiation absorbed. White skin reflects 30% to 45% of the solar radiation of the visible and ultraviolet ranges of the spectrum, whereas black skin reflects less than 1.9% of these rays (Frisan-cho, 1979, p. 14). The surface of a substance also affects its ability to reflect or absorb heat. Smooth surfaces absorb more heat than; do rough surfaces. These factors are reflected in the Stefan-Boltzmann constant in the formula. The effective radiating surface area of a person standing with arms and legs spread is approximately 85% of the total skin area. In the sitting position, it is approximately 70% to 75% of the total body surface area.

Conduction

Conduction (K) of heat occurs whenever two surfaces with differing temperatures are in direct contact. The transfer of heat energy from one substance to another is directly related to the difference in temperature between the two (the thermal gradient or ΔT). It is also a direct function of the thermal conductivity (k) of each substance. *Conductors* are substances that conduct heat readily. *Insulators* (nonconductors) are substances that do not conduct heat readily. Metals are good conductors, whereas nonmetals are better insulators. Still air is an excellent insulator, whereas water is an excellent conductor. This explains why a naked body experiences greater thermal stress in 10°C (50°F) water than in 10°C air. Fat tissue is a better insulator than muscle tissues. Therefore, a fatter person loses less heat when immersed in cold water than a leaner subject. The rate of conductive heat exchange is inversely related to the thickness of the insulating substance. This is why the thick layer of still air trapped in goose down clothing is so effective in cold weather and why the layer principle of dressing for the cold is advocated. Conductive heat loss represents only a small percentage of the total heat exchange between the body and the environment. Thus, conduction is usually not considered separately but is discussed in conjunction with radiation and convection. The area of skin contact with external objects is usually small, and people usually avoid direct contact with highly conductive materials. However, body heat is conducted from skin to clothing. When body heat reaches the clothing, it is dissipated from the outer clothing surfaces by evaporation, convection, or radiation depending on the vapor pressure, air movement, and the skin-clothing-ambient temperature gradients.

Convection

Convection (C) or convection heat exchange requires that one of the media be moving, as occurs with a fluid or gaseous medium. This is referred to as a convective current. Heat is transported by a stream of molecules from a warm object toward a cooler object. The coefficient of convective heat transfer is a function of the convective current, the viscosity and density of the medium, and the thermal conductivity of the substances involved. Convection is directly related to the temperature gradient between the substances as well as to the effective convective surface area and surface coefficient at each boundary layer. An example of convective heat exchange is the devastating effect of high winds on a cool day (wind chill factor). Convective heat exchange occurs *within* the human body as well. When warmed blood from metabolically active areas of the body flows past cooled blood from the periphery of the body, the warmed blood is cooled, and the cooled blood is warmed. This is known as *countercurrent heat exchange*. This phenomenon can become complicated during exercise. The most common exchange of body heat by convection begins with heat conduction from a warm body to surrounding air molecules. The heated air expands, becomes less dense, and rises-taking heat with it. The area immediately adjacent to the skin is then replaced by cooler, denser air, and the process is repeated.

Evaporation

Evaporation (E) occurs when water changes from a liquid to a gas. For this to happen, heat must be supplied (note that heat can never be gained via evaporation and hence the sign is always negative). The thermal energy required is called the *latent heat of vaporization* and equals 580 calories per gram of distilled-deionized water. For human sweat this value is lower because of electrolytes in the fluid. Evaporative heat loss is directly related to the heat of vaporization and to the amount of liquid vaporized (evaporated). In the human body, evaporative heat losses occur as a result of insensible perspiration (diffusion of water through the skin), thermal and non-thermal (nervous) sweating, and, water losses from the respiratory tract during respiration. A man at rest who is comfortably warm loses water from his respiratory tract and by insensible perspiration at a rate of about 30 g/hr (Carlson & Hsieh, 1974, p. 63). Higher respiratory rates or very low relative humidity may significantly increase this value. High environmental temperatures and/or strenuous exercise may result in thermal sweating rates as high as 1.5 to 2.0 L/hr.

Evaporative heat losses from the respiratory tract are usually not significant. However, under such conditions as high altitude and/or extremely cold and dry air, evaporative heat losses from respiration can become physiologically significant. The density of saturated air varies with temperature. Relative humidity is a function of how much water the air can hold at a given environmental temperature. Everyone knows that evaporation is very slow in areas of high relative humidity. That is why hot, humid environments are so much more stressful than hot, dry environments. Evaporative heat losses from the skin surface depend primarily on three factors. One is the rate of evaporation, which is dependent on the relative humidity of the surrounding air and the amount of air movement across the skin. A second factor is the rate of sweat secretion from the sweat glands. The third factor is the latent heat of evaporation for the sweat secreted, which varies with the electrolyte concentration of the sweat.

Most often evaporative heat losses are determined by carefully measuring the total amount of water lost from the body per unit of time. This is done by calculating total weight loss and correcting for fluid intake and the weight of excess carbon dioxide produced.

The roles played by the four avenues of heat exchange depend on the interactions between the ambient temperature, the relative humidity, and the dry skin temperature gradient. Simply in a comfortable climate of 25°C, a seated nude person loses heat mostly by radiation (67%) and evaporation (23%). In a warmer climate of about 30°C, radiative losses decrease slightly, and convective losses increase. At temperatures higher than 35°C, little body heat can be lost via radiation and convection, and evaporative heat losses become extremely important. In the event that vapor pressure is high (high relative humidity), then the evaporation of sweat is minimal, and heat tolerance is limited.

Recently some interesting innovations have occurred in clothing design concepts for cold weather. using "breathable" external fabrics and carefully designed venting in the underarm, back, wrist, and ankle areas, the concept of layering with polypropylene undergarments is gaining popularity. "Vapor barrier" clothing is designed to rid the body of perspiration and dampness without losing heat by evaporation. Mountaineers, backpackers, and cross-country skiers are aware that strenuous exertion in the cold generates plenty of body heat and sweat. When one stops, slows down, or encounters high winds, the loss of heat via evaporation can be extremely chilling and even life-threatening. Vapor barrier clothing is supposed to end all this by "wicking" the body's excess moisture to the surface of the clothing for evaporation while retaining the body's heat. Although it sounds like a great idea and it sometimes works, not all the problems have been solved. Under some conditions, vapor barrier clothing can create an internal heat stress of its own. Nevertheless, it is an excellent example of an attempt to apply our knowledge of the physical avenues of heat exchange to our practical advantage.

