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Assessment of energy balance in nutritional counseling – fact or myth?

Review

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Abstract

Evaluating energy balance in nutritional counseling is always prone to error. This study explains the reasons for this situation, energy expenditure types and methods of estimation, various categories of energy, the relationship between the caloric content of food and ATP production, the idea of fat balance, the concept of the energy homeostat, and other issues. Awareness of the tools' limitations draws more attention to simple dietary recommendations and the role of physical activity. It also helps avoid the frustration of putting too much faith in uncertain caloric value and energy balance estimations.

Keywords

energy balance • fat balance • energy homeostat • food • ATP • nutritional counseling

1. Introduction

One of the body's primary features is its ability to maintain homeostasis, i.e., the stability of body composition despite the intake and processing of food and changing environmental conditions. The human body is an open system. There is a constant exchange of matter and energy—both with the environment and within the body. Evolutionarily faced with food shortages, humans now face an excess of food sources in developed countries. Available products are often not optimal (too processed, with inappropriate proportions of nutrients, numerous preservatives, acidity regulators, thickeners, emulsifiers, etc.). Still, they are sensorily attractive and safe in terms of microbiology and toxicology. Excessive supply of energy in food contributes to overweight and obesity, which affect 40% and over 16% of the adult population in Poland, respectively [1]. Healthcare systems are faced with the complications of excessive energy intake in food.

Medical professionals—dietitians, physicians, physiotherapists, and others—estimate the energy balance based on publicly available databases. Along with patients, they believe that such assessments are accurate. Yet this belief is unfounded.

2. Objective of the work

The study aims to discuss selected limitations of energy balance assessment in nutritional counseling. Types of energy expenditure and estimation methods, various categories of energy obtained from food, the relationship between calories and ATP, and the concept of the energy homeostat will be presented. Also, the reasons why popular methods to estimate energy supply may fail and should be perceived as estimates at best are discussed.

3. Energy balance of the body

According to Blaxter, the most general energy balance equation is as follows:

R = I – F – U – G – H (where R = rate of energy retention in the body, I = rate of energy intake in food, F = rate of energy excretion in feces, U = rate of energy excretion in urine, G = rate of energy excretion in gases, H = rate of excretion of thermal energy) [2]. Suppose the thermal energy release rate corresponds to the heat production rate in the body. In that case, the body's energy retained corresponds to the components' energy value by which body weight increases. The organism cannot convert heat energy into other forms of energy.

4. Caloric values and ways of estimating them

The most general measure of the energy content of a food is its gross energy. It is determined in a device called a bomb calorimeter in conditions that have nothing to do with physiology (drying, an atmosphere of pure oxygen, high pressure). The analyzed substances are burned more efficiently, and the results are averaged. For example, in a bomb calorimeter, amine groups (-NH2), which are physiologically excreted as urea, are oxidized. The conditions of a bomb calorimeter have little in common with those of the human body. Caloric content assessed by this method is unlikely to provide virtually valuable information, although the standardization of measurement is an advantage [3].

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Based on the food's protein, fat, carbohydrate, and fiber content, its gross energy can be calculated. The apparently digestible energy can be established by reducing gross energy by the energy contained in gases released in the digestive tract (mainly hydrogen and methane) and feces—'apparently' because feces contain not only undigested food remains but also digestive juices, bacterial flora (several dozen percent of the mass), metabolic products, and exfoliated gastrointestinal epithelium. A person fed a protein-free diet still excretes proteins in the feces, and approximately 2/3 of the proteins digested in the human digestive tract are of endogenous origin [4]. Apparently digestible energy is difficult to specify and impractical due to diverse transit times through the digestive tract (some ingredients up to 7 days), individual and time-varying frequency of bowel movements, and interactions between dietary components (e.g., fiber limits the absorption of certain nutrients). In experimental studies, some of these problems can be eliminated by feeding a person with the same diet for many days. According to James and Schofield, the digestibility of food energy in humans is, on average, 96% [5].

