CHAPTER 5

Energy, Work, and Power of the Body

Energy is a basic concept of physics. In the physics of the body energy is of primary importance. All activities of the body, including thinking, involve energy changes. The conversion of energy into work such as lifting a weight or riding a bicycle represents only a small fraction of the total energy conversions of the body. Under resting (basal) conditions about 25% of the body's energy is being used by the skeletal muscles and the heart, 19% is being used by the brain, 10% is being used by the kidneys, and 27% is being used by the liver and spleen.

The body's basic energy (fuel) source is food. The food is generally not in a form suitable for direct energy conversion. It must be chemically changed by the body to make molecules that can combine with oxygen in the body's cells. We do not discuss this complex chemical process (Krebs cycle) here. From a physics viewpoint we can consider the body to be an energy converter that is subject to the law of conservation of energy.

The body uses the food energy to operate its various organs, maintain a constant body temperature, and do external work, for example, lifting. A small percentage (~5%) of the food energy is excreted in the feces and urine; any energy that is left over is stored as body fat. The energy used to operate the organs eventually appears as body heat. Some of this heat is useful in maintaining the body at its normal temperature, but the rest must be disposed of. (Other energy sources such as radiant solar energy and heat energy from our surroundings can help maintain body temperature but are of no use in body function.)

In this chapter we discuss the conservation of energy in the body (first law of thermodynamics), the conversion of energy in the body, the work done by and power of the body, and how the body loses heat.

5.1. CONSERVATION OF ENERGY IN THE BODY

Conservation of energy in the body can be written as a simple equation:

$$\begin{bmatrix}\text{change in stored energy}\\ \text{in the body (i.e., food}\\ \text{energy, body fat, and}\\ \text{body heat)}\end{bmatrix} = \begin{bmatrix}\text{heat lost}\\ \text{from the body}\end{bmatrix} + \begin{bmatrix}\text{work done}\end{bmatrix}$$

This equation, which is really the first law of thermodynamics, assumes that no food or drink is taken in and no feces or urine is excreted during the interval of time considered. In this section we discuss this law.

There are continuous energy changes in the body both when it is doing work and when it is not. We can write the first law of thermodynamics as

$$\Delta U = \Delta Q - \Delta W \tag{5.1}$$

where ΔU is the change in stored energy, ΔQ is the heat lost or gained, and ΔW is the work done by the body in some interval of time.* A body doing no work ($\Delta W = 0$) and at a constant temperature continues to lose heat to its surroundings, and ΔQ is negative. Therefore, ΔU is also negative, indicating a decrease in stored energy. The energy term ΔU is discussed in Section 5.2, the work term ΔW is discussed in Section 5.3, and the heat term ΔQ is considered in Section 5.4.

It is useful to consider the change of ΔU, ΔQ, and ΔW in a short interval of time Δt. Equation 5.1 then becomes

$$\frac{\Delta U}{\Delta t} = \frac{\Delta Q}{\Delta t} - \frac{\Delta W}{\Delta t} \tag{5.2}$$

where $\Delta U/\Delta t$ is the rate of change of stored energy, $\Delta Q/\Delta t$ is the rate of heat loss or gain, and $\Delta W/\Delta t$ is the rate of doing work, that is, the mechanical power.

Equation 5.2, which is used extensively in this chapter, is merely another form of the first law of thermodynamics. It tells us that energy is conserved in all processes, but it does not tell us whether or not a process can occur. For example, according to the first law if we put heat into the

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*Conventionally, the first law is written as $\Delta Q = \Delta U + \Delta W$, that is, if heat is added to a gas it can increase the internal energy ΔU and also do work ΔW.

body we could expect the body to produce an equal amount of chemical energy or work. The physical law governing the direction of the energy conversion process is given in the second law of thermodynamics. We refer readers interested in more details on this subject to the book by Kleiber listed in the bibliography.

5.2. ENERGY CHANGES IN THE BODY

Several energy and power units are used in relation to the body. Physiologists usually use *kilocalories* (kcal) for food energy and kilocalories per minute for the rate of heat production. The energy value of food referred to by nutritionists as a Calorie (C) is actually a kilocalorie; thus a diet of 2500 C/day is 2500 kcal/day.

The most widely accepted physics unit for energy is the newton-meter or joule (J); power is given in joules per second or watts (W). The energy unit in the cgs system is the erg, and that in the English system is the foot-pound (ft-lb).

A convenient unit for expressing the rate of energy consumption of the body is the *met*. The met is defined as 50 kcal/m^2 of body surface area per hour. For a normal person 1 met is about equal to the energy consumption under resting conditions. A typical man has about 1.85 m^2 of surface area (a woman has about 1.4 m^2), and thus for a typical man 1 met is about 92 kcal/hr or 107 W.

In this chapter we use kilocalories and joules for energy units and kilocalories per second, minute, or hour, watts, and horsepower (hp) for energy rates (power). These units are summarized as follows:

1 kcal = 4184 J
1 J = 10^7 ergs = 0.737 ft-lb
1 kcal/min = 69.7 W = 0.094 hp
100 W = 1.43 kcal/min
1 hp = 642 kcal/hr = 746 W = 550 ft-lb/sec
1 met = 50 kcal/m^2 hr = 58 W/m^2
1 kcal/hr = 1.162 W

Lavoisier was the first to suggest (in 1784) that food is oxidized. He based his arguments on measurements of an experimental animal that showed that oxygen consumption increased during the process of digestion. He explained this effect as work of digestion. We now know that this explanation is incorrect; the correct explanation is that oxidation occurs in the cells of the body.