Now that the general concepts of thermal regulation have been discussed, we can move to more specific situations involving the physiological mechanisms for resisting and adjusting to the stresses imposed by our environment and we will elaborate on the human response to heat stress.

HEAT STRESS AND PERFORMANCE

We have described the physical means by which heat can be exchanged (avenues of heat exchange), and we have described the control mechanisms by which internal temperature can be regulated (mechanism temperature regulation). Heat dissipation is the fundamental problem for regulating organisms exposed to heat stress. Successful tolerance of heat stress requires coordinated responses that facilitate heat loss to maintain homeostasis. We will discuss the role of the physiological effector mechanisms of heat stress and how they relate to the topics already discussed.

The Effector Mechanisms of Heat Stress

Vasodilatation

The anterior portion of the hypothalamus regulates blood flow through the deep and superficial vessels of the body. The hypothalamus sends neural commands to the vasomotor center in the brain stem and directly affects the smooth muscles of the metarterioles that control the flow of blood between deep and superficial vessels. By directing warm blood from the core of the body to the surface layers, body heat can be dissipated from one group of tissues to another and in some instances eliminated from the body. The core-shell concept is a particularly important one to understand.

The essential organs of the body include the brain, heart, lungs, liver, and kidneys. It is important that these organs, which are very active metabolically, are protected from extreme losses of body heat under cold environmental conditions. These organs and surrounding tissues are referred to as the body core, and they always receive a large supply of blood. Under certain conditions, however, these organs must also be protected from high body temperatures. For example, when the body is exposed to extremely high environmental temperatures, heat must be removed from the body to prevent tissue damage (particularly to the brain). Even without exposure to high environmental temperatures, the body can become severely overheated, for example, during prolonged and strenuous exercise in a humid environment. By directing blood flow away from the core tissues to the peripheral tissues, it is possible to redistribute and remove heat that could be deleterious to survival. By diverting blood flow from deep to superficial vessels, heat can be transferred to other tissues (conduction, convection) or transferred to the environment (conduction, radiation). The principal factor involved here is the temperature gradient (ΔT) between the blood and the surrounding tissues and between the skin and the surrounding environment. If the shell (the peripheral tissues) is cooler than the core (the deeper tissues), heat will be exchanged and the core will cool down. This is, of course, a very dynamic mechanism that is under constant adjustment and control. As long as the body surface layers are cooler than the external temperatures, heat can be lost via radiation, conduction, or convection. If the environmental heat load is so extreme that the skin surface becomes as warm or warmer than the core temperature, then heat will be gained from the environment and internal heat can no longer, be exchanged via these mechanisms.

Secondary Consequences of Vasodilatation

Vasodilatation plays an important role in regulating body temperature during exercise and environmental heat stress. Nevertheless, this valuable effector mechanism can also cause some significant physiological problems. With increased blood flow to the peripheral tissues, blood flow to other areas of the body must decrease. There is, after all, only a finite amount of blood available. When the body is suddenly forced to distribute 5 or 6 L of blood over a vascular area that may suddenly double or triple in size, some immediate adjustments must be made. Central blood pressure must be maintained. One mechanism is for blood flow to decrease in certain less-necessary organs and tissues. For example, renal and splanchnic blood flow usually decrease during heat stress. The corresponding decline in urine excretion conserves plasma water. Digestive processes also slow down. Another physiological adjustment to vasodilatation is an immediate increase in cardiac output (Q). Cardiac output is a function of the heart rate (HR) and the stroke volume (SV) of the heart (Q = HR X SV). The increase in cardiac output accompanying vasodilatation is affected by a sometimes dramatic increase in heart rate. Persons exposed to high environmental heat often have near-maximal heart rates-even with mild exercise or rest. Because cutaneous blood vessels may not be affected by the exercise and are characterized by low blood pressures, venous return usually decreases considerably when vasodilatation occurs because of heat stress. Consequently, the stroke volume may decrease significantly. This means that the heart rate is the primary mechanism for maintaining cardiac output. In the heat, one often experiences general weakness, which is probably related to the deprivation of blood (oxygen and fuel) to the muscles and a corresponding fall in arterial blood pressure. Some people, in the heat, experience tunnel vision (a narrowing of peripheral vision), which is probably a manifestation of this. If vasodilatation is extreme (much blood going to the periphery and little remaining in the core), one, may experience cardiac insufficiency or compromise. This is especially prevalent among obese, elderly, and sedentary people, and during periods of heavy exercise in extremely high environmental temperatures.

Sweating

Sweating is an effective means by which to lose body heat. However, heat is lost only if evaporation occurs. When the ambient temperature exceeds the skin temperature, the temperature gradient favors heat gain, and evaporation of sweat is the only mechanism by which the body can dissipate internal heat. Under such conditions, radiation, conduction, and convection will result in body heat gain. When relative humidity is high or when there is insufficient air flow past the skin surface, evaporation is limited. When both air temperature and relative humidity are high, the body will soon reach its limit of heat tolerance. There are two types of sweat glands. Both are found in the dermal layer of the skin just above the subcutaneous tissue. Apocrine glands secret a watery substance that contains lipid molecules, has a trace of color, and has a slightly musky odor. These glands are found predominantly on the palms of the hands, the soles of the feet, the armpits, and the groin. They are also sometimes found on the face, particularly in the area of the upper lip. Apocrine sweat is known as nervous or emotional sweat, because it is secreted in response to various neurochemical stimuli and not by thermal stress. Eccrine sweat glands, on the other hand, are distributed more evenly about the body, although several distinct sweat gland distribution patterns have been reported (Kuno, 1956).