Absorption of an ingredient in the digestive tract does not mean that it will be "burned" (oxidized) in the body. The amino groups of proteins are excreted as urea or uric acid, and the organism cannot utilize many compounds. Therefore, the concept of metabolic energy (ME) of food was introduced, i.e., the amount of energy available for use by the organism. It is defined as digestible energy reduced by the combustion heat of urine excreted on a given diet. This energy can be determined in several ways, which include: -replacing part of the cellulose in the diet with the tested ingredient (ME of cellulose = 0 as the human body does not digest cellulose), - replacing part of the diet with the tested ingredient, - feeding the subject only with the analyzed ingredient. The last method provides the lowest results, and the first delivers the highest. According to James and Schofield, the average diet's ME constitutes 91% of gross energy [5].

The caloric value of food assessed from dedicated databases, traditionally given in kcal/100 g, and according to the SI system expressed in kJ (where 1 kcal is equal to 4.184 kJ), is calculated from the net Atwater equivalents (see below) and not from the calorimetric bomb combustion. This investigator used the physical equivalents (heat of combustion) of carbohydrates, fats, proteins, and energy losses in urine after consuming these ingredients, as well as the average degree of their digestion and absorption from food [6,7]. Thus, for 1 g of protein and carbohydrates, the body obtains 4 kcal, and 1 g of fat provides 9 kcal. However, individual equivalents can be determined for particular products, considering their components' composition and digestibility. For example, for milk, the specific equivalent of carbohydrates is based on the heat of lactose combustion (3.95 kcal/g) and the lactose digestibility coefficient (98%, although there is significant individual variability). Thus, it is 3.95 × 0.98 = 3.87 kcal/g. The value obtained from caloric tables does not fully correspond to the energy utilized by the body, though it approximates ME and is perceived as such.

The net energy of food is obtained by subtracting the heat energy released in metabolic processes from the ME. In scientific research, it can be measured based on fat conserved due to food consumption, assuming that the body has been malnourished for a long time (subsequently, no glycogen stores existed, and the energy was obtained from reserve fat). Although such issues remain irrelevant to practical nutritional counseling, they reasonably reflect the complexity of the problem.

4.1. Food energy conversion factors

Since the end of the 19th century, attempts have been made to determine the energy content of food. The three systems that conceptually relate to ME are:

- The Atwater general factor system (based on the heats of combustion of proteins, fats, and carbohydrates, corrected for losses in digestion, absorption, and urinary excretion of urea),
- More extensive general factor system (considers available carbohydrates and fibers),
- Atwater specific factor system (considers coefficients of digestibility of different proteins, fats and carbohydrates). Considering that ME only approximates energy supply by nutrients. In 2001, Livesey proposed the net metabolizable energy (NME) system [8]. In this system, ME values can be modified further to account for the energy lost as heat from different substrates via the heat of fermentation and obligatory thermogenesis. The NME indicator turned out to be more robust, and the results obtained using calorimetry and calculation of free energy or net ATP yield were very similar. The emergence of hybrid systems has deepened the confusion [9,10].

5. Calories versus ATP

A calorie (1 cal) was historically defined as the amount of heat needed to raise the temperature of 1 g of chemically pure water by 1 degree Celsius, from 14.5 to 15.5 degrees Celsius, at a pressure of 1 atmosphere. According to the SI system, joules are favored as the unit of energy. Thus, one calorie defined as above corresponds to 4.1855 J. However, according to the conversion factor used in physical sciences (the so-called international calorie), this value is 4.1868 J. In bioenergetics/nutrition research, the so-called thermochemical calorie corresponds to 4.184 J [11].

ATP (adenosine triphosphate) is a specialized nucleotide containing adenine, ribose, and three phosphate groups. In eukaryotic cells, ATP participates in reactions in the form of a complex with Mg^{2+}. The role of this compound in bioenergetics was suggested by experiments on muscle contractions, indicating that ATP and phosphocreatine are broken down, and

their re-synthesis depends on the energy supply from oxidation reactions (de-electronation) inside myocytes. Since Lipmann introduced the concept of energy-rich phosphates, ATP has been in the spotlight of researchers [12]. Although it is not the only compound containing energy-rich bonds, it is quantitatively the most important [13]. The central role of ATP in cell bioenergetics results from the fact that its standard hydrolysis energy is in the middle of the group of organic phosphates (-30.5 kJ/mol, while, for example, for phosphocreatine, it is -43.1 kJ/mol and for glucose-6-phosphate it is -13.8 kJ/mol). Energy-rich phosphates act as the "energy coin" of the cell. They enable the coupling of thermodynamically unfavorable reactions with favorable ones, which allows the synthesis of complex compounds using the energy stored in high-energy bonds. This energy comes from food.

