University of Hillah
The first stage
Medical Physics

Energy, Work, and Power

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Introduction:

We cannot function without energy. The processes involved in the body's energy intake, storage, and use are collectively called metabolism.

More generally, metabolism is any energy used by the body and is the sum of all chemical processes performed by the cells to keep the body alive.

For a complete picture, we need to include input of food and oxygen to the body, energy storage, and loss of energy by the body through the loss of heat and work done by the body, as is shown in Fig. 1.

Metabolic processes can be divided into catabolic and anabolic reactions.

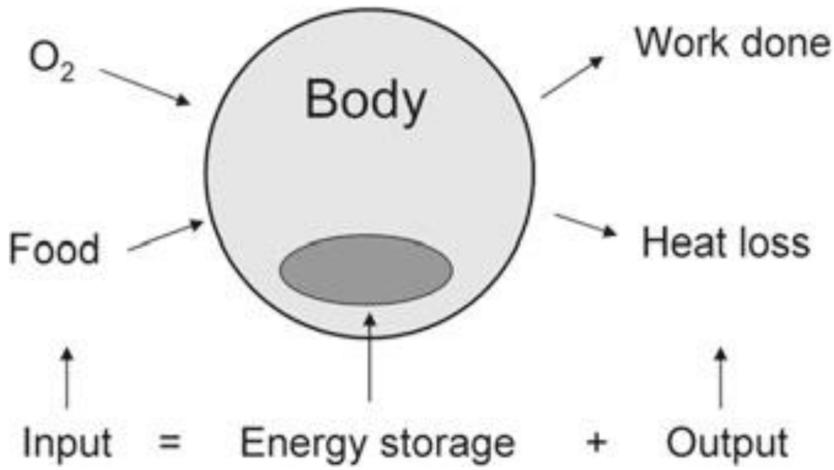
In catabolic reactions complex molecules are broken into simple ones, for purposes such as energy usage.

In anabolic reactions simple molecules are combined to form complex ones, for purposes such as energy storage.

The body uses food to :

- Operate organs.
- Maintain a constant temperature by using some of the heat that is generated by operating the organs (while the rest is rejected).
- Do external work.
- Duild a stored energy supply (fat) for later needs.
- Grow to adulthood.
- Help the fetus grow during pregnancy and then nurse infants. About 5–10% of the food energy intake is excreted in the feces and urine.

Fig.1. Energy flow into and from the body



Conservation of Energy and Heat Flow

ΔU=Q−W …………1

This equation represents the First Law of Thermodynamics, which is essentially a statement of the conservation of energy. Here's a breakdown of each variable in the equation:

ΔU: represents the change in the internal energy of a system.

Note: A positive ΔU indicates that the internal energy of the system has increased, while a negative ΔU indicates a decrease in internal energy.

Q: represents the heat added to the system

Note: If Q is positive, it means heat is being absorbed by the system (increasing its internal energy). If Q is negative, it indicates that heat is being released from the system to the surroundings.

W: represents the work done by the system on its surroundings.

Note: If W is positive, it means the system is doing work on the surroundings, which results in a decrease in the internal energy of the system. Conversely, if W is negative, it indicates that work is being done on the system by the surroundings, which increases the internal energy.

$$\Delta U = Q_{me}t + Q_{loss} - W \text{ ……..2}$$

This equation expands on the First Law of Thermodynamics by incorporating specific terms related to metabolic processes and heat flow in the body. Here's a breakdown of each variable in the equation:

ΔU: represents the change in the internal energy of the body. It indicates how much energy has been added to or removed from the body's internal energy stores.

Note: A positive ΔU indicates an increase in internal energy, while a negative ΔU indicates a decrease.

Q_{met} : represents the heat produced by metabolic processes within the body. This includes energy released from biochemical reactions, such as the oxidation of food.

Note: This term is positive, indicating that metabolic processes contribute energy to the body, increasing its internal energy.

Q_{loss}: represents the heat lost from the body to the environment. This can occur through various mechanisms such as radiation, convection, conduction, and evaporation.

Note: This term is typically negative in the context of the equation, as it indicates energy leaving the body. A negative Q_{loss} means that heat is flowing away from the body, which decreases its internal energy.

W: represents the mechanical work done by the body on its surroundings. This includes activities such as lifting, moving, or any other form of mechanical exertion.

Note: This term is positive when the body is doing work on the environment, which results in a decrease in the body's internal energy. Conversely, if work is done on the body by the environment, W would be negative, contributing to an increase in internal energy.

