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Energy metabolism

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INTERNAL ENERGY

What is the role of food in the energy (E) process? One could say that is important to produce E within the body, but this goes against the law of conservation of E, which says that E can be neither created nor destroyed. Another could say that food's necessary to maintain thermal balance by converting its E into heat; so that way we can resist the heat E lost into the environment. But it's also incorrect as a man can't live without food and, in this supposition, it would be possible if he was placed in an insulating material.

How does our body need E? We have to answer to this question to understand the role of food in our lives. E must be restored (converted from one form to another) but it has to bend some conditions. First, bodily processes are essentially isothermal, so mechanical, electrical and chemical E can be converted into heat, but the reverse is impossible. Second, other form of external E (light, electricity or mechanical) cannot fuel the body because it doesn't have the appropriate energy-complying mechanisms.

Thus, the single form of E which animals can use is the chemical free E of food. The development of the biochemical, structural and physiologic apparatus permits the transformation of this type of E into other essential forms. This chemical free E is provided by plants (directly, when plants are eaten; or indirectly, when they are eaten by animals whose meat we eat).

Energy units

Many units are used: ergs, joules, kW-hour, watt-second, electron volts, calories… But when we're talking about human metabolism, we normally use kilocalorie (kcal). In terms of heat, one kcal is approximately the quantity of E required to raise 1 kg of water (or 1 l) by 1ºC. And 1 kcal=1000 cal.

When we talk about kcal per hour, we use the term power. The conversion into joules per second or watts is as follows: 1 kcal/h=1.16 watts.

Internal E utilization

As the man is a thermodynamic machine who consumes E from food, converting and degrading it and then passing to the environment, the E metabolism requires three considerations:

a)The amount of E intake.

b)The E output.

c)The general utilization of E within the body.

Entropy and free E

The heat E content and the free E content of food are not necessarily identical (or the entropy of metabolic end products is greater than that of the initial substrates). This results as an application of the thermodynamic relation: $AG=AH - TAS$, where AG is the free E change and represents the maximum amount of free E that can be extracted from a constant temperature (T) and pressure (P) process; AH is the enthalpy change, which represents the total heat plus useful E change (also at constant T and P); AS is the entropy change; and T is the temperature.

High E intermediates

Perhaps 95% of ingested E is potentially available as free E. But before it is used, it must be presented in the appropriate chemical form.

But the conversion of food E is far from perfectly efficient. For example, in the complete oxidative metabolism of 1 mol of glucose (686 kcal/mol of free E) only 38 mol of ATP are produced, in which the free E of the hydrolysis is about 9 kcal/mol. Thus, half of the potential free E is lost in the process.

Biochemical and structural steady state

When the free E is converted into the useful form, it is used in many bodily functions, as the maintenance of the biochemical and structural integrity of the body. In our body there are high E compounds that are breaking down constantly. As they are important for our chemical machinery, we need to build them up; and it requires part of the free E. It also happens in the cellular and subcellular elements.

Internal work

To maintain our vital signs our body wastes E. This E has to be restored by the conversion of mechanical or electrical potential into thermal E, and this, again, needs the free E.

External work

When skeletal muscle is activated, its rate of chemical E conversion increases. But, since skeletal muscle can cause external movement, some of the chemical E may be utilized to perform external physical work in the form of force applied through a distance. The fraction of total E converted into mechanical work depends on the pattern of contraction and is determined by the loading of the muscle. Under the most favorable conditions, in an isolated muscle, approximately 40% of the total E may be converted into mechanical work. And what happens in an isometric contraction? Physicists would say that there's no physical work, since there is no movement. In the other hand, physiologists would say there is a physiologic work, since the subject's oxygen consumption, heat production, metabolic rate, etc. have increased.

Both are correct, as we have to separate (when discussing about work) the external, physical, force-time-distance work from the internal rate of free E expenditure.

We have to notice that muscles can convert chemical free E into mechanical E but the reverse is impossible.

Efficiency of exercise

Gross efficiency = external work/total internal E conversion rate

Net efficiency = external work/ internal E conversion rate increase

necessary to accomplish the work

Under optimal conditions, the net efficiency of the body as a machine is about 25%. The body's efficiency in exercise is less than that of isolated muscle, since in exercise E expenditure is increased for circulation, respiration and other internal supportive activities not shown in isolated muscle. In typical circumstances, though, the mechanical efficiency of the body is considerably less than 25%. For example, reading. The efficiency is close to 0, as there is almost no external work.