There are three primary sources of ATP in cells:

- Oxidative phosphorylation (quantitatively dominating – energy is released in the mitochondrial respiratory chain, as described below),
- Glycolysis (conversion of glucose to pyruvate).
- The citric acid cycle (Krebs cycle; series of enzymatic mitochondrial reactions to catalyze nutrients' deelectronation and to transfer electrons to NAD^+ and FAD; reduced cofactors continually accept and donate electrons to the respiratory chain composed of a number of cytochromes that use electrons for reduction of O_2 coupled with ATP regeneration; it is also a metabolic pathway connecting carbohydrate, fat, and protein metabolism).

When ATP is quickly consumed, phosphagens (e.g., phosphocreatine) become a source.

According to Denton and McCormack, the average adult body contains approximately 50 g of ATP; this amount is broken down and resynthesized approximately 4,000 times a day, giving a total ATP consumption of 200 kg/day. Attempts to convert the amount of energy in food into the amount of ATP produced are challenging. For example, the oxidation of 1 mole of glucose (180 g) provides a net amount of 36 moles of ATP. However, the actual efficiency is lower because approximately 20% of the glucose released from the liver enters the Cori and alanine-glucose cycles, which reduces the total efficiency by approximately 10%. A large part of absorbed carbohydrates reaches the muscle gluconeogenesis pathway, is converted into lactate captured by the liver, and subsequently converted into glucose. Consequently, the efficacy of the process drops to approximately 80%. The food-induced thermogenesis phenomenon must also be considered (this introduces a correction of roughly 10% of the energy value of consumed glucose, increasing the cost of ATP production) [13,14]. The energy efficiency of glucose oxidation in the body is approximately 60% net. Worse, the estimates are much more complicated for complex carbohydrates, fats, and proteins.

6. cAMP-activated kinase (AMPK) as the vital energy sensor

Cells recover ATP via ADP phosphorylation. They usually strive to maintain the ATP:ADP ratio within a specific range, but numerous factors disturb this balance. The critical energy sensor and hub of metabolic control is cAMP-activated kinase (AMPK) [15]. This heterotrimeric nuclear-cytoplasmic enzyme is activated by increasing AMP concentrations during an energy deficit. Subsequent activation of catabolic pathways and inhibition of energy-consuming anabolic processes help restore balance. AMPK activity is allosterically regulated by AMP binding to the γ regulatory subunit and phosphorylation of the α catalytic subunit by other kinases. Decreased AMPK activity is typical of type 2 diabetes, insulin resistance, and obesity, while AMPK activation inhibits the mTOR kinase pathway, which is excessively activated in many cancers. Also, inflammation affects AMPK activity [16].

7. Energy homeostat, fat balance, fat synthesis, and oxidation

The energy homeostat concept represents a mechanism of systemic regulation. Increased fatty acid concentration and consumption compensate for decreased glucose concentration (and the energy obtained). The biochemical transformation pathways of individual food ingredients are interconnected, and the existence of a homeostat is an expression of their comprehensive integration and regulation in the body. Pyruvate dehydrogenase complexes (PDC) are multi-component megacomplexes that link between cytoplasmic glycolysis and the mitochondrial tricarboxylic acid cycle. They also affect the metabolism of branched-chain amino acids, lipids, and oxidative phosphorylation [17]. The homeostat promotes the body's adaptation to changing conditions to maintain systemic homeostasis. Of course, specific tissues exhibit "preferences" for metabolic fuel, e.g., glucose under normal conditions is practically the only energy source for the central nervous system. However, during starvation, the brain can replace almost half of the oxidized glucose with the oxidation of ketone bodies [18,19]. Also, increased myocardial ketone body metabolism may be observed in cardiomyocytes in heart failure [20]. A homeostat secures the body's energy needs in various external conditions (different types of diet, varying levels of physical activity, nutritional status, etc.). Recently, a relationship between underreporting of energy intake and blood ketone levels has been reported [21].