In oxidation by combustion heat is released. In the oxidation process within the body heat is released as energy of metabolism. The rate of oxidation is called the *metabolic rate*.

Let us consider the oxidation of glucose, a common form of sugar used for intravenous feeding. The oxidation equation for 1 mole of glucose ($C_6H_{12}O_6$) is

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 686 \text{ kcal}$$

That is, 1 mole of glucose (180 g) combines with 6 moles of O_2 (192 g) to produce 6 moles each of H_2O (108 g) and CO_2 (264 g), releasing 686 kcal of heat energy in the reaction. Using this information we can compute a number of useful quantities for glucose metabolism. (Remember that 1 mole of a gas at normal temperature and pressure has a volume of 22.4 liters.)

$$\text{Kilocalories of energy released per gram of fuel} = \frac{686}{180} = 3.80$$

$$\text{Kilocalories released per liter of } O_2 \text{ used} = \frac{686}{22.4 \times 6} = 5.1$$

$$\text{Liters of } O_2 \text{ used per gram of fuel} = \frac{6 \times 22.4}{180} = 0.75$$

$$\text{Liters of } CO_2 \text{ produced per gram of fuel} = \frac{6 \times 22.4}{180} = 0.75$$

Ratio of moles of CO_2 produced to moles of O_2 used—called the *respiratory quotient* (R) = 1.0

Similar calculations can be done for fats, proteins, and other carbohydrates. Typical caloric values of these food types and of common fuels are given in Table 5.1. Table 5.1 also lists for the various types of food the

Table 5.1. Typical Energy Relationships for Some Foods and Fuels

Food or Fuel	Energy Released per Liter of O_2 Used (kcal/liter)	Caloric Value (kcal/g)
Carbohydrates	5.3	4.1
Proteins	4.3	4.1
Fats	4.7	9.3
Typical diet	4.8–5.0	—
Gasoline	—	11.4
Coal	—	8.0
Wood (pine)	—	4.5

energy released per liter of oxygen consumed; thus by measuring the oxygen consumed by the body, we can get a good estimate of the energy released.

The caloric values in Table 5.1 for the foods are the maximum that might be expected. Not all of this energy is available to the body because part is lost in incomplete combustion. The "unburned" products are released in feces, urine, and flatus (intestinal gas). What remains is the metabolizable energy. The body is usually quite efficient at extracting energy from food. For example, the energy remaining in normal feces is only about 5% of the total energy contained in the consumed food. When the body is at constant temperature the energy that is extracted from food plus the body fat make up the available stored energy.

When completely at rest, the typical person consumes energy at a rate of about 92 kcal/hr, or 107 W, or about 1 met. This lowest rate of energy consumption, called the *basal metabolic rate* (BMR), is the amount of energy needed to perform minimal body functions (such as breathing and pumping the blood through the arteries) under resting conditions. Clinically an individual's BMR is compared to normal values for a person of the same sex, age, height, and weight. The BMR depends primarily upon thyroid function. A person with an overactive thyroid has a higher BMR than a person with normal thyroid function.

Since the energy used for basal metabolism becomes heat which is primarily dissipated from the skin (see Section 5.4), one might guess that the basal rate is related to the surface area or to the mass of the body. Figure 5.1 shows a plot of BMR (kcal/day) for various animals of widely different weights. The slope of the line indicates that the BMR is proportional to mass$^{3/4}$. Thus as animals get larger their BMR increases faster than their surface area but not as fast as their volume (mass).

The metabolic rate depends to a large extent on the temperature of the body. Chemical processes are very temperature dependent, and a small change in temperature can produce a large change in the rate of chemical reactions. If the body temperature changes by 1°C, there is a change of about 10% in the metabolic rate. For example, if a patient has a temperature of 40°C, or 3°C above normal, the metabolic rate is about 30% greater than normal. Similarly, if the body temperature drops 3°C below normal, the metabolic rate (and oxygen consumption) decreases by about 30%. You can see why hibernating at a low body temperature is advantageous to an animal and why a patient's temperature is sometimes lowered during heart surgery.

