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Modern Problems of Energy Exchange in Humans and Mammals

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Abstract

In a living organism 72% of energy exchange occurs in the inner organs, which comprise only 5-6% of the total body mass. Other energy expenditures occur at the expense of skin, bones, connective tissue, muscles at rest. The level of energy consumption determines the general physiological state of a human organism, serves for the diagnostics of various diseases, especially of the endocrine system diseases, of disruptions of thermoregulation, disruptions of peptide exchange, of carbohydrate and lipometabolism, etc. We emphasize that in modern textbooks of physiology and biology the problem of energy exchange in humans and animals is covered inadequately. Usually it takes only 2-2.5% of the volume. Whereas new problems of energy exchange appeared recently, which were not advanced before. These are, for example, the reasons and mechanisms of a high energy consumption under conditions of metabolism, the physiological significance of the efficiency of a human organism, special processes of the heat exchange between an organism and environment, physiological and social components of human energy exchange. There is also a problem of theoretical possibility of life without energy.

Keywords: energy exchange in humans, heat exchange in humans, efficiency of an organism, life without energy

Energy exchange is the central and the most general problem of life and, consequently, of modern physiology, biology, and medicine. It plays the main role in all the stages of generation and development of life. All the functions of an organism from the brain activity to the growth of nails and hair depend on the availability and consumption of energy. Unfortunately, nowadays the interest to theoretical and practical problems of energy exchange decreased. In the old and modern textbooks on physiology and pathophysiology only 2-2.5% of the volume is usually assigned to the energy exchange. In the table of contents of some textbooks on physiology the problems of energy exchange are totally absent. Such is, for example, the textbook “Fundamental and clinical physiology” (2004), 1050 pages in volume published by “Academia” publishing house. Whereas the process of energy exchange must occupy an important place in medical investigations, since the level of energy exchange determines the physiological state of an organism and is an important criterion of health. A decrease or an increase in the energy exchange are important for the diagnostics of various diseases, for determining the changes in the organism metabolism, for observation over the development of physiological adaptation to various factors of the environment (low or high temperature, the deficit of nutrition, a reinforced muscle load, etc.). Modern development of the studies of energy exchange is associated with the fact that nowadays new problems appeared in this region of science, which were never advanced before. This is due to the natural development of science. It is interesting that a number of important problems, which seemed apparent, were simply ignored by the specialists for a long time.

For a modern physician the widening of the knowledge of energy exchange is very important since energetics is rapidly developing now. Our small paper is devoted to the problems of energetics of a living organism forgotten to some extent or pushed out of the way along which the most important stages of studying life go.

The First Problem. Under the conditions of metabolism a man spends about 1800 kcal per day. The question arises, for which work this energy is spent, if a man is in complete physical and mental rest, on an empty stomach, at a comfort environmental temperature. Energy expenditures for respiration, heart and kidney activity were assumed to account for these energy expenditures. However, it appeared to be completely wrong. Under metabolism only 22-23% of the energy budget of a human organism is spent on respiration, heart and kidney activity. This is about 405 from 1800 kcal (Schmidt-Nielsen, 1972). The question is for which work the remaining 1400 kcal are spent. It is interesting that this question almost never arose during the whole époque of physiological investigations. The examination of this phenomenon must be started from the fact that all the tissues of a living organism are continuously disrupting and regenerating according to the laws of thermodynamics. Both the disruption of molecules, having served their time, and the creation of new molecules require energy. The peptide synthesis is well studied by modern science (Lehninger, 1972). The disruption of each peptide bond releases about 5 kcal per mole of an albumine. However the synthesis of such bond requires about 30 kcal/mol. Therefore, the efficiency of this work is only 16%. It is believed that every day about 400 g of protein is disintegrated and regenerated in an organism of adult man (Lehninger, 1972). However the energy expenditure is difficult to calculate since a fraction of molecules is repeatedly renovated and a fraction is newly synthesized. Moreover, a large number of compounds results from the synthesis of a protein, their synthesis costs many kilocalories of energy. These are a minimum of 20 activating enzymes, 70 ribosome proteins, 4 ribosome RNA, no less than 20 transport RNA, no less than 10 auxiliary enzymes. All this additional mass of reagents is synthesized only for several episodes of synthesis. Then they are synthesized again. It is best to judge about the continuous synthesis of proteins and other products of metabolism by the actual data. For example, we know that the restoration of the human liver by half occurs during 5-6 days. If the liver weighs 1.5 kg, this means that every day 300 g of the substance of liver is restored (in a mouse the liver is restored by half during 1-1.5 days). By the data of H.W.Hochachka and G.N.Somero (Hochachka & Somero, 2002) 52% of the energy budget of the liver is spent for the synthesis and restoration of proteins. About 17% of the energy budget of liver is spent for the synthesis of carbohydrates, and the most important of the functions of liver – the urea synthesis consumes only 3% of energy.

