Energy, Work and power of the body

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All body activities including thinking, doing work, or keeping the body temp. constant involve energy changes, for example under resting(Basal)conditions the skeletal muscles and the heart using 25% of the body's energy ,another 19%is being used by the brain,10%is being used by the kidneys, and 27% is being used by the liver and the spleen. A small percent of about 5% of food energy being excreted in feces and urine.

Extra food energy will be stored mainly as fat. External heat energy from environment can help maintain the body temp. , but it has no use in body function.

Conservation of energy

Change in the stored energy (i.e. food energy, body fat and the body heat) =Heat lost from the body + Work done

Assumes that no food or drink is taken and no feces or urine is excreted during the interval of time considered.

- This is similar to the first law of thermodynamic:-

$$\Delta Q = \Delta u + \Delta w$$

- Where ΔQ is the change of quantity of heat of the system.

Δu is the change in the internal or stored energy.

Δw is the work done.

This can be written as

$$\Delta u = \Delta Q - \Delta w$$

A body doing no work ($\Delta w=0$) and at constant temp. continues to lose heat to its surroundings, and ΔQ is negative. Therefore, Δu is also negative, indicating a decrease in stored energy.

The rate of change of their variables is just taken per unit time (by dividing on Δt) .

$$\Delta u / \Delta t = \Delta Q/\Delta t - \Delta w/\Delta t$$

The body's basic source of energy is the food energy; it must be chemically changed by the body to make molecules that can combine with oxygen in the body's cells.

Energy change in the body

The units are joule or calorie 1cal= 4.184J or 1Kcal=4184J

The power is defined as energy or work per unit time =J/s=watt.

In the oxidation process within the body, heat is produced as energy of metabolism. The rate of oxidation is called metabolic rate.

For example the oxidation of one mole of glucose can be shown as:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6H_2O + 6CO_2 + 686\text{Kcal}$$

1 mole	**6 mole**	**6 mole**	**6 mole**
180g	**192g**	**108g**	**264g**

Co_2 and O_2 are gases (1 mole of a gas at normal temp. and pressure has a volume 22.4 liters)

From the above equation we can calculate useful quantities for glucose metabolism:

- Kcal of energy released/g of fuel (glucose) =686/180=3.8
- Kcal of energy released/L of O_2 used=686/ (22.4×6) =5.1
- Liters of O_2 used/g of fuel glucose = (22.4×6)/180=0.75
- Liters of Co_2 produced /g of fuel glucose= (22.4×6)/180=0.75

So the ratio of moles of Co_2 produced to moles of O_2 used, called the (respiratory quotient) R=1

No. of moles of Co_2/No. of moles of O_2 =1

Similar calculation can be done for fats, proteins, and other Carbohydrates.

By measuring the energy released per liter of O_2 we can get a good estimation of the energy released. Table 5.1 shows the caloric values for different types of foods and fuels. It gives the maximum values expected because not all food energy is available, as part of it is lost in incomplete combustion (not metabolized).

When the body is completely at rest, it will have the lowest rate of energy consumption this is called the basal metabolic rate (BMR), which is the amount of energy needed to perform minimal body functions (such as breathing