Obviously, in order to keep a constant weight an individual must consume just enough food to provide for basal metabolism plus physical activities. Eating too little results in weight loss; continued too long it results in starvation. However, a diet in excess of body needs will cause

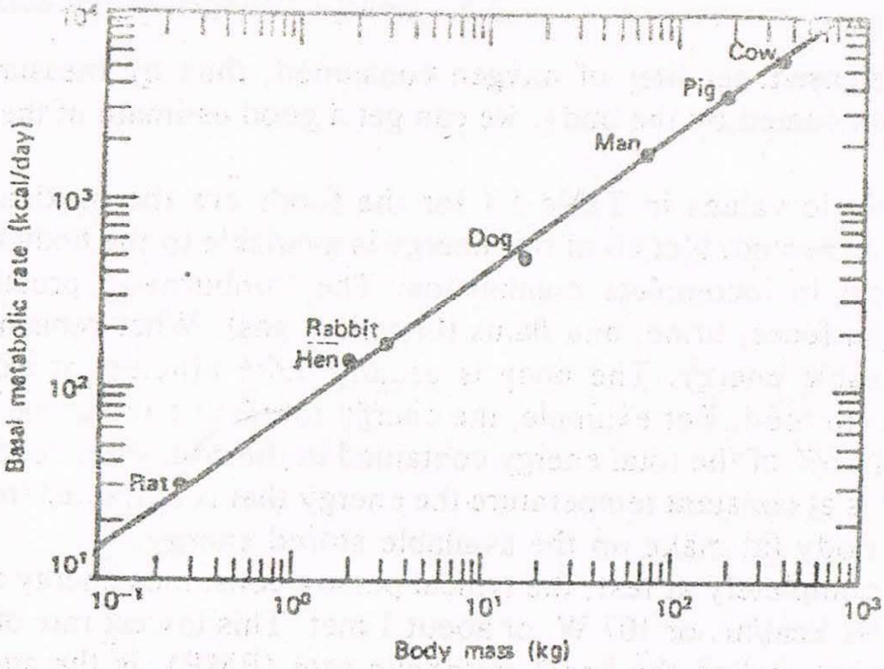

Figure 5.1. Relationship between the basal metabolic rate and the body mass for several different animals.

an increase in weight. Weight loss through dieting and physical exercise is discussed in Example 5.1.

Example 5.1

Suppose you wish to lose 4.54 kg (10 lb) either through physical activity or by dieting.

a. How long would you have to work at an activity of 15 kcal/min to lose 4.54 kg of fat? (Of course, you could not maintain this activity rate very long.)

From Table 5.1 you can expect a maximum of 9.3 kcal/g of fat. If you worked for T minutes, then

$$(T\ \text{min})\left(\frac{15\ \text{kcal}}{\text{min}}\right) = (4.54 \times 10^3\ \text{g})\left(\frac{9.3\ \text{kcal}}{\text{g}}\right) = 4.2 \times 10^4\ \text{kcal}$$

$$T = 2810\ \text{min} \simeq 47\ \text{hr}$$

Note that a great deal of exercise is needed to lose a few pounds.

b. It is usually much easier to lose weight by reducing your food intake. If you normally use 2500 kcal/day, how long must you diet at 2000 kcal/day to lose 4.54 kg of fat?

$$T = \frac{\text{energy of 4.54 kg fat}}{\text{energy deficit per day}} = \frac{4.2 \times 10^4\ \text{kcal}}{5 \times 10^2\ \text{kcal/day}} \simeq 84\ \text{days}$$

The BMR is sometimes determined from the oxygen consumption when resting. We can also estimate the food energy used in various physical activities by measuring the oxygen consumption. Table 5.2 gives some typical values for various activities.

Oxygen consumption for various organs has been measured, and these values are given in Table 5.3. Note that some of the organs use rather large amounts of energy and that the kidney uses more energy per kilogram than the heart.

5.3. WORK AND POWER

Chemical energy stored in the body is converted into external mechanical work as well as into life-preserving functions. We now discuss external work ΔW, defined as a force F moved through a distance Δx:

$$\Delta W = F \, \Delta x$$

Table 5.2. Oxygen Cost of Everyday Activities for a Man with a Surface Area of 1.75 m², Height of 175 cm, and Mass of 76 kg[a]

Activity	O_2 Consumption (liters/min)	Equivalent Heat Production kcal/min	Equivalent Heat Production W	Energy Consumption (mets—50 kcal/m² hr)
Sleeping	0.24	1.2	83	0.82
Sitting at rest	0.34	1.7	120	1.15
Standing relaxed	0.36	1.8	125	1.25
Riding in automobile	0.40	2.0	140	1.35
Sitting at lecture (awake)	0.60	3.0	210	2.05
Walking slow (4.8 km/hr)	0.76	3.8	265	2.60
Cycling at 13–17.7 km/hr	1.14	5.7	400	3.90
Playing tennis	1.26	6.3	440	4.30
Swimming breaststroke (1.6 km/hr)	1.36	6.8	475	4.65
Skating at 14.5 km/hr	1.56	7.8	545	5.35
Climbing stairs at 116 steps/min	1.96	9.8	685	6.70
Cycling at 21.3 km/hr	2.00	10.0	700	6.85
Playing basketball	2.28	11.4	800	7.80
Harvard Step Test[b]	3.22	16.1	1120	11.05

[a] Adapted from P. Webb, in J. F. Parker and V. R. West (Eds.), *Bioastronautics Data Book*, National Aeronautics and Space Administration, Washington, D.C., 1973, pp. 859–861.

[b] A test in which the subject steps up and down a 40 cm step 30 times/min for 5 min.