Eccrine sweat is the primary topic of this section, because this is the so- called thermal sweat. These glands are under the direct control of the anterior portion of the hypothalamus. Stimulation of this portion of the master gland results in sweating and the increased production of a clear, watery, odorless fluid, which is an ultrafiltrate of blood plasma; Thermal sweat glands can also be stimulated by the effects of radiant heat applied to the skin (Bullard et al., 1967, 1968). Sweating in response to heat stress is usually very rapid and effective. Much body heat can be lost if evaporation is sufficient and the skin surface remains reasonably dry. There is considerable evidence to suggest that sweating gradually declines if the skin surface becomes thoroughly wet.

Secondary Consequences of Sweating

As with vasodilatation, a number of physiological events occur secondary to significant thermal sweating. One event is a shift of body fluid from the interstitial space to the vascular bed. This occurs so rapidly that blood volume may actually increase temporarily. Because thermal sweat comes from the plasma water, this fluid shifts so that the blood will not become concentrated too, rapidly. Only after prolonged periods of sweating does blood concentration become a serious problem to the well-hydrated individual. When that occurs, intracellular water shifts into the extracellular space so that sweating can be maintained, but the body tissues may become severely dehydrated. Because sweat is an ultrafiltrate of plasma water, it possesses almost every thing that is found in blood except the plasma proteins. Nevertheless, sweat is hypotonic (less concentrated) to the plasma water, and therefore, the substances are found in lesser concentrations. The major elements in sweat are the extracellular electrolytes sodium (Na^+) and chloride (Cl^-),and the intracellular electrolyte potassium (K^+). Other components in sweat include urea, lactic acid, CO2, PO4, Mg+, nitrogen, bicarbonate (HCO3), iron, and zinc. Some water-soluble vitamins are probably also lost in sweat.

Because sweat is hypotonic to plasma water, the major substance lost from the body is water. Nevertheless, many people are concerned about electrolyte losses and advocate glucose and electrolyte replacement solutions (Gatorade, Powerade, etc.) during sport or work situations in which large amounts of water are lost. However, because the sweat glands effectively conserve the body components, there is probably too much emphasis on electrolyte replacement and not enough emphasis on fluid (water) replacement. Far more solvent (water) is lost from the body than solutes (substances). Fluid and electrolyte replacement will be discussed more thoroughly.

Decreased urinary output is another consequence of prolonged or profuse sweating. This is, of course, a protective response against a severe loss of blood volume. The kidney vigorously regulates water balance. Whenever fluid losses threaten to upset water balance, arterial blood pressure declines, which decreases renal blood flow and glomerular filtration rate. Under these conditions, urine output is held to a minimum. In addition, because sweat is hypotonic to the body fluids, plasma osmolarity is elevated with prolonged sweat losses. Elevated osmolarity elicits an increase in the secretion of antidiuretic hormone (ADH) from the pituitary. Antidiuretic hormone acts on the tubules of the kidney, causing increased reabsorption of water and a consequent water conservation. Electrolyte excretion by the kidneys is coupled with the regulation of water balance. When sweating rates are high, the kidney conserves Na+ by increasing the reabsorption of that electrolyte at the site of the distal tubule. The steroid hormone, aldosterone, from the adrenal cortex plays a significant role in this mechanism as does decreased arterial blood pressure.

Prolonged and profuse sweating can result in circulatory distress. To the extent that fluids are not adequately replaced during heat stress, water losses can lead to dehydration. If fluid losses are sufficient to cause an increase in the viscosity of the blood (decreased plasma volume), then the strain on the heart can become severe. In this event, heart rate will be very high, stroke volume will decline considerably, and the individual is likely to suffer syncope (fainting) and even become comatose. Elderly, obese, sedentary people, and people with heart disease are particularly susceptible.

Other Mechanisms of Body Heat Loss

Vasodilatation and sweating are usually observed together. Both mechanisms occur simultaneously and are somewhat dependent upon each other. Vasodilatation, of course, brings an increased supply of blood (and water) to the dermal sweat glands, and the evaporation of sweat serves to cool the skin surface so that the thermal gradient between surrounding tissues and the ambient air is favorable to heat loss. There are few additional and effective mechanisms. With an elevated body temperature (hyperthermia), respiration rate and respiration volume usually increase. Because relatively little heat can be lost from the respiratory tract, this response has only a small effect on temperature regulation. In fact, elevated minute ventilation is likely to cause hyperventilation, a corresponding decrease in the partial pressure of carbon dioxide, respiratory alkalosis, and syncope.

Additional mechanisms of body heat loss are not physiological but behavioral in nature. When people are exposed to heat stress they usually make conscious efforts to enhance heat loss or prevent heat gain. These behavioral alterations include selecting light-weight and light colored clothing, removing clothing to allow for better ventilation, resting in the shade, drinking water, decreasing work rate, and planning the activities to avoid discomfort.

The Concept of Thermoneutrality

The concept of thermal neutrality comes from the study of the changes that occur in a homeotherms physiological responses when environmental temperature is varied. At low ambient temperatures, the metabolic rate is elevated so that heat production increases. The degree of cold that the organism can tolerate is determined by its maximal rate of cold-stimulated heat production and its thermal insulation. As the ambient temperature increases, the thermal demand of the environment decreases, and heat production is no longer required to maintain internal body temperature. The point at which the metabolic rate is minimal depends on a number of factors including body composition (fatness, muscularity, linearity, and body surface area), diet, acclimatization, clothing, and various environmental factors. With exposure to higher environmental temperatures, physiological mechanisms that aid the dissipation of body heat come into action. The environmental range of temperatures at which the body makes the least thermoregulatory effort is called the *zone of thermal neutrality.* The width of such a zone varies considerably among different homoeothermic species and also among individuals of the same species. Humans have a fairly wide zone of thermal neutrality. They are able to elevate metabolic heat production (both voluntarily and involuntarily) and to conserve heat via vasoconstriction in response to cold temperatures. They are able to bring internal heat to the body surface via vasodilatation and to sweat profusely in response to warm temperatures. The lower limit of the zone is set at the environmental temperature at which metabolic heat production first rises (a resting body is assumed), and the upper limit of the zone is set by the onset of sweating and increased evaporative heat loss. This concept allows us to study the relationships between heat production, evaporative and non-evaporative heat losses, and deep body temperatures in response to ambient exposure.