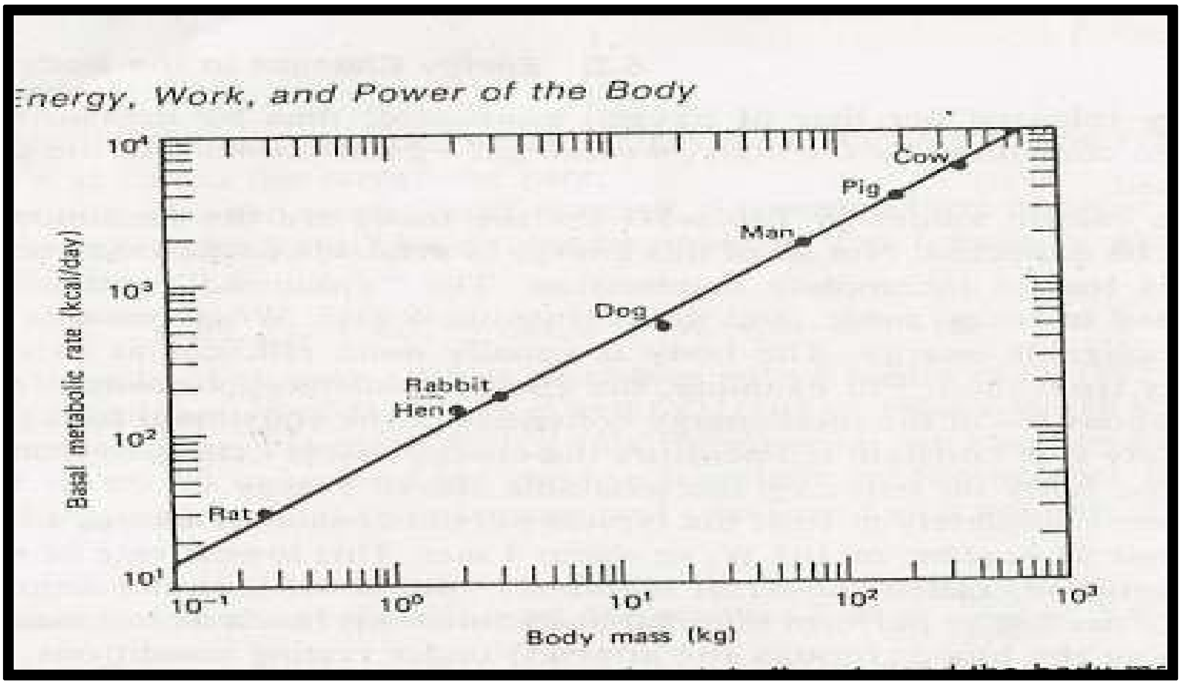
Table 5.1. Typical Energy Relationships for Some Foods and Fuels

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

and pumping the blood through the arteries) under resting conditions, and for typical person 92 Kcal/hr ≈ 107w or about 1 met (met is 50 Kcal/m^2hr).
m^2: body surface area

BMR depends on sex, age, height, and weight; it depends primarily on thyroid function, overactive thyroid gives higher BMR.

Since the energy used for basal metabolism becomes heat which is mainly dissipated from the skin, so the basal rate is related to the surface area or to the mass of the body. In figure 5.1 the graph represents the change between BMR (kcal/day) and the mass of different animals, the slope of the graph indicates that the BMR is proportional to mass.



When the animals gets larger the BMR increases faster than their increases in surface area but BMR increases even more faster with their mass(volume).

The BMR depends to large extent on the body temp., for an increase of 1°C it will change by 10% in the metabolic rate, so for 3°C the change will be 30% greater than normal. Similarly ,if the body temp. drops 3°C below normal, the metabolic rate decreases by about 30%. For this reason hibernating animals at low body temp. will reduce the metabolic rate very much. A man who is taking food energy equivalent to his BMR plus his other physical activities will keep on constant weight.

Less food will cause weight lose and for longer time cause starvation.

Excess food of body needs will cause food storage and increase in weight.

BMR is sometimes determined from oxygen consumption when resting, we can also estimate the food energy used in various physical activities by measuring the oxygen consumption, table (5.2) shows some typical values for various activities.

Table 5.2. Oxygen Cost of Everyday Activities for a Man with a Surface Area of 1.75 m^2, 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 $kcal/m^2$ 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.

Example: Suppose you wish to lose 4.54kg either through physical activity or by dieting.

1-How long would you have to work at an activity of 15Kcal/min to lose 4.54kg of fat?

From table 5.1 maximum of 9.3kcal/g of fat, if you worked for T minutes, then

$T(15\text{kcal/min})=(4.54\times10^3\text{g})(9.3\text{kcal/g})=4.2\times10^4\text{kcal}$

T=2810 min≈47hr

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

T= (energy of 4.54kg fat/energy deficit per day) $4.2\times10^4\text{kcal} / 5\times10^2\text{kcal/day} \approx 84$ days

Table 5.3 gives oxygen consumption for various organs, some organs use rather large amount of energy ,the kidney uses more energy per kilogram than the heart.

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. 1, Blackwell, Osney Mead, England, 1968, p. 4.9.

Work and power

Chemical energy stored in the body is converted into external mechanical work as well as into life-preserving functions.

Mechanical work is usually defined by $\Delta w = F.\ \Delta x$ where F is the force on the same line of displacement x, or it can be also written as:

($\Delta w = F\ \Delta x \cos \Theta$) where Θ is the angle between F and the direction of movement, the power is work per unit time.