Table 5.3. Oxygen Use and Metabolic Rate Contribution of the Principal Organs of a Resting, Healthy Man Weighing 65 kg[a]

Organ	Mass (kg)	Average Rate of O_2 Consumption by Experiment (ml/min)	Average Rate of Energy Consumed (kcal/min)	Power per kg (kcal/min/kg)	Percent of BMR
Liver and spleen	—	67	0.33	—	27
Brain	1.40	47	0.23	0.16	19
Skeletal muscle	28.0	45	0.22	7.7×10^{-3}	18
Kidney	0.30	26	0.13	0.42	10
Heart	0.32	17	0.08	0.26	7
Remainder	—	48	0.23	—	19
		250	1.22		100%

[a] Adapted from R. Passmore, in R. Passmore and J.S. Robson (Eds.), *A Companion to Medical Studies*, Vol. I, Blackwell, Osney Mead, England, 1968, p. 4.9.

The force and the motion Δx must be in the same direction. The rate of doing work is the power p; thus for a constant force

$$p = \frac{\Delta W}{\Delta t} = \frac{F \Delta x}{\Delta t} = Fv$$

where $\Delta x/\Delta t$ equals the velocity v.

Obviously, external work is done when a person is climbing a hill or walking up stairs. We can calculate the work done by multiplying the person's weight (mg) by the vertical distance (h) moved. When a man is walking or running at a constant speed on a level surface, most of the forces act in the direction perpendicular to his motion. Thus, the external work done by him appears to be zero. However, his muscles are doing internal work which appears as heat in the muscle and causes a rise in its temperature. This additional heat in the muscle is removed by blood flowing through the muscle, by conduction to the skin, and by sweating. These processes are considered in Section 5.4.

In this section we want to study the human body as a machine for doing external work. This topic lends itself well to experiment. For example, we can measure the external work done and power supplied by a subject riding on an ergometer, a fixed bicycle that can be adjusted to vary the amount of resistance to the turning of the pedals (Fig. 5.2). We can also measure the oxygen consumed during this activity. The total food energy

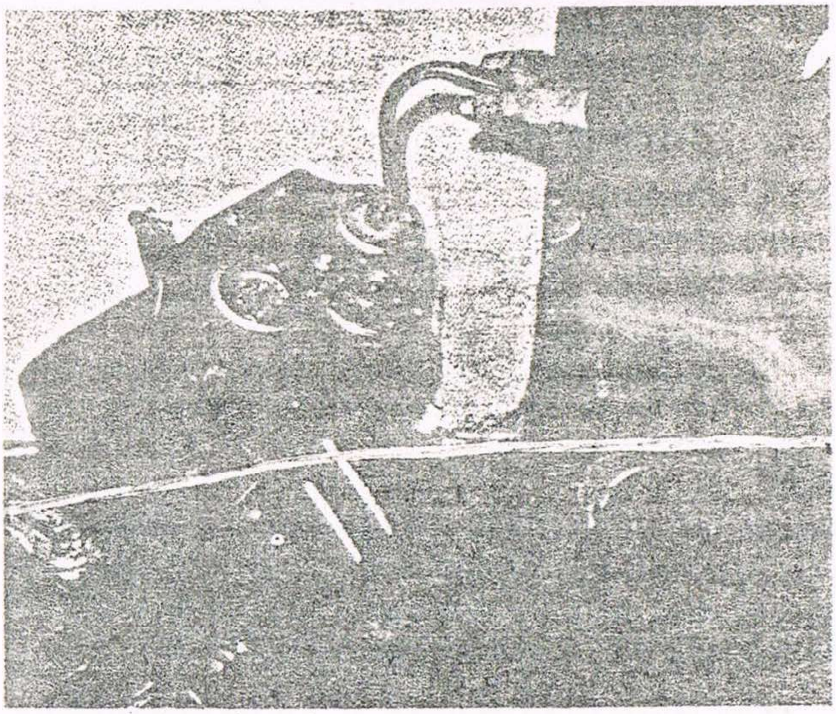

Figure 5.2. The ergometer, a stationary bicycle with adjustable friction that permits studies of oxygen consumption under various work loads. One of the meters indicates the power produced.

consumed can be calculated since 4.8 to 5.0 kcal are produced for each liter of oxygen consumed.

The efficiency of the human body as a machine can be obtained from the usual definition of the efficiency ϵ:

$$\epsilon = \frac{\text{work done}}{\text{energy consumed}}$$

Efficiency is usually lowest at low power but can increase to 20% for trained individuals in activities such as cycling and rowing. Table 5.4 shows the efficiency of man for several activities along with the efficiency of several mechanical engines. It is difficult to compare different activities (such as swimming and cycling).

Studies have shown that cycling is one of our most efficient activities (see Example 5.2). For a trained cyclist the efficiency approaches 20% with an external power production of 370 W (0.5 hp) and a metabolic rate of 1850 W. If the cyclist is on level ground and moving at a constant speed there is no change in potential or kinetic energy and the power supplied is used primarily to overcome wind resistance and friction of tire flexing. (See *Bicycling Science: Ergonomics and Mechanics*, listed in the bibliography.)

Table 5.4. Mechanical Efficiency of Man and Machines

Task or Machine	Efficiency (%)
Cycling	~20
Swimming (on surface)	< 2
(underwater)	~ 4
Shoveling	~ 3
Steam engine	17
Gasoline engine	38

Example 5.2

Compare the energy required to travel 20 km on a bicycle to that needed by an auto for the same trip. Gasoline has 11.4 kcal/g and a density of 0.68 kg/liter. Assume that the auto can travel 8.5 km on a liter of gasoline.