Vasodilatation occurs at some point beyond the critical temperature. This facilitates an increase in the transfer of heat from the core to the surface; that is, it increases thermal conductance through body tissues. The critical temperature is the lower end of the zone of minimal metabolism. Below this ambient temperature, mechanisms of heat conservation must be used to maintain internal body temperature (Ingram & Mount 1975, p. 26).

The Hot Environment

Humans encounter heat stress in tropical zones surrounding the equator and during summer months in the temperate zones. Hot climates can generally be classified as hot-dry or hot-wet. Hot-dry climates have high ambient air temperature (99 – 125 °F) and low relative humidity (0 – 15%). The high solar load and high air and ground temperatures of the hot-dry climates prevent body heat loss via radiation, conduction, and convection, but the low moisture content favors heat loss via evaporation which is therefore the primary thermal regulatory effector mechanism.

In the tropical and subtropical climates, the conditions are characterized by moderately high air temperature (usually less than 95 °F) and very high relative humidity usually exceeding 50%. In this sort of climate, evaporation is limited, and little body heat can be lost via the sweating mechanism.

Exercise in the Heat

A resting person produces about 75 kcal/hr of metabolic heat. When exercise begins, heat production increases in a corresponding manner. With prolonged or intense exercise, metabolic heat production can be elevated some 20-fold, to about 1,500 kcal/hr. It is obvious that this extra heat must be dissipated, or body temperature will rapidly rise above normal levels. Even without environmental heat stress, this internal heat load will eventually become a problem. It is common for deep body core temperatures to range from 38.0 to 41.0 °C (100.0 to 106.0 °F) during periods of exercise. To perform strenuous exercise under climatic conditions that prevent the almost-immediate loss of body heat or that add an external heat load immensely compounds the physiological problems. With the increase of muscular activity, oxygen uptake increases, ATP is broken down, and energy is released. Much of this energy is not bound up in mechanical or cellular work. Instead it is lost as heat to the surrounding cells, which include other muscle tissues, connective tissues, and the cells and fluids of the blood stream. Consequently, there is a general heating of the surrounding areas. Because this would elevate deep temperatures in relation to surface (skin) temperatures, the ensuing temperature gradient would favor the loss of deep body heat via the mechanisms of radiation, conduction, and convection. In addition, muscular contraction almost immediately stimulates thermal sweating. If sweat secretions evaporate, skin temperature declines, which further increases the temperature gradient between the deep tissues and the skin surface. As described so far, then, temperature regulation ought to be no problem whatsoever. And that is the case as long as the surrounding air remains cool, the solar load is not excessive, and evaporation keeps up with sweat secretion. In short, there is little problem with body temperature regulation during exercise under ideal environmental conditions such as cool air temperatures, moderate air flow, and low vapor pressure. However, if even one of these variables changes, the task of adequately regulating the deep body core temperature is magnified considerably.

For example, let's assume that the solar heat load is increased so that the body begins to gain heat via radiation. As surface tissues gradually heat up, the temperature gradient situation discussed above (T *deep tissues*> T *surface tissues)* is reduced, or even reversed; that is, the temperatures of the surface tissues become equal to or even greater than the temperatures of the deep tissues. This means that the methods of dissipating the increased metabolic heat of muscle contraction are seriously jeopardized. Deep body heat is no longer able to flow to the surface or release to the environment. Now the body must rely exclusively on the sweat mechanism and the evaporative power of the environment for removal of excess metabolic heat.

Another example is also relevant. Often our exercise environment is only moderately warm (21 – 26 °C or 70 – 80 °F) but rather humid (50 – 95% relative humidity). In this situation, the evaporative power of the environment is not very high, and body sweat accumulates on the skin surface. Without sufficient evaporation, the skin temperature gradually rises. Here again the temperature gradient between the deep tissues and the surface tissues becomes smaller and smaller, and body heat loss is retarded. Without the constant removal of metabolic heat, deep body temperature will rise almost immediately. Exercise tolerance under such a condition could be limited depending on one's environmental acclimatization.

Convective heat dissipation within the body is also affected by exercise and increased metabolic heat load. Countercurrent heat exchange was described under normal resting conditions. With exercise, considerable body heat may be produced in the peripheral tissues-that is, in the muscles of the limbs. In such a situation, venous blood temperature becomes elevated, perhaps even higher than that of the arterial blood supply corning into the limb from the deep tissues. Rather than heat flow from the arterial blood warming the cooler venous blood and vice versa, the heat flow is from the heated venous blood to the already warm arterial blood. In this event, peripherally produced metabolic heat is being carried to the body core. To the extent that this condition occurs, exercise tolerance will be limited.

The ability to tolerate strenuous exercise in the heat is probably determined more by on one's cardiovascular efficiency than by any single physiological factor. With exercise, the active muscle cel1s require an increased amount of oxygen and metabolic substrate. In addition, more carbon dioxide and possibly lactic acid and ammonia are produced. These waste substances must be removed. The circulatory system serves as the major transport system for these and other components of metabolism. In a cool or cold environment there is little problem with increasing blood flow to the active muscle cells. Under conditions of elevated heat load, however, the circulatory system is also increase the blood supplied to the skin and subcutaneous tissues. In fact, at work loads above about 1 L/min of oxygen, there is usually an increase in cutaneous as well as muscle blood flow. In a cool, dry environment, probably about 70% of the heat loss during exercise is due to radiation and convection and about 30% is lost as a result of evaporation (Astrand and Rodahl, 1977). In this situation, skin temperatures usually decrease because of the cooling effect of the evaporation of sweat. Skin temperatures do not usually increase during exercise except under hot, humid conditions. The more stressful the exercise environment, the muscle, cutaneous blood flow occurs. This means of course, the environment at less blood is available for the muscles. Less blood flow also means less oxygen, less substrate, and less removal of metabolic waste products. The person who less cardiovascularly fit will first experience the sensation of heavy limbs, then extreme fatigue, dizziness, nausea, tunnel vision, and finally collapse. The more cardiovascularly fit individual will be better able to supply blood to the muscles as well as to the cutaneous layers. In addition, highly trained subjects have an earlier onset of sweating and a heightened sweating response. All this means more body cooling, less physiological stress, and better exercise performance. The fitter, endurance-trained individual will be more capable of maintaining venous return. Because of this, stroke volume will not fall as much, heart rate will not be as elevated, and cardiac output will be maintained or elevated for a longer period.