In summary, chemical free E is used in a variety of body processes in which the end product is heat, or, for skeletal muscle contraction, both heat and external work, being the distribution between them variable depending on the circumstances.

ENERGY INTAKE

Energy equivalents

The available E is completely independent of the particular chemical pathway by which the reaction proceeds (intermediates formed, enzymes utilized…); but the path is very important because it controls both the particular uses to which the E is put, and the fraction of the available free E which is usefully used instead of simply being degraded into heat. But, however, the E in the food is only determined by the initials and final products.

Measurement of food E

The most used way is measuring the inherent in various foods under the most convenient conditions in vitro outside the body. For this, they generally use a bomb calorimeter, in which a known amount of food tested is ignited electrically. By measuring the heat released upon oxidation and dividing by the amount of food, the caloric value in kcal/g can be calculated.

We have to take care of something: the bomb calorimeter burns food to the final oxidation products, and that doesn’t happen in the human body; so the E released by the bomb is always higher than that of the body. Of course, this can be corrected to about the amount burned by the human body. And there’s another fact: in the bomb everything can be burned. Even cellulose, which shows high E values as carbohydrates. So we have to be very careful, because cellulose can’t be absorbed by the human body.

E content

a) Carbohydrates. Physiologic caloric value (PCV) : 4 kcal/g (4.1 kcal/g in the bomb)

b) Proteins. PCV: 4 kcal/g (5.4 kcal/g in the bomb). Not all the absorbed proteins are oxidized. Some are being incorporated as cellular constituents, hormones, etc. but this way it is also replacing some catalyzed proteins and increasing the body E stores.

c) Lipids. PCV: 9 kcal/g (9.3 kcal/g in the bomb of average between animal and vegetable fat)

d) Alcohol. PCV: 7 kcal/g (7.13 kcal/g in the bomb). This is about ethanol.

In inorganic materials, such water, sodium, potassium, chloride ions, etc. undergo no chemical transformations within the body, so there’s no “E” in them. Other organic materials, as vitamins, are simply too small in amount to add a significant amount to the total available E. So carbohydrates, proteins, lipids and, in some cases, alcohol can be only considered in terms of E intake.

METABOLISM ENERGY OUTPUT

Measurement of metabolic rate

a) Direct measurement. It’s based on a device call the human calorimeter or whole body calorimeter. The subject is placed in a sealed chamber, where you can measure the rate of heat transferred. We can also add an ergometer for the performance of external work. When the subject and the chamber reach the steady state temperatures so that no heat is being stored, the total E loss from the chamber must be equal to the subject’s rate of E utilization.

Advantage: 1) It´s based only in conservation of E and not upon any assumptions about the physiology of E metabolism; and 2) it´s limited only by technical skill in the construction of the calorimeter and the heat measuring instruments.

Disadvantage: 1) It requires a large, expensive and elaborate device (the human calorimeter); and 2) it is limited to measurements of activities which can be carried out within a sealed chamber.

b) Indirect measurement.- E output can be estimated from the following consideration: a subject, in a steady-state, oxidizing an “average” diet generates about 4.83 kcal/l oxygen he consumes. The kcal/l O2 is not strongly dependent upon which type of food is being burnt. The deviation between true (5% carbohydrates, 8% proteins, 2% lipids and 1% ethanol) and calculated values would be expected to be no more than a few per cent (in the case of proteins). So the formula Metabolic rate = 4.83 VO_2, if properly employed, yield reasonably accurate results.

c) Indirect techniques. The method most frequently used clinically for determining consumption rate is the closed circuit technique. It uses spirometer, as for measuring lungs volumes, filled with O_2, and a CO_2 absorber in the expired air line. At the completion of a number of respiratory cycles, the volume contained in the spirometer will have decreased by just that amount of O_2 which was consumed. So the rate of change of the spirometer volume is a direct measure of O_2 consumption rate.