The auto requires 2.35 liters to travel the 20 km.

$$(2.35 \text{ liters})\ (0.68 \text{ kg/liter}) = 1.6 \text{ kg of gasoline}$$
$$(1.6 \times 10^3 \text{ g})\ (11.4 \text{ kcal/g}) = 1.8 \times 10^4 \text{ kcal for } 20 \text{ km}$$

The energy consumption for bicycling at 15 km/hr (~9 mph) (Table 5.2) is 5.7 kcal/min, so (5.7 × 80) or 456 kcal is used in the 80 min needed to travel the 20 km. It thus takes almost 40 times more energy to move by car than by bicycle.

The maximum work capacity of the body is variable. For short periods of time the body can perform at very high power levels, but for long-term efforts it is more limited. Experimentally it has been found that long-term power is proportional to the maximum rate of oxygen consumption in the working muscles. For a healthy man this consumption is typically 50 ml/kg of body weight each minute.

The body supplies instantaneous energy for short-term power needs by splitting energy-rich phosphates and glycogen, leaving an oxygen deficit in the body. This process can only last about a minute and is called the anaerobic (without oxygen) phase of work; long-term activity requires oxygen (aerobic work). Figure 5.3 shows these phases of work for a cyclist.

5.4. HEAT LOSSES FROM THE BODY

Birds and mammals are referred to as *homeothermic* (warm-blooded), while other animals are considered *poikilothermic* (cold-blooded). The

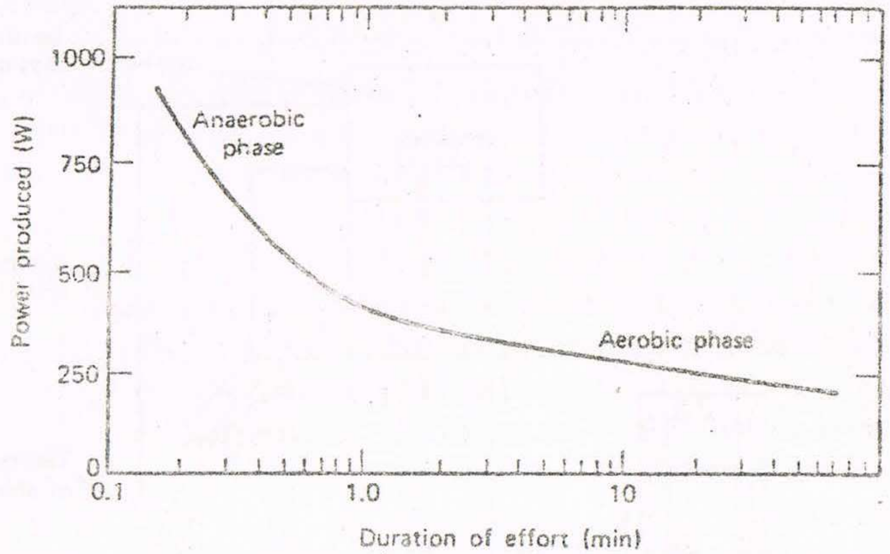

Figure 5.3. Typical power output on a bicycle versus duration of effort for an average healthy adult. Anaerobic work can only be maintained about 1 min.

terms *warm-blooded* and *cold-blooded* are misleading, for a poikilothermic animal such as a frog or a snake will have a higher body temperature on a hot day than a mammal. Birds and mammals both have mechanisms to keep their body temperatures constant despite fluctuations in the environmental temperature. Constant body temperatures permit metabolic processes to proceed at constant rates and these animals to remain active even in cold climates.

Because the body is at a constant temperature it contains stored heat energy that is essentially constant as long as we are alive. However, when metabolic activity ceases at death, the stored heat is given off at a predictable rate until the body cools to the surrounding temperature. The body temperature can thus be used to estimate how long a person has been dead.

Although the normal body (core) temperature is often given as 37°C, or 98.6°F, only a small percentage of people have exactly that temperature. If we measured the temperatures of a large number of healthy people, we would find a distribution of temperatures, with nearly everyone falling within ±0.5°C (~1°F) of the normal temperature. The rectal temperature is typically 0.5°C (~1°F) higher than the oral temperature. The temperature depends upon the time of the day (lower in the morning); the temperature of the environment; and the amount of recent physical activity, the amount of clothing, and the health of the individual. The rectal temperature after hard exercise may be as high as 40°C (104°F).