Because of the alterations in blood flow, oxygen uptake at the active muscle site is diminished. Because the total blood flow to the active muscles is reduced, the muscles are shortchanged in terms of oxygen delivery and waste product removal. This usually results in an accumulation of lactic acid and a reduction in maximal oxygen uptake in the heat. This is the major cause of the decline in work performance in hot-dry and hot-humid environments. There are also psychological and motivational factors involved in exercise tolerance in the heat. For some persons, the physical discomforts are so psychologically devastating that they will stop exercising before they reach their physiological limitations.

Gender Differences in Heat Tolerance

Early research indicated that women had poor tolerance to exercise in the heat. Careful examination of this research showed that the results were largely dependent on the subjects chosen for study. In most cases these early studies compared young male army trainees with somewhat older, fatter, and less-active army nurses. The male soldiers were either in training or had just completed boot camp training. The women nurses, although on their feet a great deal as a result of their employment, were not particularly fit. The most important physiological factor in regard to one's ability to tolerate heat, and particularly exercise in the heat, is cardiovascular efficiency, and it is obvious that the army nurses were not nearly as cardiovascularly fit as the young men after training camp. In addition, the men and women in these studies were always assigned some sort of standardized work task (either walking on a treadmill at a given speed and grade or riding a bicycle ergometer at a given resistance). Because the women were not as fit as the men, they were exercising harder in relation to their capacity than the men. No wonder they did not do so well. One study during these early years of investigation of heat tolerance used more fit women, and the results of that study differed from the others. This study indicated that women were as able as men to exercise in the heat (Weinman et al., 1967). More recent studies (Paolone, Wells, & Kelly, 1977; Wells, 1977; Wells & Paolone, 1977) that assigned exercise tasks on the basis of percentage of individual maximal oxygen uptake and that had subjects who had more similar cardiovascular efficiency indicated that the women tolerated heat at least as well as the men.

Several observations about women exercising in the heat have been verified, however. One is that women do not generally sweat as much as men, even though they have as many sweat glands. One well-known investigator even refers to the male as a "wasteful, prolific sweater," while he describes the female as able to adjust her "sweat rate better to the required heat loss" (Wyndham et al., 1965). It has been suggested that the sex hormones account for this difference (Kawahata, 1960). The reasoning was that because testosterone is anabolic in nature, it stimulates sweating, and because estrogen is catabolic, that it inhibits sweating. So far, however, this has not been satisfactorily demonstrated. Wells and Horvath (1973, 1974) postulated that the female hormones were responsible for lower sweat production, the cyclic variations in "'sweating response should occur during different phases of the menstrual cycle. However, they found no significant differences in heat responses. Although luteal phase sweating (onset of sweating) and evaporative rates tended to lag behind values during the other two menstrual phases when estrogen values were higher, the values were essentially the same after 40 minutes of heat exposure. Sargent and Weinman (1966) also failed to detect differences in sweat gland activity during phases of the menstrual cycle. And so, the fact that women generally do not seem to sweat as much as do men remains unexplained.

Another gender difference in heat stress response that has been noted by many investigators is the higher heart rates in women during heat exposure. Because women also have higher skin temperatures than men, the assumption is that women have a lesser venous return to the heart as a result of a higher cutaneous blood flow. This would indicate that women exercising in the heat have a smaller stroke volume at a given cardiac output than men.

Women capable of sustaining a high heart rate in the face of a lesser venous return will be as able as men to tolerate heat stress. Recent research indicates that the cardiovascularly fit woman is capable of tolerating exercise in the heat. It is interesting that there are few heat injuries in sport (note particularly the information available on road racing in the heat) among women. It is apparent that cardiovascular fitness is more important than gender in heat tolerance.

Children's Tolerance to Exercise the Heat

Young children are more prone than adults to heat-related injuries (Bar-Or, 1982). The reasons for this are related primarily to the morphological and functional differences between children and adults. A young child has about 35 % to 40% more surface area per kilogram of body weight than a young adult. This results in a significantly greater heat transfer between the skin and the environment through conduction, convection, and radiation. When the air temperature exceeds skin temperature, the child will be at a distinct disadvantage. (The same is true when the air temperature is below skin temperature.) There are also distinct differences in energy expenditure between children and adults. Walking or running side-by-side, children may expend 20% to 30% more energy per kilogram of body weight than an adult. This means that in both neutral and in hot environments children produce more metabolic heat (Bar-Or et al., 1969; Haymes et al., 1974; Astrand, 1952).

Sweating rates in children are lower than in adults (Drinkwater et al., 1977; Haymes et al., 1975; Inbar, 1978; Wagner et al., 1972). This difference stems from a lower production of sweat per gland rather than a smaller number of sweat glands (Bar-Or, 1982). Even though sweat losses are not as great as in adults, children do not instinctively drink enough fluid to replenish what is lost during prolonged exercise, and therefore, they are especially prone to dehydration (American Academy of Pediatrics, 1983).

Children do not have as well-developed cardiovascular systems as adults. At a given metabolic rate, the cardiac output of children is lower than that of adults in both neutral and hot environments (Bar-Or et al., 1971; Drinkwater et al., 1977). This means that the child has a somewhat limited ability to bring internal heat to the surface of the body for dissipation to the environment. Despite these disadvantages, children and preadolescents can acclimatize to exercise in the heat-but they do so to a lesser degree than adults (Inbar, 1978; Wagner, Robinson, Tzankoff & Marino, 1972). The American Academy of Pediatrics (2000) has provided guidelines for children exercising in the heat (http://www.aap.org/policy/re9845.html).

GUIDELINES FOR EXERCISE PERFORMANCE IN THE HEAT

Heat Injury

Heat disorders occur when the effector mechanisms are incapable of adjusting body heat loss in relation to heat gain. There is insufficient statistical information to describe the frequency of these disorders, but the most common heat disorders are probably heat syncope and water depletion/heat exhaustion.