Summary of the Equation:

The equation $\Delta U = Q_{me}t + Q_{loss} - W$ illustrates how the internal energy of the body changes based on metabolic heat production, heat loss to the environment, and mechanical work done by the body.

Note : All types of energy have the same units, including heat (often expressed in terms of calories) and work (often expressed in terms of joules). One important conversion between units is
1 calorie *(*cal*)* = 4.184 joule *(*J*)*.

$\Delta T = Q/mc$……….3

This equation relates the temperature change of an object to the heat flow into it. Here's a breakdown of each variable in the equation:

ΔT: represents the change in temperature of the object. It quantifies how much the temperature of the object increases or decreases as a result of heat flow.

Note: A positive ΔT indicates an increase in temperature, while a negative ΔT indicates a decrease in temperature.

Q represents the amount of heat energy transferred to the object. This is the energy that flows into the object, causing its temperature to change.

Note: If Q is positive, it means heat is being added to the object, leading to an increase in temperature. If Q is negative, it indicates that heat is being removed from the object, resulting in a decrease in temperature.

m : represents the mass of the object. It is a measure of the amount of matter contained in the object.

Note: The mass of the object affects how much its temperature will change in response to a given amount of heat. A larger mass will require more heat to achieve the same temperature change compared to a smaller mass.

c: represents the specific heat capacity of the material of the object. It is defined as the amount of heat required to raise the temperature of one unit mass of the material by one degree Celsius (or one Kelvin).

Note: The specific heat capacity is an intrinsic property of the material and determines how much heat energy is needed to change the temperature of the material. Different materials have different specific heat capacities, which affects their temperature response to heat flow.

Heat Capacity (C) and Specific Heat (c)

1. Heat Capacity (C):

Heat capacity is defined as the amount of energy (heat) required to raise the temperature of an object by 1 °C. It is a measure of how much heat energy an object can store and is crucial in understanding thermal dynamics.

2. Specific Heat (c):

Specific heat is the heat capacity per unit mass of a material. It indicates how much heat is needed to raise the temperature of one unit of mass (e.g., 1 gram) of a substance by 1 °C. Specific heat is a characteristic property of the material itself.

3. Extensive vs. Intensive Properties:

Explanation: Heat capacity (C) is classified as an extensive property, meaning it depends on the amount of material present (e.g., larger objects have greater heat capacity). In contrast, specific heat (c) is an intensive property, which means it does not depend on the amount of material and is inherent to the material itself.

1. Specific Heat of Water:

- Explanation: The specific heat of water is cwater=1.0cal/g-°C=1.0kcal/kg-°C. This indicates that it takes 1 calorie of energy to raise the temperature of 1 gram of water by 1 °C, or 1 kilocalorie to raise 1 kilogram of water by the same amount.

2. Specific Heat of the Human Body:

- Explanation: The average specific heat of the human body is cb =0.83cal/g-°C=0.83kcal/kg-°C. This value is slightly lower than that of water, indicating that the body requires less energy to raise its temperature compared to an equivalent mass of water.

3. Energy Requirement for Temperature Change:

- Explanation: It takes 83 kilocalories (kcal) to raise the temperature of a 100 kg person by 1 °C. This quantifies the energy needed for a significant temperature change in a large mass, illustrating the relationship between mass, specific heat, and temperature change.

4. Food Energy Content:

- Explanation: The 83 kcal required to raise the body temperature by 1 °C is approximately equivalent to the energy content of a slice of bread. This comparison helps to contextualize the amount of energy consumed in terms of everyday food items.

5. Question of Temperature Increase:

- Explanation: A question arises as to why the body temperature does not increase by 1 °C each time we eat and metabolize food, given that most of the metabolized energy becomes heat. The text suggests that this does not happen due to heat loss mechanisms in the body.

6. Heat Loss Mechanisms:

- Explanation: The body has various mechanisms for heat loss (e.g., radiation, convection, conduction, and evaporation) that prevent a significant increase in body temperature despite the heat produced from metabolism. This is crucial for maintaining homeostasis and preventing overheating.