Figure 5.4 is a schematic diagram of the body's heating and cooling system. The figure does not show food, drink, and wastes (feces, flatus, and urine) or the energy that appears as external work. The heat is

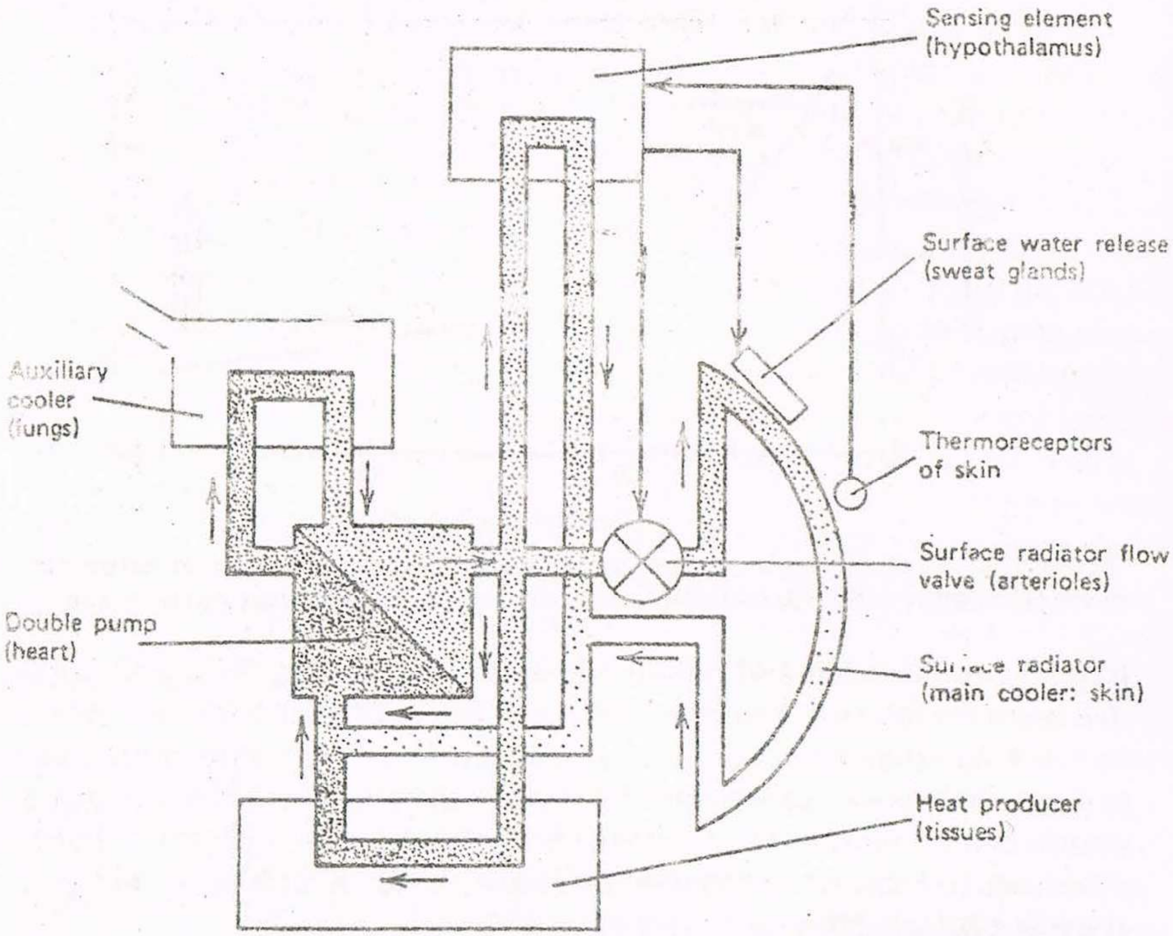

Figure 5.4. Schematic of the heat loss system of man. The amount of heat in the blood is indicated by the density of the dots. (From R.W. Stacy, D.T. Williams, R.E. Worden, and R.O. McMorris, *Essentials of Biological and Medical Physics*, McGraw-Hill, New York, 1955, p. 158.)

generated in the organs and tissues of the body; most of it is removed by several processes that take place on the skin's surface. The main heat loss mechanisms are radiation, convection, and evaporation (of perspiration). In addition, some cooling of the body takes place in the lungs where the inspired air is usually heated and vaporized water is added to the expired air. Eating hot or cold food may also heat or cool the body.

For the body to hold its temperature close to its normal value it must have a thermostat analogous to a home thermostat that maintains the temperature of the rooms nearly constant. The hypothalamus of the brain contains the body's thermostat. If the core temperature rises, for example, due to heavy exertion, the hypothalamus initiates sweating and vasodilation, which increases the skin temperature. Both of these reactions increase the heat loss to the environment. If the skin temperature drops, the thermoreceptors on the skin inform the hypothalamus and it initiates shivering, which causes an increase in the core temperature.

The rate of heat production of the body for a 2400 kcal/day diet (assuming no change in body weight) is about 1.7 kcal/min or 120 J/sec (120 W). If the body is to maintain a constant temperature it must lose heat at the same rate. The actual amount of heat lost by radiation, convection, evaporation of sweat, and respiration depends on a number of factors: the temperature of the surroundings; the temperature, humidity, and motion of the air; the physical activity of the body; the amount of the body exposed; and the amount of insulation on the body (clothes and fat). We now discuss each of the mechanisms of heat loss for the case of a nude body.

