4 ENERGY CONSUMED DURING PHYSICAL ACTIVITY

Living organisms do work by means of muscular movement. The energy required to perform the work is obtained from the **chemical energy** in the food eaten by the living organism. In general, only a **small fraction** of the energy consumed by the muscles is converted to work.

Only **1/5** of the chemical energy consumed by the muscle is converted to work **(20%)**. The rest is dissipated as heat (**80%**). The energy consumed per unit time during a given activity is called the **metabolic rate**.

Example: The amount of energy consumed by a 70-kg person jumping up 60 cm for 10 minutes at a rate of one jump per second. Find the muscle efficiency and total consumed energy?

Solution: The external mechanical work performed by the leg muscles in each jump is

$$Work = Weight \times height\ of\ jump = 70 \times 9.8 \times 0.6 = 411\ \text{J}$$

The **muscle efficiency** during the 10 minutes of jumping is

$$411 \times 600\ \text{jumps} = 24.7 \times 10^4\ \text{J}$$

If we assume a muscle efficiency of 20%, then **total consumed energy** in the act of jumping the body is

$$24.7 \times 10^4 \times 5 = 1.23 \times 10^6\ \text{J} = 294 \times 10^3\ \text{cal} = 294\ \text{kcal}$$

Note that there is a difference between the muscle efficiency and mechanical efficiency.

The **muscle efficiency** is the total mechanical work done by all muscles divided by the metabolic work done by the muscles.

The **mechanical efficiency** is the total mechanical work done (internal + external) divided by the metabolic energy cost in excess of the resting metabolic cost.

4.1 HEAT AND LIFE

The degree of hotness, or temperature, is one of the most important environmental factors in the functioning of living organisms. The rates of the metabolic processes necessary for life, such as cell divisions and enzyme reactions, depend on temperature.

The functioning of most living systems, plants and animals, is severely limited by seasonal variations in temperature.

All living systems need energy to function. In animals, this energy is used to circulate blood, obtain oxygen, repair cells, and so on. The amount of energy consumed by a person depends on the person's weight and build.

The amount of energy consumed by a person during a given activity divided by the surface area of the person's body is called metabolic rate.

$$Metabolic\ rate = \frac{\text{consumed energy per hour}}{Surface\ area}\ [\frac{\text{Cal}}{\text{m}^2.\text{hr}}]$$

$$Surface\ area\ of\ a\ person = 0.202 \times M^{0.425} \times H^{0.725}$$

M is the mass and H is the height of the person.

For example, a person with 70 Kg mass and height of 1.55 m spends energy per hour at rest about 70 Cal/hr. The metabolic rate would be

$$Metabolic\ rate = \frac{\text{consumed energy per hour}}{Surface\ area} = \frac{70}{0.202 \times 70^{0.425} \times 1.55^{0.725}}$$

$$= 41\frac{\text{Cal}}{\text{m}^2.\text{hr}}$$

This metabolic rate at rest is called the basal metabolic rate.

4.2 REGULATION OF BODY TEMPERATURE

People and other warm-blooded animals must maintain their body temperatures at a nearly constant level. For example, the normal internal body temperature of a person is about 37°C. A deviation of one or two degrees in either direction may signal some abnormality.

The body temperature is sensed by specialized nerve centres in the brain and by receptors on the surface of the body. The various cooling or heating mechanisms of the body are then activated in accord with the temperature.

Most of the heat generated by the body is produced deep in the body, far from the surfaces. In order to be eliminated, this heat must first be conducted to the skin. Therefore, the temperature of the skin must be lower than the internal body temperature.

The tissue of the body, without blood flowing through it, is a poor conductor. Simple thermal conductivity through tissue is inadequate for elimination of the excess heat generated by the body.

Thermal conduction or heat flux by conduction can be calculated by

$$H_c = \frac{K_c A \Delta T}{L}$$

where H_c (Cal/hr) is heat conductivity, K_c ($\frac{\text{Cal.cm}}{\text{m}^2\text{.hr.℃}}$) is the coefficient of thermal conductivity A (m^2) is the area perpendicular to heat flux, L (m) is the length of along which the heat flux passes and ΔT (°C) is the temperature gradient.

For example, if the thickness of the tissue between the interior and the exterior of the body is 3 cm, the average area through which conduction can occur is 1.5 m^2 and the temperature difference ΔT between the inner body and the skin of 2°C, the heat flux would be (K_c for tissue without blood is 18 $\frac{\text{Cal.cm}}{\text{m}^2\text{.hr.℃}}$)

$$H_c = \frac{K_c A \Delta T}{L} = \frac{18 \times 1.5 \times 2}{3} = 18 \text{ Cal/hr}$$

Most of the heat is transported from the inside of the body by blood in the circulatory system. The circulatory system carries the heated blood near to the surface skin. The heat is then transferred to the outside surface by conduction.