The major distinction between heat exhaustion, which is fairly common, and heat stroke, which is rarer, is often said to be a dry skin. This is not absolutely reliable, and reasonable field guidelines for distinguishing between the two are the level of central nervous system disorder and core body temperature. It is important to be able to do so, because heat stroke is immediately life threatening. To prevent death, the elevated body temperature *must* be lowered as soon as possible. With heat stroke, there is a failure of thermoregulation. That is, the heat loss mechanisms are not even attempting to cool the body. With heat exhaustion, the mechanisms have been hard at work but are inadequate to sufficiently cool the body. Sometimes this happens because the environment is too stressful for the person to adjust to, and sometimes it occurs because the individual is incapable of the necessary responses. Some people are particularly susceptible to heat disorder-for example, those who are not accustomed to the heat, have been ill recently, have circulatory or heart diseases, are obese, are elderly, and are extremely sedentary and suddenly exercise strenuously in the heat. A common denominator here is lack of sufficient cardiovascular fitness to make the physiological adjustments necessary for adequate thermoregulation under unusual circumstances.

Environmental Guidelines

One accepted and useful method of evaluating environmental stress is the wet bulb globe temperature (WBGT) index. This index combines wet bulb temperature (T_{wb}) with dry bulb temperature (T_{db}) and radiant temperature from the environment. Radiant heat is measured with the globe thermometer mentioned earlier *(Tg)*.

$$WBGT = 0.7\ T_{wb} + 0.2\ T_g + 0.1\ T_{db}$$

Because relative humidity is the most important environmental factor, it is given more weight in the WBGT index. Under conditions where radiant heat is not an important factor, T_g is omitted, and the constant for T_{db} becomes 0.3. The American College of Sports Medicine (1984) has published a position stand on the "Prevention of thermal injuries during distance running." The College recommends that summer distance races be conducted before 8 a.m. and after 6 p.m. to minimize solar radiation and that races be rescheduled or delayed when WBGT exceeds 28.0 °C (82.0 °F). The statement places the onus of responsibility on race sponsors (1) to educate participants regarding thermal injury, susceptibility and prevention, (2) to provide water before the race and every 2 to 3 km during the race, and (3) to provide adequate medical care.

The Importance of Fluid Replacement

Water is the most abundant constituent in the human body, and it may be the most valuable as well. Water constitutes about 63% of the body weight in men and about 52% in women. About half of this water is within the cells (intracellular water), where it acts as an active support medium for metabolic reactions. The extracellular compartment provides about 22% of the body weight and serves as the major transportation system for respiratory gases, cellular substrates and by-products, and metabolic heat. Water is the basis of the circulatory system. The ability to perform endurance exercise is directly related to the capacity of the circulatory system to transport oxygen to the working muscles. Because there is not sufficient blood volume to fill the entire circulatory system all at once, blood is distributed throughout the body on the basis of need. During rest blood flows freely to the internal organs and to the skin for heat dissipation (if necessary), but relatively little flows to the muscles. During strenuous and prolonged exertion, however, blood flow pattern is altered significantly from the inactive tissues to the active tissues. Now it is essential to circulate blood to the contracting muscles. The capacity to do that depends on the volume of blood available for distribution and the ability to divert a large part of that volume to the muscles (Costill, 1980). Anything that interferes with this function will seriously affect an athlete's performance.

A significant decline in body water will result in a corresponding decline in plasma volume and consequently of blood volume. Not only will blood flow to the muscles be impaired, but so will the ability to dissipate internal body heat via vasodilatation of the subcutaneous vessels. When even as much as 2% of the body weight has been lost from sweating, performance will be negatively affected. Eventually, the important thermoregulatory function of sweating will decline and fail. When that happens, water-depletion heat exhaustion has occurred, and the athlete will collapse.

Dehydration

Dehydration equivalent to even 2% of body weight can noticeably impair performance by compromising the circulatory and thermoregulatory functions (Pitts, Johnson, & Consolazio, 1944; Adolph, 1947; Astrand and Saltin, 1964; Saltin, 1964). The decline in performance is caused by (a) the reduction in blood volume and consequently in maximal cardiac output and peripheral circulation; (b) the disturbance in central nervous system control of the sweat glands and/or peripheral vasculature from thermal or osmolar effects on the hypothalamus; (c) a reduction in the capacity of the sweat glands to secrete sweat (sweat gland fatigue); and (d) suppressed cellular function leading to a reduction in anaerobic capacity.

With increasing levels of dehydration, there are striking declines in endurance performance and elevations in heart rate and body core temperature. It is obvious that to prevent this, the exercise participant must replace the water that is lost via sweating. What is not quite so obvious is the best method to do this. The ideal situation would be not only to replace the fluid lost but to duplicate its composition. Let's examine what is lost in sweat in more detail.

Sweat Composition

Sweat is filtrate of blood plasma and as such contains many of the same substances. As described earlier, however, the sweat glands are capable of conserving certain substances.

Consequently, sweat is more dilute than the other fluids of the body. Because sweat has approximately one third of the concentration of Na+ and Cl- as plasma, sweat is hypotonic to plasma.

The most abundant minerals in sweat are sodium and chloride. These electrolytes are located in the extracellular fluid compartment and are primarily responsible for maintaining the water content of that compartment. This control requires a steady relationship between the concentration (number) of ions, and significant electrolyte loss can disrupt this relationship. When that occurs, body water must be redistributed to maintain the proper water-ion relationship (Costill, 1980). However, when sweat is lost, far more water is lost than electrolytes, leaving the remaining electrolytes in the body water more concentrated. Therefore, as far as the cells are concerned, there is an excess rather than a depletion of electrolytes. The point of all this is that *it is far more important to replace the water than the electrolytes*. In fact, although this is not an absolutely closed question, it is probably not important to replace electrolytes during an athletic event. The primary need is fluid replacement.

Potassium loss in sweat has been emphasized by the popular press. Contrary to the opinions offered by various health food advocates, potassium loss in sweat is low. Potassium is located primarily in the intracellular fluid compartment and is found only in low concentration in the extracellular fluid space from which most of the sweat comes. The actual loss in sweat is about 0.01 oz of potassium per quart of sweat (Senay, 1979). Even with low dietary potassium intake and high potassium losses in sweat, little change in total body potassium (less than 2%) has been reported (Costill, 1980). Therefore, potassium loss in sweat is probably of little consequence, and one need not be concerned about replacing it during exercise.