All objects regardless of their temperature emit electromagnetic radiation (see Chapter 4, p. 70). In general, the amount of energy emitted by the body is proportional to the absolute temperature raised to the fourth power. The body also receives radiant energy from surrounding objects. The approximate difference between the energy radiated by the body and the energy absorbed from the surroundings can be calculated from the equation

$$H_r = K_r A_r e(T_s - T_w)$$

where H_r is the rate of energy loss (or gain) due to radiation, A_r is the effective body surface area emitting the radiation, e is the emissivity of the surface, T_s is the skin temperature (°C), and T_w is the temperature of the surrounding walls (°C). K_r is a constant that depends upon various physical parameters and is about 5.0 kcal/m^2 hr °C. The emissivity e in the infrared region is independent of the color of the skin and is very nearly equal to 1, indicating that the skin at this wavelength is almost a perfect absorber and emitter of radiation. (If we could see the deep infrared emitted by the body we would all be "black.")

Under normal conditions a large fraction of our energy loss is due to radiation even if the temperature of the surrounding walls is not much lower than body temperature. For example, if a nude body has an effective surface area of 1.2 m^2 and a skin temperature of 34°C, it will lose about 54 kcal/hr to walls maintained at 25°C (77°F). This amounts to about 54% of the body's heat loss. Most of the remaining heat loss is due to convection.

The heat loss due to convection (H_c) is given approximately by the equation

$$H_c = K_c A_c (T_s - T_a)$$

where K_c is a constant that depends upon the movement of the air, A_c is the effective surface area, T_s is the temperature of the skin, and T_a is the temperature of the air. When the body is resting and there is no apparent wind, K_c is about 2.3 kcal/m² hr °C. When the air temperature is 25°C, the skin temperature is 34°C, and the effective surface area is 1.2 m², the nude body loses about 25 kcal/hr by convection. This amounts to about 25% of the body's heat loss. When the air is moving, the constant K_c increases according to the equation $K_c = 10.45 - v + 10\sqrt{v}$, where the wind speed v is in meters per second (Fig. 5.5). This equation is valid for speeds between 2.23 m/sec (5 mph) and 20 m/sec (45 mph).

The equivalent temperature due to moving air is called the wind chill factor and is determined by the actual temperature and wind speed. For example, at an actual temperature of −20°C and a wind speed of 10 m/sec (a stiff breeze), the cooling effect on the body is the same as −40°C on a calm day (Table 5.5). See the book by Mather listed in the bibliography for more details.

The method of heat loss that most of us are familiar with is the evaporation of sweat. Under normal temperature conditions and in the absence of hard work or exercise, this method of cooling is rather unimportant compared to radiative and convective cooling. Under extreme conditions of heat and exercise, a man may sweat more than 1 liter of liquid per hour. Since each gram of water that evaporates carries with it the heat of vaporization of 580 calories, the evaporation of 1 liter carries with it 580 kcal. Of course, the sweat must evaporate from the skin in order to give this cooling effect; sweat that runs off the body provides essentially no

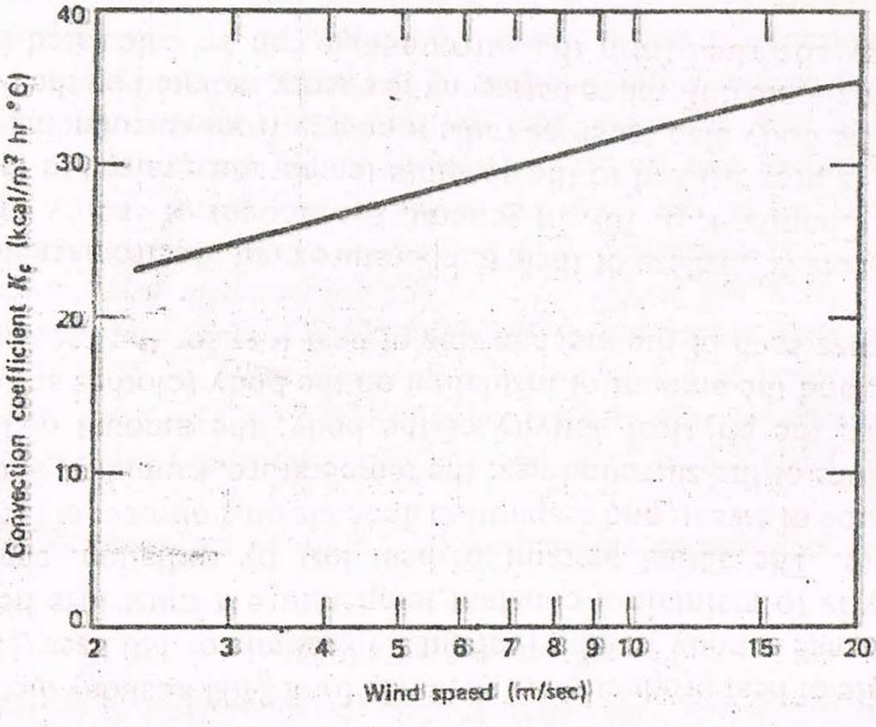

Figure 5.5. Dependence of convection coefficient K_c on wind speed for exposed skin.

Table 5.5. Wind Chill Factor Chart

Wind Speed (m/sec)	Actual Temperature (°C)						
	30	20	10	0	−10	−20	−30
	Equivalent Temperature (°C)						
2.23	30	20	10	0	−10	−20	−30
5	29	17	5	−7	−19	−31	−43
10	29	15	1	−13	−27	−40	−54
15	29	14	−1	−16	−30	−45	−60
20	28	13	−2	−17	−32	−48	−63

cooling. The amount evaporated depends upon the air movement and the relative humidity.

