Subject: Medical Physics 1/9

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CH.5

Energy, Work, and Power of the body

The body'sbasic energy (fuel) source is food (consider Krebs cycle).

Under resting (basal) conditions about 25% of the body's energy is being used by the skeletal muscles and the heart, 19% by the brain, 10% by the kidneys, and 27% by liver and spleen.(~5%) is excreted in feces and urine, the remaining is stored as body fat.

5.1 Conservation of Energy in the Body

Conservation of energy in the body can be written as a (the first law of thermodynamics) simple equation

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

Also can be written as

$\Delta U = \Delta Q - \Delta W$ (conventionally, $\Delta Q = \Delta U + \Delta W$)

Where ΔU is the change in stored energy

ΔQ is the heat lost or gained

ΔW is the work done by the body

- A body doing no work $\Delta W=0$, and at a constant temperature ΔQ(also ΔU) is negative

In a short interval of time, $\frac{\Delta U}{\Delta t} = \frac{\Delta Q}{\Delta t} - \frac{\Delta W}{\Delta t}$

$\frac{\Delta U}{\Delta t}$ is the rate of change of stored energy

$\frac{\Delta Q}{\Delta t}$ Is the rate of heat loss or gain

$\frac{\Delta W}{\Delta t}$ is the rate of doing work(mechanical power) 2/9

5.2 Energy Changes by the Body

Several energy and power (energy rate) units are used in relation to the body.

1 kcal(kilocalories) = 4184J --for food energy—

1 J (newton-meter or joule (J)) =10^7 ergs=0.737 ft-lb (foot-pound)

For the rate of heat production we use:

1 kcal/min = 69.7 W(joules per sec. or watts (W))= 0.094hp (horse power)

Note: a diet of 2500 C (Calorie) is actually 2500 kcal/day

100 W =1.43 kcal/min

1 met =50 kcal/m^2hr of body surface area per hour=58W/m^2, a where met is convenient unit for expressing the rate of energy consumption of the body

1 hp =642 kacl/hr =746 W=550 ft.lb/sec.

1 kcal/hr =1.162 W

- A typical man has about 1.85m^2 of surface area (a woman of 1.4m^2), thus for a typical man 1 met is about 92kcal/hr or 107W. woman 70
- In the oxidation process within the body heat is released as energy of metabolism. The rate of oxidation is called metabolic rate.

Example: Consider the oxidation of glucose

The oxidation equation for 1 mole of glucose is:

$C_6H_{12}O_6$+$6O_2$→ $6H_2O$ + $6CO_2$ +686 kcal

1 mole(180g) +6moles(192) → 6moles(108g) + 6moles(246g) +646kcal(heat)

- 1 mole of a gas at normal temperature and pressure has a volume of 22.4 liters.
- *Mole(L or N_A): the basic SI unit of amount of substance; the amount that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.*

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

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

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

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

Respiratory quotient (R) =1, is the ratio of moles of CO_2 produced to moles of O_2used. (0.75/0.75)

Similarly for fats, proteins, and other carbohydrates.

Table5.1 Typical Energy Relationships for Some Foods and Fuels

Food or Fuel	Energy Released per Liter of O_2 Used (kcal/liters)	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

- Measuring the oxygen consumed by the body gives estimation of the energy released.
- Unburned (Incomplete combustion) products released in feces, urine, and flatus. The remaining is the metabolized energy.
- Basal Metabolic Rate (BMR) is the amount of energy (lowest rate) needed to perform minimal body functions (breathing and pumping the blood through the arteries) under resting condition.

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- BMR depends primarily upon thyroid function. Overactive thyroid has a high BMR than normal thyroid function.

- BMR is related (proportional) to the surface area or to the mass of the body, see Fig. 5.1.
- MR depends on the temperature of the body.(10% for 1^{0}C change). For a patient of 40 ^{0}C, MR is about 30% greater than normal. Similarly, for a body temperature of 34 ^{0}C, MR decreases by about 30%.