There are at least three benefits to ingesting fluids during exercise when significant sweat losses occur: First, by minimizing the degree of dehydration that would occur from prolonged sweating, the stress placed on the circulatory system is significantly reduced. Consequently, more blood is available to transport metabolic substrates and by-products and to transfer heat to the body's shell. Second, by taking fluids during exercise, the threat of overheating is significantly reduced. And third, possible benefit is that fluid replacement offers an opportunity to add to or replace the metabolic substrate (carbohydrate) consumed during exercise. This third benefit may, however, prove detrimental to the first two. Nonetheless, many people advocate glucose ingestion during exercise.

Glucose Ingestion during Prolonged Exercise

When the duration of exercise exceeds several hours, the liver releases glucose into the blood from its glycogen store for use by the active tissues. Eventually, the liver will become depleted of glycogen and the blood glucose level will drop below that desired to maintain the working cells. Readers are probably familiar with the expression "hitting the wall" that is used by marathon runners (cyclists use the expression "getting the bonks"). When this occurs, performance deteriorates considerably, and the race is usually abandoned. Blood glucose levels can be maintained if glucose is absorbed from the small intestine. A fluid replacement substance that contains carbohydrates is often prescribed to re-supply the glycogen and glucose used by the working tissues. This solution has a serious drawback when exercising in the heat, however. It is clear that the most important substance to replace during exercise in the heat is water. Replacing other substances such as sodium, chloride, potassium, magnesium, and calcium is of minimal importance. However, the amount of water replaced by consuming fluids during exercise depends on how quickly the drink leaves the stomach. Several factors can affect the rate of gastric emptying-the volume consumed the temperature of the fluid, and the sugar content. The most important factor, however, is the concentration of sugar (glucose) in the solution. All sugars (including honey and fructose) significantly retard the rate at which solutions leave the stomach. Thus, consuming a sugar solution is a poor method of replacing the body water lost as sweat. (See the classic studies: Costill & Saltin, 1974; Coyle, Costill, Fink, & Hoopes, 1978; Costill & Sparks, 1973). As a result of several studies on this topic the best recommendation is to drink water when that is the substance that is most important to replace under the exercise and environmental circumstances. When it is imperative to replace the glucose lost during exercise, the best replacement solution is a mild concentration of carbohydrate such as 2.0 to 2.5 g of glucose per 100 ml of water (Costill, 1980; "Prevention of Thermal lnjury," 1984).

Thirst

Under normal environmental conditions, the thirst mechanism is usually adequate to maintain water balance. The urge to drink is mediated by the hypothalamus, which is responsive to increased body fluid osmolarity (concentration) with water depletion (Astrand and Rodahl, 1977). Because more water than body salts are lost through sweating, blood osmolarity increases. If sufficient water is drunk to replace losses the osmolarity is reduced, and water balance is reestablished. However, when individuals sweat profusely during exercise, they invariably fail to voluntarily replace their losses (Adolph, 1947). This is called *voluntary dehydration*, and it has been noted by many investigators. For example, marathon runners drink so sparingly that weight deficits exceeding 5% of body weight are common (Pugh, Corbett, & Johnson, (1967). Generally, coaches should teach athletes that thirst is not an adequate indicator of the need for water and that they should maintain a proper state of hydration during participation.

Subjects allowed ad libitum water intake during a prolonged march had lower heart rates, lower rectal temperatures, and fewer dropouts than subjects not receiving any water (Strydom, Wyndham, van Graan, Holdsworth, & Morrison, 1966), However, the thirst mechanism was inadequate to prevent dehydration, and the ad libitum water drinkers had a water deficit of 2.9% at the end of the march. Other studies have verified that most sport competitors undergo voluntary dehydration between 2% and 7% of their body weight, and the more successful competitors usually incur the largest water losses. Competitors who consume the largest amounts of water usually show the least elevation in rectal temperatures (Wyndham and Strydom, 1969).

In studies comparing ad libitum water consumption and forced replacement of sweat losses it is clear that the latter procedure is the least stressful. With forced ingestion of fluids (i.e., fluid ingestion is matched with sweat losses), subjects showed lower rectal temperatures, better heat dissipation, and sometimes lower heart rates (Pitts, et al., 1944; Dill, Yousef, & Nelson, 1973; Costill, Kammer, & Fisher, 1970).

Practical Suggestions Regarding Fluid Replacement during Exercise in the Heat

Optimal physical performance is not possible if one becomes dehydrated. It is therefore extremely important that fluids betaken during exercise when large amounts of sweat are lost. Hyperhydration (taking ample water *before* performance) has been found to aid performance and was associated with significantly lower rectal temperatures, lower heart rates, higher sweat rates, and longer treadmill performance times (Herbert, 1980).

Costill (1980) has provided some guidelines for fluid replacement during hot weather exercise. He suggests that the drink be hypotonic, low in sugar concentration (less than 2.5 g per 100 ml of water), cold (roughly 45°F to 55°F or 8°C to 13°C), consumed in volumes ranging from 100 to 400 ml (3 to 5 oz), and of palatable taste. He further suggests that 400 to 600 ml (13.5 to 20.0 oz) of water be consumed 30 minutes before the competition, and 100 to 200 ml (3 to 6.5 oz) be consumed during activity. For electrolyte replacement, Costill suggests modest salting of foods after the event. For any event exceeding 50 or 60 minutes, fluid replacement is essential. Keeping a record of early morning body weight from day to day is a good method of detecting dehydration.