In the human brain the restoration of proteins occurs also very intensively (Palladin, Belik, & Polyakova, 1972) and is highly competitive with liver. The brain consumes 16-18% of the total energy budget of the human organism. This energy is spent for maintaining the electrical potentials in the brain cells, but predominantly for the restoration and replacement of the protein molecules. Energy consumption is quite the same at a complete mental rest, during sleep, and during intensive intellectual work. The brain in such a case can be compared with a computer, in which all the energy is spent for maintaining the anodic voltage (in the brain – for the exchange of proteins). The very calculation by a computer almost does not use energy, as in the brain the intellectual activity is almost not accompanied by the energy consumption. The brain tissue in itself is very sensitive to the energy deficit. A decrease in the consumption of oxygen by 15-20% results in heavy disruptions in the brain functions (Ivanov, 1993).

It is interesting that the heart consumes a large amount of energy – about 10.7% of the total energy budget of an organism. The contractions of myocardium are believed to be the main reason for a high energy consumption. However, the arrested, not contracting heart is known to continue consuming from 20 to 30% of the energy of beating heart (Ivanov, 2007-2008). It is believed that this energy expense comprises the "heart metabolism" and is consumed for restoration of protein structures. We must note that in other organs there are indications to a rapid restoration of proteins. They are estimated by the duration of the cell life. Thus, for example, the lifetime of the cells of the mucous membrane of the stomach is 1.8 days; of the small intestine – 1.3 days; of the liver – 10 days; of the large intestine – 10 days; of the rectum – 5 days; skin epithelium – 5-6 days. The erythrocytes live for 100-120 days, leukocytes – 1-2 days etc.

Therefore, a living organism is a substance with dynamically restored composition according to the laws of thermodynamics. The basis of this restoration is the protein composition of an organism. From birth to death an organism seems to be restored very many times. The dynamic restoration of the body composition is energetically very expensive. That is why even at a complete rest and visual inactivity an organism spends a lot of energy. If we calculate the energy spent by mankind for maintaining life during a year, it appears to be equal or exceed the amount of electric energy produced by all the power plants of modern world per year (Ivanov, 2007-2008). This is not an abstraction. This is a modern view on life and physiology of a living organism. We think that every physician and every student must know this most important law of the living world.

The Second Problem. This problem deals with a special role of adenosine triphosphoric acid (ATP) in an organism of any living organism and humans. The matter is that almost all the flow of energy in a living organism passes ATP, since only the energy released upon ATP hydrolysis is the free energy capable of producing physiological work and of taking part in the synthesis of other macroergs. On this basis we may say that almost all the energy of human metabolism (1800 kcal/day) is spent for the ATP synthesis with the help of ATP-synthetase enzyme. It is used for the work of the synthesis of various compounds in an organism necessary for its vital activity, for the ion transport against the concentration gradient in a cell and intercellular medium, it is necessary for muscle contractions, for restoration of cellular populations etc.

The fact that all the flow of energy proceeds via the only carrier is very important. This allows the energy to be accumulated in a cell at the expense of only one carrier and its expenditure to be regulated in the most efficient manner. However the synthesis of ATP has a number of problems, which have been discovered and studied by the science only recently. First, the work of ATP synthesis has the efficiency of only 40% (Lehninger, 1972). This means that from 1800 kcal only 40%, i.e. only 720 kcal, place at an organism disposal the free energy capable of producing physiological work. The remaining 60% is the bound energy, which cannot produce any physiological work. Second, the most important special feature of ATP is its very small energy capacity. Upon hydrolysis of a mole of ATP to give ADP and P only 10 kcal/mol is released. Consequently, with the aim of providing a human organism with energy for a day 72 energy full-value moles of ATP must be synthesized. But each mole has a mass of 506 g. In such a case every day 506·72 = 36 432 g of ATP must be synthesized. It is interesting that nobody ever calculated the reproduction of ATP mass. We were the first to make such a calculation in 1972 and showed that the reproduction of ATP mass comprises 36 kg per day for a man, i.e. more than a half of his body mass. If we apply to comparative physiology, we can obtain quite fantastic numbers. In a rabbit, for example, the mass of ATP synthesized during a day will be almost equal to the body mass of an animal. In a rat it will be twice as much as the body mass. In a dwarfed mouse it will exceed the body mass by a factor of 10-12. All this points to the fact that we still scarcely know the price of life and vital activity. From medical point of view such knowledge seems to be very important for physicians. They allow the quantitative estimations to be made of the energy processes necessary for life and health.