The open circuit method of measuring consumption is also used. It’s based upon the Fick principle: the decrease in O_2 concentration between inspired and expired gas (O_2 extraction) at a given gas volume flow is an index of the O_2 consumption rate.

d)Gas volume corrections. The measurement of gas volume is only meaningful when you make some correction due to changes in volume depending upon its temperature, pressure and water vapor saturation. Since, in the physiological range, gases behave approximately as ideal gases, the mols and volumes are directly proportional, but the constant of proportionality depends upon the state of the gas. By convention, for metabolic work, the standard state is taken at: 0ºC of temperature, 760 mmHg of pressure and dry, in which state one mol of gas occupies 22.4 l.

e)Determination of the energy source. When we’re studying the whole body metabolic function, it is frequently essential to determine the type of substrate furnishing the E in any particular circumstance. When dietary intake is limited to the normal constituents of carbohydrates, proteins and lipids, such a determination is possible from the measurement of O_2 consumption, CO_2 production and urinary nitrogen, due to this formulas (all measurements in grams):

I.N = 0.16 P, where N is the quantity of nitrogen obtained from chemical analysis of urine, and P is the quantity of protein. (The average nitrogen content of protein is 16% by weight).

II.$VO_2 = 0.81\ C + 0.94\ P + 1.96\ L$

III.$VCO_2 = 0.81\ C + 0.75\ P + 1.39\ L$

This is using the volumes equivalents (in l/g) of carbohydrates (C), proteins (P) and lipids (L). C, P and L are the amounts of metabolized C, P and L. If quantities on the left of the equation (N, VO_2 and VCO_2) are measure, the three unknowns C, P, L can be calculated.

f)Oxygen debt. In steady state the proportional relation between E output and O_2 consumption is stable. But when the E output is rapidly changing, the response of O_2 consumption tends to lag behind. This is what is called O_2 debt. When someone suddenly starts to exercise vigorously, it will take several minutes before his rate of O_2 uptake gets to the appropriate value. In this interval, his O_2 consumption is not enough for the metabolic requirements, so he has incurred in an O_2 debt or an O_2 deficit. The amount of the deficit is defined by the difference between the O_2 volume necessary to maintain the steady-state and the volume actually consumed. This also happens from exercise to rest, in the opposite way. This is the period of repayment of the oxygen debt and it's defined as the excess volume consumed above the steady-state requirements.

During the O_2 debt, there are three E sources that are involved to administrate rapidly E:

I.ATP-phosphocreatine.- Initial source of internal E (high E intermediates).

II.Cellular glycogen and blood glucose.- They can resynthesize high E phosphate via anaerobic glycolysis (without extra O_2 intake). The consequence is the accumulation of the end product of the glycolysis: lactic acid.

III.O_2 stored in the blood and muscle myoglobin

After the exercise, the body has to get back to the initial state. We need an extra O_2 consumption and also an increased internal work (higher heart rate, increase cardiac output…) which needs extra O2 consumption too. That way we can restore the concentration of high E phosphate, the lactate gets oxidized or glycogen resynthesized and the O_2 in myoglobin and venous hemoglobin returns to resting levels.

The amount of O_2 debt is roughly proportional to the severity of the exercise. For severe work, we can get a 5 l O_2 debt. The repayment is about the same but not identical, and it's only completed after the exercise is finished. But this O_2 debt is not a cardiopulmonary system fault. It is necessary to raise the O_2 consumption because it is the stimulus. And the consumption remains high until the debt is repaired.

Factors determining E expenditure

A) Size. When we talk about size we refer to the body surface area (m^2). Metabolic rates are expressed in terms of E output per unit time per unit area (kcal/m2hr). The surface area can be accurately predicted from height and weight, computed from the equation: $A = 0.202\ W^{0.425}\ H^{0.725}$, where A is the area ($m^2$), W is the weight (kg) and H is the height (m).

The relation between body surface area and metabolic rates is fortuitous (it has no physiologic basis) so they have proved other measures. One of them is measuring only the lean body mass, based on the idea that fat tissue has such a low metabolism that adds very little to the body E output. Another alternative is based on an observation that if you put metabolic rates against body weight on a logarithmic graph, a straight line results (this was obtained using animals from small birds to cattle). As the slope of this line is 0.75, it is claimed that metabolic rate should be expressed in terms of $(kg)^{0.75}$.

The lean body mass is recommended, but the measurement is so difficult that can’t be used for specialized investigations. The $(kg)^{0.75}$ may be good for animals, particularly when we don’t have any surface table available. But for human works, the surface area measure is a better choice because:

- It is easy to calculate.
- It is as suitable as the substitutes.
- It has been used for a long time in physiologic researches, so we should have to recalculate all the results if we used another measure, and it is not worth it.