There is some heat loss due to perspiration even when the body does not feel sweaty. It amounts to about 7 kcal/hr, or 7% of the body's heat loss. A similar loss of heat is due to the evaporation of moisture in the lungs. When we breathe in air, it becomes saturated with water in the lungs. The additional water in the expired air carries away the same amount of heat as if it were evaporated from the skin. Also, when we inspire cold air, we warm it to body temperature and lose heat. Under typical conditions the total respiratory heat loss is about 14% of the body's heat loss.

Since the radiation of heat from the body and the transfer of heat to the air depend upon the skin temperature, any factors that affect the skin temperature also affect the heat loss. The body has the ability to select the path for blood returning from the hands and feet. In cold weather blood is returned to the heart via internal veins that are in contact with the arteries carrying blood to the extremities. In this way some of the heat from the blood going to the extremities is used to heat the returning blood. This *counter-current* heat exchange lowers the temperature of the extremities and reduces the heat loss to the environment. In the summertime or in a warm environment, the returning venous blood flows near the skin, raising the temperature of the skin and thus increasing the heat loss from the body.

Our discussion of heat loss mechanisms has so far been concerned with heat loss from the nude body—an interesting, but somewhat uncommon case. Including the insulation of clothing in the heat loss equations makes the calculations more difficult. The optimum skin temperature for comfort is about 33°C (92°F). This temperature can be maintained by suitably adjusting the clothing to the activity. Studies with clothing have led to the definition of a unit of clothing, the *clo*, which corresponds to the insulating value of clothing needed to maintain a subject sitting at rest in comfort in a room at 21°C (70°F) with air movement of 0.1 m/sec and air humidity of less than 50%. One clo of insulation is equal to a lightweight business suit.

Obviously, 2 clos of clothing would enable a man to withstand a colder temperature than 1 clo. Likewise, a man would need a larger clo value to remain comfortable when he is inactive than when he is active. It is possible to determine the optimum clothing for comfort under various environmental conditions of temperature and air movement and for different physical activities. For example, studies show that an individual in the arctic needs clothing with insulation equal to about 4 clos. (Fox fur has an insulating value of about 6 clos.)

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REVIEW QUESTIONS

1. Under resting (basal) conditions, what percent of the body's energy is being used by the skeletal muscles and the heart?
2. What is a met?
3. For a hypothetical animal that has a mass of 700 kg,
   (a) Use Fig. 5.1 to estimate the basal metabolism rate.
   (b) Assuming 5 kcal/g of food, estimate the minimum amount of food needed each day.
4. By what percent does your metabolic rate increase if you have a fever 2°C above normal?
5. (a) What is the energy required to walk 20 km at 5 km/hr?
   (b) Assuming 5 kcal/g of food, calculate the grams of food needed for the walk.
6. Which organ uses the greatest power per kilogram?

7. Suppose that the elevator is broken in the building in which you work and you have to climb 9 stories—a height of 45 m above ground level. How many extra calories will this external work cost you if your mass is 70 kg and your body works at 15% efficiency?
8. What is the approximate maximum work efficiency of a trained cyclist? How does this compare to the maximum work efficiency of a steam engine?
9. A 70 kg hiker climbed a mountain 1000 m high. He reached the peak in 3 hr.
   (a) Calculate the external work done by the climber.
   (b) Assuming the work was done at a steady rate during the 3 hr period, calculate the power generated during the climb.
   (c) Assuming the average O_2 consumption during the climb was 2 liters/min (corresponding to 9.6 kcal/min), find the efficiency of the hiker's body.
   (d) How much energy appeared as heat in the body?
10. What is the anaerobic phase of work? How long will it last?
11. Are humans homeothermic or poikilothermic?
12. What are the main mechanisms of heat loss from the body?
13. (a) Calculate the convective heat loss per hour for a nude standing in a 5 m/sec wind. Assume $T_s = 33°C$, $T_a = 10°C$, and $A_c = 1.2\ m^2$.
    (b) If the wind speed were 2.23 m/sec, find the still air temperature that would produce the same heat loss (the wind chill equivalent temperature).
14. When an individual is in water, the convective heat loss term is greatly increased. For water immersion, $K_c \approx 16.5$ kcal/m² hr°C. Assuming the BMR of a resting man is 72 kcal/hr, find the water temperature at which the water heat loss is just balanced by the BMR. Assume $A_c = 1.75\ m^2$ and $T_s = 34°C$.
15. Consider a nude male on a beach in Florida. It is a sunny day so he is receiving radiation from the sun at the rate of 30 kcal/hr. He has an effective body surface area of 0.9 m², $T_s = 32°C$, and the temperature of his surroundings is 30°C.
    (a) Find the net energy gained by radiation per hour.
    (b) If there is a breeze at 4 m/sec, find the energy lost by convection per hour.
    (c) If he loses 10 kcal/hr by respiration and his metabolic rate is 80 kcal/hr, how much heat is lost by evaporation?
16. Under typical conditions, what percent of the body heat loss is due to respiration?
17. When is counter-current heat exchange involved in controlling the heat loss to the environment?
18. What is a clo?