Since it is not possible to realistically estimate calorie or ATP balance, a promising alternative could be body fat balance. Reducing the entire complex bioenergetics of the body to the balance of one component would be an oversimplification, yet analogous concepts have long appeared. For example, according to Flatt, the glycogen balance could reflect the body's bioenergetics [22]. The rate of change of the body fat reserves reflects the difference in fat consumption and oxidation rates.

The amount of fat oxidized in the body (assuming nitrogen and energy balance) corresponds to the difference between a person's energy expenditure and the energy provided by dietary carbohydrates and proteins. Therefore, the diet's composition and the body's current condition significantly influence the synthesis and oxidation of fat [3, 22]. Several factors modulate fat metabolism. Carbohydrate consumption inhibits fat oxidation. Fat consumption does not significantly affect its oxidation, which depends mainly on the amount of stored fat in the body. However, fat oxidation increases when the energy value of the diet is lower than the body's energy expenditure. Fat synthesis from carbohydrates does not occur with the average diet. Although a biochemical pathway exists, only 600–700 g of carbohydrates daily allows their transformation into fat. However, fat synthesis may occur with an excessively high supply of amino acids in the diet. The organism does not store amino groups, so excess amino acids must either be oxidized or converted into glucose or fat. Fats "burn in the fire of carbohydrates." For acetyl-CoA to be oxidized, three-carbon oxaloacetate from glucose metabolism must be supplied. On an extremely low-carbohydrate diet, amino acids are the source of glucose.

Lipogenesis is regulated by nutritional status. Its speed increases on a carbohydrate-rich diet but decreases with limited access to energy in food, consumption of high-fat food, and insulin deficiency. Fats in food reduce hepatic lipogenesis, and if their content in food is >10%, the conversion of food carbohydrates into fats does not occur. Lipogenesis increases when sucrose (or fructose) replaces food's glucose (fructose bypasses the control step of glycolysis—phosphofructokinase—and activates the lipogenesis pathway); fructose stimulates pathways in the liver, leading to the synthesis of fatty acids, their esterification, and VLDL secretion, as well as an increase in the concentration of triacylglycerols in the blood serum. Lipogenesis is also regulated by short-term mechanisms (allosteric and covalent modifications of enzymes) and long-term mechanisms (changes in the rate and degradation of enzymes). The limiting step for the lipogenesis pathway is acetyl-CoA carboxylase, activated by citrate (and inhibited by acyl-CoA—feedback inhibition by the final reaction product); citrate is an indicator of the abundance of acetyl-CoA, and its concentration increases with good nutrition of the body. Recently, acetyl-CoA carboxylase has been suggested to be a promising therapeutic target in metabolic syndrome, steatohepatitis, and cancers [23-25].

The availability of acetyl-CoA is regulated by the proportion of active and inactive forms of pyruvate dehydrogenase, which shows an inverse correlation with the concentration of free fatty acids [17]. Lipogenesis and lipolysis are hormonally regulated and influenced by other signaling molecules (e.g., cytokines). Insulin stimulates lipogenesis (by enhancing glucose transport to the adipocyte it increases the availability of pyruvate for the synthesis of fatty acids and glycerol-3-P for the esterification of fatty acids). The clinical manifestation is that most people with predominant insulin resistance in type 2 diabetes have hyperinsulinemia and are obese. Insulin converts the inactive form of pyruvate dehydrogenase into the active one (in adipose tissue but not in the liver), activates acetyl-CoA carboxylase, and inhibits lipolysis (by reducing cAMP concentration). In turn, glucagon and adrenaline activate lipolysis (increasing cAMP and inhibiting acetyl-CoA carboxylase). The fatty acid synthase complex and acetyl-CoA carboxylase are adaptive enzymes. Their activity decreases during starvation, in the case of diabetes, on a high-fat diet, and increases in satiety.