B) Activity. The level of activity leads to large changes in metabolic rates. The metabolic rates for a normal 20 years old male are (in $kcal/m^2hr$):

- Sleeping: 35
- Awake but lying quietly in bed: 40
- Sitting upright: 50
- Exercise of any kind: raises the metabolic rate depending on the severity
- Max. steady-state E output of a good physical condition person: 350
- Over 350 two or three times: only possible for a short time

Note: Mental activity doesn’t increase the metabolic rate, even the most vigorous mental exercise.

C) Age and sex. Under standard conditions:

- It rises rapidly in the first few weeks after birth.
- It reaches a peak in the early youth (around 2 years old).
- It declines slowly and more or less continuously the rest of the life.

Women have about 10% lower metabolic rate under standard conditions, which has been attributed to the greater proportion of body mass in subcutaneous fat.

D) Temperature. Body temperature affects the metabolic rate in two ways:

I.A decrease of the body temperature has an effect to all the body functions: slower heart rate, lower cardiac output, reduced rate constants for chemical reactions involved in E utilization, etc., which leads to a lower metabolic rate. The opposite happens in a temperature increase.

II.To maintain body temperature in a cold environment, homeotherms convert chemical E into heat by shivering. The E expended depends on the cold stress; in extreme stress, it can reach up to 250 kcal/m^{2}hr. This also happens in heat stress, but the magnitude is not large.

E) Specific Dynamic Action (SDA). When someone who has been fasting eats a protein-rich food, his metabolic rate will increase about one hour later and it will last for several hours. The amount increased is proportional to the one ingested, and it will be around the 30% of the caloric value of the protein. This effect is known as SDA of protein. The most likely explanation for this (although this mechanism is not completely understood) is an influence of amino acid concentration upon intermediary metabolism, but the details are not clear. For carbohydrates and lipids the increase of the metabolic rate is about 5% of their caloric E value.

F) Endocrine. The most important are:

Epinephrine.- It mobilizes and increases utilization of carbohydrates.

Thyroxin.- It affects the basic metabolism of most body tissues.

G) Race and climate. Natives of the tropics have a resting metabolic rate about 10% below the standard values for North Americans or Europeans. But also some (not all) people who move to the tropic show a drop of the same magnitude. So it’s not possible to know if this is due to climate or race.

H) Pregnancy. The mother’s metabolism rate begins to increase about the sixth month and keeps increasing until the birth, when is about 20% above the normal level. This increase is due almost entirely to the additional metabolism of the fetus.

Basal metabolic rate

a) Basal state. The metabolism rate is called basal metabolic rate (BMR) when it is measured under the following standard conditions:

- Size: The rate is expressed in terms of kcal/m^{2}hr.
- Activity: The measurement is taken in steady-state, lying quietly awake.
- Age, sex, race: The measurement would be expressed as a percentage of the deviation from the metabolic rate of normal subjects of the same age, sex or race.

- Temperature: The measurement will take place in a thermal neutral environment and when the subject's internal temperature is normal.
- SDA: The measurement will take place in the morning, in fasting conditions.
- The subject is instructed to relax (eliminates effects of excitement and sympathetic activity and epinephrine release).

b) Range of normal BMR. The precision of a single BMR measurement is better than 5%.

c) BMR abnormalities. The most common cause of an abnormal BMR is associated with thyroid disease. The measure of BMR works as a diagnostic for endocrine abnormalities and biochemical aberrations. When there's an excess of the secretion (hyperthyroid) the metabolic rates are higher; the contrary (hypothyroid) leads to a lower metabolic rate.

ENERGY BALANCE

Normally, the mechanisms of hunger, satiety, voluntary work rate, etc. act to maintain the balance between E input and output in the proper way. When, for physiological or psychological reasons, it doesn't happen, the E difference must be made up by internal storage. And normally an excess of E output leads to a loss of stored body fat (not in extreme starvation). Quite the contrary, when the intake remains over the output, the body fat increases. This is the basis of a dietary control of the body weight.

In contrast to the adult, the child requires an excess of E intake over expenditure to furnish substrates for natural increase in body mass. But if the child's E intake exceeds his E output plus growth requirements, this excess, as in the adult, will be deposited as body fat. ●

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