$P = \Delta w/\Delta t = F\ \Delta x / \Delta t = F\ v$ where v is the velocity

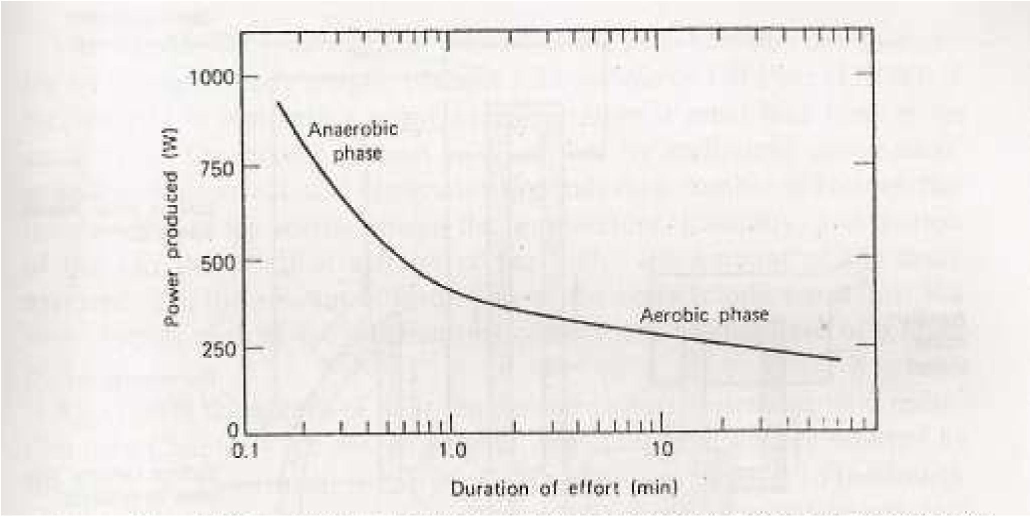
When the force is perpendicular to the displacement work will be zero, such as walking body, his weight is perpendicular to distance of movement but practically it will not be zero because the uses energy against friction and other movement of his body, but in the case of climbing person for distance (h) the weight is on the same line of displacement then the work = mgh, the efficiency of human body is

E = work done/ energy consumed

Efficiency is usually lowest at low power but can increase to 20% for trained individuals in activities such as cycling and rowing.

The maximum work capacity of the body is variable, for short period of time the body can perform at very high power levels,(like running very fast but it is more limited for longer periods).It is found that long term power is proportional to the maximum rate of oxygen consumption in the working muscles.

For healthy man this consumption is 50ml/kg m of body weight each minute. The body can supply an instantaneous energy for short term power needs, this can be done 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) .For longer term work requires oxygen aerobic. Fig (5.3)



Heat loses from the body

(Homeothermic)(Warm-blooded) such as birds and mammals, (poikilothermic)(cold-blooded) such as frog and snake, will have a higher body temp. on a hot day than mammals, birds and mammals both have mechanisms to keep their body temp. constant despite fluctuations in the environmental temp. Constant body temp. permit metabolic processes to produce at constant rates and these animals to remain active even in cold climates.

The normal human temp. is 37°C which is obtained from taking the temp. of large # of people. For a single individual the body temp. may vary about ≈0.5°C.The rectal temp. is about 0.5°C higher than the oral temp.

The temp. of the body depends on the:

1-Time of the day (lower in the morning)

2- Environment temp.

3-The amount of clothing

4-Health of the person

5- On his recent physical activity.

For example rectal temp. after hard exercise may be as high as 40°C ,the body losses heat mainly by radiation, convection, and evaporation, all these processes can take place in the skin. The evaporation of perspiration from the skin can cool down the skin by absorbing the latent heat of evaporation from it.

Evaporation takes place also in breathing causing cooling effect. If the air is cold it will also cool down the body. Eating and drinking cold or hot food can also decrease or increase the body temp.

The body temp. is kept constant for this reason the hypothalamus in the brain can control the body temp.(thermostate like).After heavy exercise the body is heated the hypothalamus initiate the sweating and vasodilation is the first causes heat loss by evaporation and the second increasing the blood supply to the skin for more loss of heat. On the other hand if the environment temp. drops the thermo receptors on the skin signals to the hypothalamus which in turn induce shivering to increase the body temp. The production of heat in the body for 2400 Kcal/day (assumeing no change in body weight)=1.7Kcal/min=120J/sec =120W.