Ex. 5.1a- How long would you have to work at an activity of 15 kcal/min to lose 4.54 kg of fat?(caloric value for fats is 9.3 kcal/g)

Sol: Energy of 4.54 kg fat = $4.54 * 10^3$ g *9.3 kcal/g =$4.2 * 10^4$ kcal

(T)(15 kcal/min) = $4.2 * 10^4$ kcal

$$T = 4.2 * 10^4/15 = 2810 \text{ min} \cong 47 \text{ hr.}$$

b- How long must you diet at 2000 kcal/day to lose 4.54 kg of fat if you normally use 2500 kcal/day?

Sol:

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

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- The BMR is sometimes determined from the oxygen consumption when resting;

Table 5.2 Oxygen Cost of Everyday Activities for a Man with Surface Area of 1.75 m^2, Height of 175 cm, and Mass of 76 kg.

Activity	O_2 Consumption (liters/min)	Equivalent Heat Production kcal/min	W	Energy Consumption (mets-50 kcal/m^2hr)
Sleeping	0.24	1.2	83	0.82
Sitting at rest	0.34	1.7	120	1.15
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

5.3 Work and Power

Chemical energy stored in the body is converted into external mechanical work as well as into life-preserving functions. External work (ΔW) is a force F moved through a distance ΔX (both in the same direction) thus:

$\Delta W = F \Delta X$

The power (the rate ΔW = (mg) (weight) * (h) (vertical distance)

of doing work) $P = \Delta W/\Delta t = F\Delta X/\Delta t = Fv$, where v is the velocity

- When climbing a hill or walking up stairs $w = mgh$
- When walking or running (most forces are perpendicular to the motion), thus ΔW appears to be zero. However, the muscles are doing internal work

  (heat in the muscle and temperature rising). Additional heat is removed by blood (by conduction to the skin and by sweating).
- The ergometer (a stationary bicycle) can be used to measure the external work done and power supplied by a subject. Also to measure the oxygen consumed during this activity. The total food energy consumed can be calculated since 4.5 to 5.0 kcal are produced for each liter of oxygen consumed.

- The efficiency ε of the human body (as a machine) is defined as:

  $$\varepsilon = \frac{work\ done}{energy\ consumed}$$

  Examples

Cycling ε≅ 20% (our most efficient activities)

Swimming (on surface) ε<2% (under water) ε~ 4%

Gasoline engine ε =38%

Ex. 5.2 Given:

- Caloric value of gasoline is 11.4 kcal/g and its density is 0.68 kg/liter, and assuming 8.5 km/liter.for auto
- The energy consumption for bicycling at 15 km/hr is 5.7 kcal/min.

Compare the energy required to travel 20 km on a bicycle to that needed by an auto.

Sol: For the auto(20km)/(8.5km/liter) = 2.35 liters of gasoline required

(2.35 liters) * (0.68 kg/liter) =1.6 kg of gasoline

$(1.6 * 10^3 g)$ (11.4kcal/g) = $1.8 * 10^4$ kcal for 20 km.

For the bicycling Time needed to travel 20 km (at 15 km/hr) = 80 min.

∴ (5.7 kcal/min) (80 min) = 456 kcal is needed for 20 km.

Thus: $(1.8 * 10^4)$ /456 = 40 times more energy to move by car than by bicycle.

Note: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 *anaerobic*(without oxygen) phase of work; long- term activity requires oxygen (*aerobic* work). 6/9

5.4 Heat Losses from the Body 7/9

Birds and mammals (keeping body temperature constant) are referred to as *homeothermic* (warm-blooded), other animals, are considered *poikilothermic* (cold-blooded), (note that frog or a snake will have a higher body temperature on a hot day than a mammal).

- Although the normal body (core) temperature is often given as 37^0C, or 98.6^0F, only a small percentage of people have exactly that temperature; distribution of temperature falling within $\pm 0.5^0$C ($\sim 1^0$F) may be found.
- The temperature depends upon 1- the time of the day, 2-the temperature of the environment, 3- the amount of recent physical activity, 4- the amount of clothing, and 5- the health of the individual.
- Body′ s heating system: The heat is generated in the organs and tissues of the body.
- Body′ s cooling system: The main heat loss mechanism are, 1- radiation, 2- convection, 3- evaporation(of perspiration), and 4- respiration. This loss depends on a number of factors: a-the temperature of the surroundings, b- physical activity of the body, c-the amount of the body exposed, and d- the amount of insulation on the body (clothes and fat).
- The hypothalamus of the brain contains the body′ s thermostat. If the core temperature rises, it initiates sweating and vasodilation, which increases the skin temperature(thus heat loss to 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 is about 1.7 kcal/min or 120 J/sec (120 W).