Energy Content of Body Fuel

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 686\ \text{kcal} \ldots\ldots 4$$

Variables in the equation:

- **$C_6H_{12}O_6$**: This is the chemical formula for glucose, a simple sugar and a primary energy source for cells. It consists of 6 carbon (C) atoms, 12 hydrogen (H) atoms, and 6 oxygen (O) atoms.
- **O_2**: This represents molecular oxygen, which is required for the process of aerobic respiration. In this equation, 6 moles of oxygen are consumed.
- **CO_2**: This is the chemical formula for carbon dioxide, a waste product of cellular respiration. In this reaction, 6 moles of carbon dioxide are produced.
- **H_2O**: This represents water, another product of the metabolic process. In this reaction, 6 moles of water are produced.
- **686 kcal**: This indicates the amount of energy released during the oxidation of one mole of glucose. The energy is expressed in kilocalories (kcal), which is a common unit of energy in nutrition.

In summary, this equation describes the process of aerobic respiration where glucose is oxidized in the presence of oxygen to produce carbon dioxide, water, and energy.

Energy Produced per Mass of Fuel:

- The statement "The energy produced per mass of fuel is 686 kcal/180 g glucose = 3.80 kcal/g glucose" explains how to calculate the energy yield from glucose.
- Here, 686 kcal is the total energy released when one mole of glucose (180 grams) is completely oxidized.
- To find the energy produced per gram of glucose, you divide the total energy (686 kcal) by the mass of glucose (180 g), resulting in approximately 3.80 kcal/g. This means that for every gram of glucose metabolized, 3.80 kilocalories of energy are released.

Basal Metabolic Rate (BMR)

The basal metabolic rate (BMR) is that of an inactive, awake body. The BMR for a 70 kg person is about 1,680 kcal/day =70 kcal/h =81W. This means that even at rest each of us gives off almost the same amount of heat as a 100W incandescent light bulb. The heavier the person the higher the BMR.

To have your BMR measured you must:

(1) Have eaten no food for at least 12 h

(2) Have had a night of restful sleep and no strenuous activity thereafter

(3) Be resting completely in a reclining position for at least 30min

(4) Be experiencing no excitement from psychic or physical factors

(5) Be in a room with a temperature from 20 to 27 ◦C (68 to 80 ◦F).

Work, and Power of the Body

Scaling of the BMR

$$BMR = [\,(10 * weight\ in\ kg\,) + (\,6.25 * height\ in\ cm\,) - (\,5 * age\,) + (men + 5)\,] * L$$

$$BMR = [\,(10 * weight\ in\ kg\,) + (\,6.25 * height\ in\ cm\,) - (\,5 * age\,) + (women - 161)\,] * L$$

Note :

L= activity Level

1. Sedentary = BMR *1.2
2. Lightly active = BMR *1.375
3. Moderate active = BMR *1.55
4. Very active = BMR *1.725
5. Extra active = BMR *1.9

Ex: The patient Ali his age 30 years old Who is 75kg and 180cm monitor BMR ? and he is in a Sedentary lifestyle

$$BMR = [\,(10 * weight\ in\ kg\,) + (\,6.25 * height\ in\ cm\,) - (\,5 * age\,) + (men + 5)\,] * L$$

$$BMR = [\,(10 * 75\,) + (\,6.25 * 180\,) - (\,5 * 30\,) + (5)\,] * L$$

$$BMR = [\,(750\,) + (\,1125\,) - (\,180\,) + (5)\,] * L$$

$$BMR = [\,1700\,] * L$$

How to "Burn" Off Food

Let us say you have just eaten a "standard" donut. You feel guilty and you want to burn off those extra calories. What can you do?

If you are sitting at rest you are naturally burning off ~103 kcal/h (70 kg man). If you decide to play basketball your metabolic rate increases to ~688 kcal/h, so you will be increasing your metabolic rate by~585 kcal/h. You will burn off that standard 280 kcal donut in

$$\frac{280 \text{ kcal}}{585 \text{ kcal/h}} = 0.48 \text{ h} = 29 \text{ min.}$$

That donut will cost you a half an hour of real up-tempo basketball.

Let us say you want to "walk off" that donut. The metabolic rate during slow walking is ~228 kcal/h, which exceeds that of sitting at rest by ~125 kcal/h. To walk off that donut you would have to walk for

$$\frac{280 \text{ kcal}}{125 \text{ kcal/h}} = 2.24 \text{ h} = 2 \text{ h } 14 \text{min}$$

Which is a little longer than most after-dinner strolls.

Q/ Why do people put on weight when they get older?

Answer: One reason is the decrease in BMR with age. The activity level fav often decreases with age. Also, sometimes people eat more (snacking).