So the body must lose the same amount of heat to stay at constant temp. .The heat loses depends on many factors:

1- The temp. of the surroundings 2-Humidity 3-Motion of the air 4-The physical activity of the body 5-The amount of the body exposed 6-The amount of the insulation of the body (like clothes and fat)

Transfer of heat by radiation

All objects regardless on their temp. emit electromagnetic radiation, the amount of energy emitted by the body is proportional to the absolute temp. raised to the fourth power. The body also receives radiant energy from surrounding objects. The amount of heat difference between the energy radiated by the body and the energy absorbed from the surrounding can be calculated from the equation:

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

Where
(H_r) is the rate of heat energy loss or gain
(K_r) is a constant depends upon various physical parameters and it's about =5Kcal/m^2 hr C° for man
(A_r) effective body surface area emitting radiation
e is the emissivity of the surface which is nearly=1,independent on the color of the skin indicating that the skin at this wavelength is almost a perfect emitter and absorber of radiation.
(T_s) is the skin temp. in C°
(T_w) is the temp of the surrounding walls
Δ Heat losses by radiation occur even the temp. differences is not high.
Example: for a nude person have a skin temp. 34°C in a room of walls temp. 25°C and his body area 1.2m^2 will lose 54 Kcal/hr which is 54% of the total losses. Most of the remaining heat will be by convection.

Transfer of heat by convection

Heat losses by convection (H_c)
$H_c = K_c A_c (T_s - T_a)$
Where:
H_c is the amount of heat gained or lost be convection
A_c is the effective surface area T_s is the skin temp.
T_a is the environment temp. or air temp.
K_c is a constant that depends on the movement of the air, for a resting body and no apparent wind K_c is about 2.3kcal/m^2 hr °C. When the air is moving K_c increases according to the equation:-

$$K_c = 10.45 - v + 10\sqrt{v} \quad \text{where v is the wind speed in m/sec}$$

This equation is valid for speeds between 2.23m/sec (5mph) and 20m/sec (45mph) (1 mile=1.6 km).

The equivalent temp. due to moving air is called the wind chill factor and is determined by the actual temp. and wind speed. For example for a windy day speed 10 m/sec an-20°C has the same cooling effect on the body as -40°C on a calm day. Table (5.5)

Transfer of heat by evaporation

Under normal temp. conditions and in the absence of hard work or exercise, heat loss mainly by radiation and convection, losses by evaporation become of less importance. Under extreme conditions of heat and exercise, a man may sweat more than 1 litter of liquid per hour. Since each gram of water that evaporate carries with it the heat of vaporization of 580 calories, the evaporation of I liter carries with it 580kcal. There is some heat losses by perspiration even if the body does not feel sweaty, it amount to about 7Kcal/hr, equivalent to 7% of the body losses. A similar loss of heat is due to the evaporation of moisture in the lungs, an additional amount of water will be evaporated during expiration. This will cool the body the same as the evaporation from the skin, also when we inspire cold air inside the lungs which also cool down the body. Under typical conditions The total respiratory heat losses is about 14% of the body's heat loss.

Under extreme condition of heat and exercise the sweat evaporation is very important, a man may sweat more than 1 lit/hr, this is if all sweat is evaporated, the un evaporated part (running down)does not contribute with cooling.

Counter current heat exchange

Since the radiation of heat from the body and the transfer of heat to the air depend upon the skin temp., any factors that affect the skin temp. also affect the heat loss. The body has the ability to select the path returning blood from the hands and feet. In cold weather blood is returned to the heart through internal veins that are in contract to the arteries carrying blood to the extremities (hands and feet).In this way some of the heat from the blood going to the extremities is used to heat thee returning blood. This counter current heat exchange lowers the temp. of the extremities and reduces heat loss from the body to the environment.

In warm weather the returning venous blood runs near the skin surface raising the skin temp. and thus increasing the heat loss from the body.

Most of the previous study involved heat losses from a nude person, if we consider the clothes, the calculation become more complicated, for this reason another unit of clothing is the (clo) is being introduced. One (clo)

corresponds to the insulating value of clothing needed to maintain a subject sitting at rest in comfort in a room at 21°C and air movement of 0.1m/sec and humidity of less than 50%.

One (clo) is equivalent to lightweight suit an individual in the arctic needs clothing of insulation of 4 clos. (A fox fur has an insulating value of 6 clos).