ACCLIMATIZATION

It has long been recognized that the human can gradually adjust to hot climates. With acclimatization, marked decreases are found in heart rate and skin and body core temperatures. In addition, the dizziness, weakness, and nausea that often occur with exertion in the heat disappear, and exercise capacity improves dramatically. Other adaptive responses include an increase in sweating rate, an earlier onset of sweating (i.e., begin sweating at a lower body temperature), and a more complete and even distribution of sweat over the skin. The increased economy of physiological responses to the heat is also shown by the decrease in electrolytes in the sweat and the improved maintenance of body fluid volume and composition. It is likely that the adrenal hormone, aldosterone, plays a major role in this adaptation. Aldosterone is known to conserve sodium, the major electrolyte in sweat. With full acclimatization there is enhanced tissue conductance in the periphery. This is accomplished by increased perfusion of the cutaneous interstitial space, which results in an increase in plasma volume (Frisancho, 1979, p. 23). Apparently, the ability to dissipate body heat is enhanced by the progressive physiological adjustments that occur with gradual acclimatization.

Early investigations of heat acclimatization revealed that physiological adaptations can occur soon-within a few days of the initial exposure-and that regular work periods in the heat are required. It has also been reasonably well established that heat acclimatization can be retained for about 3 weeks without additional exposure.

Guidelines For Athletic Participation During Hot Weather

Exercise in hot-dry, hot-humid, or even warm-humid conditions can be devastating to the unacclimatized. Precautions must be taken to avoid serious medical problems. Awareness of a few simple principles may lead to successful performance as well as safety. For example, becoming gradually accustomed to participation in hot or warm climates considerably reduces the physiological strain associated with sudden exposure. The best way to become acclimatized to hot environments is to be gradually exposed to exercise in the heat over 4 to 10 days. Mild to moderate exercise enhances the physiological responses. Athletes who are scheduled to compete in a warm or hot climate that they are unaccustomed to would be wise to arrive several days before the competition and to engage in moderately easy workouts before gradually increasing their intensity. Most physiological adjustments to heat should be completed by about the fifth day. Frequent and adequate rest can play an important role in exercise capacity in the heat. Momentarily seeking shade, finding a spot with good air movement, and avoiding the re-radiation of heat from ground surfaces or the walls of buildings can prolong one's exposure to a hot climate. It is a good idea to loosen or remove clothing when that will enhance loss of internal heat via convection or evaporative heat exchange. However, in instances of high radiative heat gain, it is best to keep the skin covered to provide a b barrier to environmental heat gain.

In the early days of exposure to a hot environment (for example, at the beginning of a new season), it may be best not to play in full uniform. This is especially true for football. Midsummer days are often hot and/or humid. Beginning football practice in full uniform and padding under these conditions has resulted in deaths.

Artificial track and field surfaces are warmer than turf surfaces (Buskirk, Loomis, & McLaughlin, 1971). The additional heat stress results from a larger radiative heat load on the athlete as well as a higher air temperature near the surface. Scheduling activity for the early morning or evening hours when the solar load is less severe can avoid heat stress problems. The regular watering of both natural and artificial turf can considerably reduce the environmental heat load.

SUMMARY

As a regulating organism, the human is able to maintain a relatively constant internal temperature within a wide range of environmental conditions. Conforming organisms, on the other hand, cannot survive extreme environmental variations as readily. Thermal regulation is under the control of the hypothalamus which acts much like a room thermostat. It senses temperature information from various sources and directs the body's responses in relation to an internal set-point temperature. Effector mechanisms mediate the conservation or dissipation of internal body heat accordingly. The physical avenues of heat exchange include radiation, conduction, convection, and radiation. To maintain thermal equilibrium, the body must quantitatively balance these factors in relation to metabolic heat production and environmental stressors. Radiative heat gain occurs whenever radiant temperature exceeds average body surface temperature. Conductive heat exchange occurs when two surfaces in direct contact differ in temperature. Transfer of heat from one surface to another is directly related to the thermal conductivity of the substances. Water is an excellent conductor of heat whereas still air is an excellent insulator. Convective heat exchange requires a moving medium. A cold wind blowing past a warm body can have a devastating effect on body temperature. Evaporative heat losses can occur from the respiratory tract and from the skin surface. Heat loss via this avenue of exchange is significantly affected by the relative humidity of the surrounding air. An understanding of the basic principles of heat exchange is of practical significance in knowing how to protect oneself from harsh environmental conditions.

The relationship between physiology effector mechanisms for heat dissipation and physical avenues of heat exchange was emphasized. Each effector mechanism, while leading to significant body heat loss, also causes secondary consequences that must be countered in some way. Vasodilatation, for example, leads to significant changes in blood flow that require an increase in cardiac output. Under some conditions, stroke volume may decrease considerably. If cardiac output cannot be maintained at a sufficient level, syncope may occur. While evaporation of sweat from the body surface is an important means for heat loss, a number of consequences occur that could seriously affect performance. Because sweat is hypotonic to body fluids, water replacement is essential to maintaining blood volume with prolonged or profuse sweating. The kidney vigorously protects water balance. With high sweating rates, ADH is elevated, and acts on the renal tubule to conserve body water. Aldosterone mediates the reabsorption of sodium which plays a significant role in maintaining the extracellular fluid compartment.

In a thermally neutral environment, no thermoregulatory effect is required. With environmental heat stress, however, considerable thermoregulatory effort is required. The ability to tolerate strenuous exercise in the heat is largely a matter of cardiovascular fitness. The endurance trained individual is able to maintain an adequate blood flow to active muscles as well as skin surfaces, and consequently, can cool the body while continuing to exercise.

There are some differences in how men and women respond to heat stress. While cardiovascularly fit women are as heat tolerant as men, they generally sweat less, and have higher heart rates and skin temperatures. Children are not as heat tolerant as adults.

There are several forms of heat injury. Heat stroke can be life threatening. The best means of prevention is having an understanding of environmental guidelines for exposure to heat as provided by the NATA and ACSM.

The most important factor in performance in the heat is fluid replacement. If body water is allowed to decline significantly, blood flow to muscles and skin surfaces will be impaired, sweating will decline, and body temperature regulation may fail. Although body electrolytes are lost in sweat, electrolyte replacement should occur *following* exercise rather than *during* exercise. Glucose containing drinks retard the absorption of water from the gastrointestinal tract. When it is imperative to replace carbohydrate substrate during prolonged exercise, only weak glucose solutions should be used or water depletion may result.

Gradual acclimatization to heat results in significant changes in physiological response. Athletes should be sure they are adequately acclimatized before competing in the heat.