We emphasize that 780 kcal are not used by the tissues completely. The work of using the energy of ATP also has an efficiency, which is about 50% (Alyukhin & Ivanov, 1984). In such a case only 360 kcal or one fifth of the total energy consumed by a man really is spent for restoration of destroying molecules, for maintaining the normal composition of the cells, and for the work of heart, liver, and lungs, their activity being necessary for fulfilling this work at the level of metabolism. This is a very important fact in the total energetics of a living organism. Unfortunately, it is not mentioned in the textbooks on physiology, it is unknown for students and often for their teachers. This fact suggests that the efficiency of an organism, taking into account the energy expenditures of an organism per day being 1800 kcal, is comparatively low - about 15-18%.

The Third Problem. Individual Energy Expenditures of a Man. How much energy is consumed by a man during his physiological and social activity? An intelligent person spends about 2500 kcal during a day of his scientific or administrative activity. Approximately 700 kcal is spent for motive activity. Other 1800 kcal are the expenditures for metabolism, i.e. for respiration, heart and liver activity, energy consumption by the brain and other various organs, for restoration of continuously disintegrating living structures. However it must be taken into account the fact that each calorie, which is received by a man with food costs by a factor of 10 more in the agriculture (Odum, 1983). Consequently, the life of a man will cost by a factor of 10 more and will comprise 25000 kcal per day. Though this is, of course, the external energy, but it is included into the energy value of food, is consumed by a man, and, consequently, increases his energy balance. But the matter is that a man for his normal life must have a roof over his head, closes, heating and lighting of his dwelling, hot water supply, transport, and in a number of other everyday things and services. An American economist Odum (Odum, 1983) believes that the expenditures of this external energy necessary for the normal life of a man increase his energy balance by a factor of 10 more. In such a case a man will cost to nature and industry 250 000 kcal or 290 kWt-hour per day. This is a very large amount of energy, but we often neglect this. In Moscow underground, for example, during rush hours about 2500 passengers are sitting, staying, or moving to the doors of 8 wagons of a train. Each of them has the power of 160 Wt (Fanger, 1970). This means that all the passengers release the total power of 400 kWt. This energy is close to the intake of electric motors setting the train in motion. Without these simple calculations it would be difficult to conceive the amount of energy consumed by the passengers of an underground train.

We believe that any scientific worker must know the limits of energy consumed by a man. For a physician this gives the notion about energy price of life of each man.

The Fourth Problem. Acquisition and Emission of Energy. As is noted in physiological textbooks, the quantity of consumed energy in calories per unit of time must be equal to the quantity of energy in calories, which an organism releases to the medium during the same time. Only in such a case, as is written in the textbooks, the body temperature may be maintained at a constant level. However, it appears incomprehensible and to some extent absurd that a man releases to the medium as much energy as he obtains. The question arises: if a man releases all the obtained energy, at what expense he maintains his life. It is interesting that this problem had been neglected for about two centuries – from the moment of determining the energy expenditures of a living organism made by Lavoisier and up to now. At any rate, there is no adequate explanations of this enigma either in the old or modern textbooks on physiology or in the special works on the problems of energy exchange in a living organism. It seems that A.Lehninger (Lehninger, 1972) was the first biologist to speak up about this problem very cautiously. He wrote that an organism consume free energy for physiological work, but releases it into the medium in the form less applicable for use. Now the main features of this problem are known. As has been noted above the whole energy used by an organism goes through the synthesis of adenosine triphosphoric acid. The efficiency of physiological work of this synthesis is about 40% (Lehninger, 1972). Then, if the energy of ATP hydrolysis is 10 kcal/mol ((ΔG^{o}~-10kcal/mol), the energy consumption for the synthesis of 1 mole of ATP will be 25 kcal/mol. On this basis the calculations were made of the quality of energy obtained by a living organism and of the energy released into the medium. If we adhere to classical thermodynamics, the total balance of energy for a system or a body is given as:

$$\Delta H = \Delta G + T\Delta S$$

where ΔH is the total quantity of energy, ΔG – the free energy, i.e. energy, which can be used to produce work, ΔS – the change in the entropy, which gives $T\Delta S$ – the so called bound energy, the heat, which cannot produce work.