First :Consider the case of nude body.

1-The heat loss due radiation

Under normal conditions a large fraction of our energy loss is due to radiation.

The approximate difference between the energy radiated by the body and the energy absorbed from the surroundings can be calculated from the equation

$H_r = K_r A_r e\ (T_s - T)_w$ 8/9

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, (nearly equal to 1 for IR skin radiation),

T_s is the skin temperature (^{o}C), and

T_w is the temperature of the surrounding walls (^{o}C).

K_r is constant (about 5.0 kcal/m^2 hr^{o}C).

Ex. If a nude body has an effective surface area of 1.2 m^2 and a skin temperature of 34 ^{o}C and the temperature of the surrounding walls is (maintained at) 25 ^{o}C, calculate the energy loss due to radiation.

Sol: H_r= 5.0 * 1.2 *1 (34 – 25) = 54 kcal/hr (about 54% of the body′ s heat loss)

Most of the remaining heat loss is due to convection.

2-The heat loss due to convection

The heat convection due to convection (H_c) is given approximately by the equation $H_c= K_cA_c (T_s- T_a)$

Where K_c(convection coefficient)is a constant that depends on air movement; it increases with the air movementso that $K_c = 10.45 - v + 10\sqrt{v}$, where v is the wind speed in m/sec,

A_c is the effective surface area,

T_s is the temperature of the skin, and

T_a is the temperature of the air.

Ex. When the body(nude) is resting and there is no apparent wind, K_c is about 2.3 kcal/m^2 hr^{o}C. Suppose T_a = 25^{o}C, T_s = 34^{o}C, and A_c =1.2 m^2, calculate the body′ s heat loss by convection.

Sol: H_c= 2.3* 1.2 (34-25) = 24.84 or about 25 kcal/hr

This amount is about 25% of the body′ s heat loss.

Note: 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,when T=0^{O}C and v = 5 m/sec the equivalent temperature (cooling effect on the body) is the same as – 7^{o}C on a calm day.

3- The heat loss due to sweat evaporation (perspiration) and respiration.

Under extreme conditions of heat and exercise, a man may sweat more than 1liter of liquid per hour. 1gm of evaporated water gives 580 calories, hence 1 liter carries with it 580 kcal. Even when the body does not feel sweaty, there is about 7 kcal/hr, or 7% of the body′ s heat loss.

A similar loss of heatis due to the evaporation of moisture in the lungs; consider 7% loss for breathe in air, and 7% for inspire cold air. Under typical conditions the total respiratory heat loss will be about 14% of the body′ s heat.

- *The body has the ability to select the path for blood returning from the hands and feet. In cold weather we have counter-current; heat exchange (between internal veins and arteries) lowers the temperature of the extremities and reduces the heat loss to the environment. In 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.*

Second: Consider the case of including the insulation of clothing.

The optimum skin temperature for comfort is about 33^o C (92^o F).

The cb; a unit of clothing which corresponds to the insulating value of clothing needed to maintain a subject sitting at rest in comfort in a room at 21^o C (70^o F) *with air movement of 0.1 m/sec and air humidity of less than 50%.*

- 1 clo of insulation is equal to a lightweight business suit.
- 2 clos enable a man to withstand a colder temperature than 1 clo. (Fox fur has 6 cols).

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5.3. For a hypothetical animal that has a mass of 700kg, the estimated basal metabolism rate is 10^4 kcal/day. Assuming 5 kcal/g of food, estimate the minimal amount of food needed each day.

Sol. $10^4/5 = 2*10^3$ g/day =2 kg/day at BMR.

5.5. In walking slow activity, the equivalent heat production is 3.8 kcal/min.

(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?