The synthesis of storage fat reflects its dietary intake. The efficiency of converting nutrients into body fat is high for fats, much lower for carbohydrates, and negligible for amino acids. Oxidation of fatty acids is a function of the difference between energy from carbohydrates and proteins. It should also be noted that the mechanisms discussed above are only a fragment of a more complex issue. In fact, they are also influenced by a complex hormonal balance (e.g., incretin hormones), cytokines, and other factors [26].

8. Estimating energy balance – where are we?

8.1. Direct calorimetry

Assessment of balance using direct calorimetry methods requires placing the patient in a calorimetric chamber, i.e., a device resembling a chamber surrounded by a water circuit [27]. The amount of heat released per time unit is determined based on the increase in the temperature of the water surrounding the chamber walls. For obvious reasons, this method is not routinely used in nutritional counseling.

8.2. Indirect calorimetry

Indirect calorimetry requires respirometers composed of a mask, respiratory gas composition analyzers, and a wireless pulse recording system. Stationary ergospirometers are used in laboratory conditions. However, portable devices also exist. This non-invasive technique takes advantage of the fact that the body obtains energy from the oxidation of carbohydrates, fats, and proteins [28]. These reactions consume oxygen and release carbon dioxide in amounts proportional to the energy expended. Determining the volume of oxygen consumed and carbon dioxide released per time unit is required. The amount of energy expended is calculated based on the energy equivalent of oxygen. It depends on the respiratory coefficient (R) (R=VCO2/VO2) and ranges from 0.70 (when obtaining energy only from fats) to 1.0 (when its only source is carbohydrates). For an R of 0.71, the energy equivalent is 4.68 kcal; for an R of 1.0, the energy equivalent is 5.05 kcal. The value of the respiratory coefficient depends on many factors, including the type of energy substrate used. One can determine the caloric cost of a given activity by measuring the oxygen cost (l/min or ml/kg/min) and knowing the energy equivalent of oxygen. This method works remarkably well for aerobic activities.

8.3. Doubly labeled water

The doubly labeled water method reflects actual physical activity well. Water labeled with isotopes 18O and 2H (deuterium) is administered orally. Then, the body elimination rates of these isotopes are determined. During catabolism, carbon dioxide and water are released. The labeled oxygen is excreted in both compounds, while deuterium is excreted only in water. The difference in the disappearance rate of both isotopes is proportional to the amount of CO2 released during metabolic processes. Thus, it allows for estimating the total energy expenditure of the examined person for up to 3 weeks. Despite high standardization, numerous interpretation problems also arise here [29].

8.4. Heart rate monitoring and motion sensors

The above methods are highly inaccurate and poorly standardized. Although wearable sensors proved to be valid tools for assessing physiological status in working environments, they are not suitable for precise assessment of energy expenditure [30].

8.5. Subjective estimations

Questionnaire methods are poorly related to actual energy expenditure. Underestimations, overinterpretations, forgetting, and numerous psychological factors make the information obtained unreliable. However, due to their common availability and cost-free nature, they are easily adapted to routine practice. Also, they can be helpful as a reference when introducing new dietary survey methods in population-based research [31].

9. Summary

This article emphasizes the problems of estimating human energy balance. Practical nutritional counseling typically disregards them, and the energy balance estimated by nutritional counselors hardly reflects the bioenergetic complexity of human biochemistry and physiology.

Knowing the tools' limitations is essential in diagnosis and therapy. Medical professionals should be aware that estimating the caloric value of food has little biological significance, and the clinical course sometimes contradicts their professional calculations. Such awareness helps to avoid frustration and may increase the effectiveness of the intervention.

The face of nutritional counseling may soon be transformed. Instead of counting calories, more attention will be drawn to diet personalization, incorporating genetic and metabolic distinctiveness, time-relevant interventions, the influence of regulatory molecules in food, and many other factors [32,33]. Instilling simple rules for healthy eating and encouraging patients to engage in regular physical activity may be more effective than calculating the caloric value of food.

Author' contribution

Miroslaw Kiedrowski is the only author and is fully responsible for the entire manuscript.

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Conflict of interest

There is no conflict of interest.

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