An organism receives energy from food, where, according to efficiency there is 40% of free energy and 60% of bound energy. Than the total balance of energy may be written as:

$$\Delta H = \underset{40\%}{\Delta G} + \underset{60\%}{T\Delta S}$$

After energy transformations and use of the free energy ΔG for various kinds of physiological work in an organism the quantity of free energy decreases and the quantity of bound energy increases. It is quite clear that after using the free energy a somewhat depreciated energy is released into the medium, energy deprived of a fraction of energy potential. Therefore, an organism lives at the expense of free energy, which it spends for various kinds of physiological work (Odum, 1983). The free energy fulfills a certain work and transforms into heat, whereas the calories of food preserving their heat equivalent lose a fraction of their energy potential. The free energy transforms into bound energy. This phenomenon is called the change in "the quality" of energy (Odum, 1983). These relationships are well explained in the textbook of V.O.Samoilov (Samoilov, 2004). Therefore we can say that an organism receives a full-value energy with a large energy potential with food and releases energy to some extent devoid of energy potential. In this case the heat identity between various calories is preserved, but there are differences in the energy potential. In such a way a puzzling equality between the energy received by an organism with food and the energy released into the medium disappears. The concept of "the quality of energy" is an energy excess from the point of view of biology and physiology, this phenomenon almost never was considered in a living organism. However, in the industrial energetics it is excessively popular. It was calculated that 1 calorie of the sun emission is equal to 0.0005 calories obtained from combustion of coal by its energy potential. 100 calories of phytodetritus (green mass) are energetically equal to 0.05 calories of coal combustion (Odum, 1983).

These numbers are quite unknown to biologists, physiologists, and physicians. It is necessary to elucidate such special features of energetics in the reference books. These numbers must be illustrated in the textbooks and lectures. Then students and their teachers will have a notion about the relationships between free and bound energy according to modern ideas.

The Fifth Problem. Life Without Energy. This is one more special feature of energy exchange. It has no direct practical relation to human physiology. But it has a great significance for the whole animate world from microorganisms to lowest vertebrates and even for some mammals.

A living tissue is known to be destroyed and lost either from necrosis or from apoptosis when deprived of energy. This happens during myocardium and brain ischemia, limb gangrene. As was noted above, the renewal of the tissue composition is the most important function of a living organism. But is life possible without this renewal and influx of energy? Cold abruptly decreases the metabolism and almost excludes the disruption and restoration of the cell composition of the tissues. At the temperature of minus 100-130°C the viability of an organism can be preserved for an uncertain time, if, of course, the method will be found of its rewarming without damaging the tissues. However the matter is that at the temperature higher than zero some organisms are capable of switching off the normal energy exchange partially or completely and preserve the viability of an organism in doing so. Thus, for example, microorganisms inhabiting the crust at a depth of 2-3 km from the surface can preserve their viability switching off their metabolism almost completely at comparatively high temperature given almost complete absence of oxygen and nutrients. They are divided only once per 100 years. During this time before division they accumulate the energy potential. This potential is not spent before the division (Ehrich, 1996) (Fredrickson & Onstott, 1996). Many insects, fly, for example, switch off their metabolism at the temperature higher than zero and exist almost without metabolism for several months.

Even some vertebrates demonstrate such a property. African Dipnoi fish buries itself into the slime during dry period and completely stops its energy exchange for a period from one year to 5 and even, by some data, to 10 years (Hochachka & Somero, 2002). It preserves the store of carbohydrates and viability in doing so. Even the nitrogen exchange is not destroyed in these fish during such a sleep. These are, of course, amazing animals. Some mammals are capable of an abrupt decrease in the energy influx for a certain period and of preserving life. The so called Widdell seal can spend 1 h and 20 min under water without respiration. It appears to be able to decrease its energy exchange by factors of 2-3 and stay alive (Hochachka & Somero, 2002). Such cases are unknown for humans. However the mechanisms of such safe for life detachments of the energy exchange are extremely interesting from scientific and practical points of view. These phenomena are studied continuously. However the mechanism of switching off the metabolism with preservation of certain stores of nutrients and maintaining the viability remain an enigma.

Each science strives for development. There are few references in this paper. This is the result of the fact that there are very few works in those directions of biology and physiology of animals and humans, which we discussed and tried to reveal their essence. We considered, of course, not all the strategically important features of energy exchange. However I believe that the small material given here nevertheless will allow us a lift by one-two steps for better understanding of life and energetics of a living organism.

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