Sol. (a) Energy = 3.8 kcal/min * (20km/5km/hr) *60 min/hr =912 kcal.

(b) 912 kcal/5 kcal/g =182g (0.4 lb).

5.7. Suppose you have to climb 9 stories – a height of 45m above ground level. How many calories will this work cost you if your mass is 70 kg and your body works at 15% efficiency? 1 kcal = 4184 J

Sol. Work =mgh = 70 (9.8) (45) J * kcal/$4.2*10^3$ J =7.3 kcal.

Calories needed = 7.3/efficiency = 7.3/0.15 = 49 kcal.

5.15. Consider a nude male on a beach. 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 $0.9m^2$,T_s=32°C, and the temperature of his surroundings is 30°C.

(a) Find the net energy gained by radiation per hour. Sol. H_r=5(0.9)(2)=9 kcal/hr.

(b) If there is a breeze at 4m/sec, find the energy lost by convection per hour.

Sol. H_c =26.5(0.9) (2) $\cong$ 48 kcal/hr.

(c) If he loses 10 kcal/hr by respiration and his metabolic rate is 80 kcal/hr, how much heat is lost by evaporation?

Sol. 80+30-48-9-10=evaporation loss of 43 kcal/hr.

Q1. If area of nude body 1.4 m^2 and sun temperature 35 c^o and surrounding walls as 24 c^o calculate the energy loss due radiation

Ans

Hr = Kr Ar e (T_S - T_W)

Kr = 5.0 Kcal \ m^2 hr c^o

Ar = 1.4 m^2

T_S = 35 c^o

T_w = 24 c^o

Hr = 5 * 1.4 * 1 * (35 – 24)

= 7 * 11

= 77 Kcal \ hr   energy loss due radiation

Q2. In walking slow activity , the equivalent heat production 3.8 Kcal\ min.

What is the energy required to walk 40 Km at 5 Km\hr?

Ans

Energy = 3.8 * 40\5

= 30.4 kcal\hr

= 30.4 * 60 = 1824 kcal

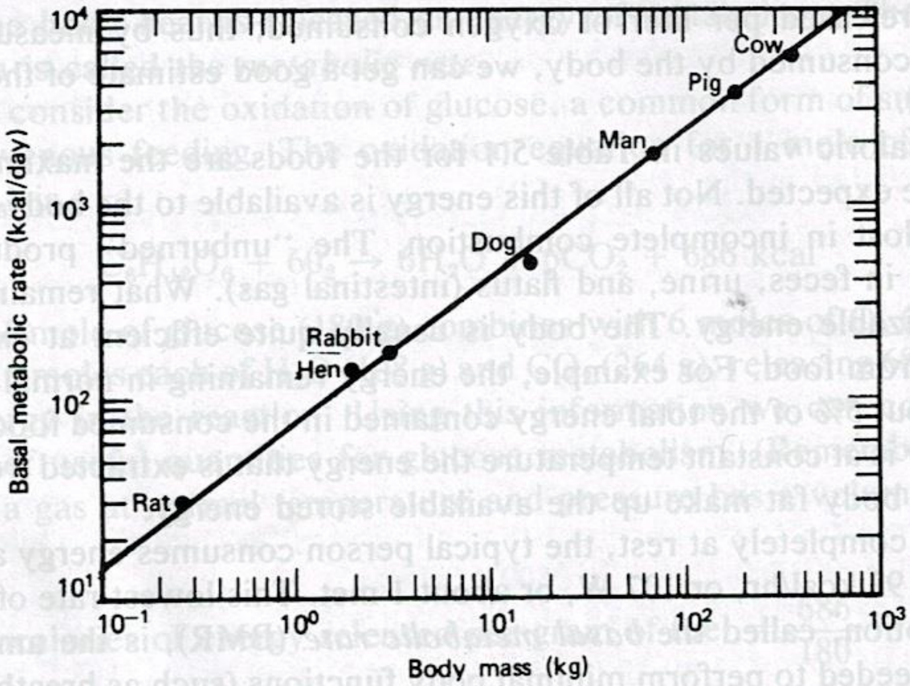

Figure 5.1. Relationship between the basal metabolic rate and the body mass for several different animals.