4.3 CONTROL OF SKIN TEMPERATURE

For heat to flow out of the body, the temperature of the skin must be lower than the internal body temperature. Therefore, heat must be removed from the skin at a sufficient rate to ensure that this condition is maintained. Because the heat conductivity of air is very low, the amount of heat removed by conduction is small. The surface of the skin is cooled primarily by convection, radiation, and evaporation.

4.3.1 Convection

When the skin is exposed to open air or some other fluid, heat is removed from it by convection currents. The rate of heat removal is proportional to the exposed surface area and to the temperature difference between the skin and the surrounding air. The rate of heat transfer by convection $\acute{H}_c$

$$\acute{H}_c = \acute{K}_c A_c (T_s - T_a)$$

where A_c is the skin area exposed to the open air, T_s is the skin temperature, T_a is the air temperature and $\acute{K}_c$ is the convection coefficient.

For example, consider a person standing straight, the exposed area is about 1.36 m^2. If the air temperature is 25°C and the average skin temperature is 33°C, the amount of heat removed is (given $\acute{K}_c$=6 Cal/m^2.hr.°C)

$$\acute{H}_c = \acute{K}_c A_c (T_s - T_a) = 6 \times 1.36 \times (33 - 25) = 65.4 \text{ Cal/hr}$$

4.3.2 Radiation

If the radiating surface is warmer than the skin surface, the skin is heated by radiation. A person begins to feel discomfort due to radiation if the temperature difference between the exposed skin and the radiating environment exceeds about 6 °C. In the extreme case, when the skin is illuminated by the sun or some other very hot object like a fire, the skin is heated intensely.

The radiative energy exchange (H_r) can be expressed by

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

where K_r is the radiation coefficient, T_s is the the skin surface temperature, T_r is the temperature of the nearby radiating surface and e is the emissivity of the surface.

For example, For a person with A_r = 1.5 m^2, T_r = 25 °C, T_s = 32 °C, K_r = 6 (Cal/m^2.hr.°C) and e = 1 for human skin, then the radiative heat loss from skin would be

$$H_r = K_r A_r e(T_s - T_r) = 6 \times 1.5 \times 1 \times (32 - 25) = 63 \text{ Cal/hr}$$

4.3.2.1 **Radiative heating by the sun**

Because the rays of the sun come from one direction only, at most half the body surface is exposed to solar radiation. As the sun approaches the horizon, the effective area for the interception of radiation increases, but at the same time the radiation intensity decreases because the radiation passes through a thicker layer of air. The amount of heat H_r that the human body receives from solar radiation is

$$H_r = \frac{1150}{2} \times e \times A\,cos\theta$$

Here A is the skin area of the person, θ is the angle of incidence of sunlight, and e is the emissivity of the skin.

The emissivity of the skin in the wavelength region of solar radiation depends on the pigmentation. Dark skin absorbs about 80% of the radiation, and light skin absorbs about 60%.

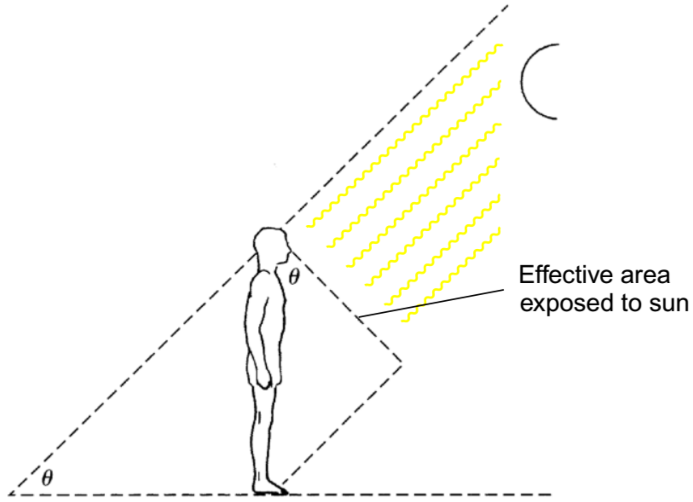

Figure 4: Radiative heating by the sun.

4.3.3 Evaporation

In a warm climate, convection and radiation cannot adequately cool a person engaged in even moderate physical activity. A large fraction of cooling is provided by the evaporation of sweat from the skin surfaces. During prolonged heavy sweating, adequate amounts of water must be drunk; otherwise, the body becomes dehydrated.

There is another avenue for evaporative heat loss: breathing. The air leaving the lungs is saturated by water vapor from the moist lining of the respiratory system. By evaporative cooling, a person can cope with the heat generated by moderate activity, even in a very hot, sunny environment.