Dietary Energy

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Dietary energy is the deceptively simple name for the scientific term *metabolizable energy*. Metabolizable energy is defined as the amount of energy available to the body from food after accounting for the obligatory energy losses, mostly in stool and urine. Most dietary energy comes from dietary fat, protein, and carbohydrate. Dietary energy is used by the body directly and indirectly through conversion to high-energy bonds in ATP to fuel all activities. Dietary energy values are typically reported in kilojoules or kilocalories (known as Calories in common parlance and in FDA labeling), with 1 kcal being the amount of heat required to raise the temperature of 1000 g of H_2O from 14.5 to 15.5 °C.

To quantify the metabolizable energy of food, the gold standard is preparation of dried homogeneous samples of the food, followed by measurement of gross energy content by combustion (bomb calorimetry) and subtraction of the obligatory energy losses in stool and urine measured for the period relating to food ingestion. Since this gold standard method is burdensome and impractical for routine use, different countries use different simplified systems. In the United States, the FDA defines 5 alternative methods, any 1 of which can be used to legally describe the energy content of a food, as summarized in **Figure 1**. Most of these methods are based on the Atwater system (1). The simplest is method 2, which estimates the macronutrient content of the food by applying the general 4-, 4-, and 9-kcal/g Atwater factors for the dietary energy contents of carbohydrate, protein, and fat, respectively; these factors account for estimated energy losses in stool and urine based on data from a small number of human subjects studied >100 y ago. Of note, there is remarkable variability in calculated dietary energy across the different FDA methods. As illustrated in the figure, a high-fiber bread has an 18% difference in calculated dietary energy among the methods, demonstrating that dietary energy is not the simple and accurate number that it is widely assumed to be. The FAO of the UN has its own methods for calculating dietary energy (2), but for the most part these are based on the same Atwater factors used by the FDA.

Deficiencies

Human physiology has evolved to support considerable variation in dietary energy intake: a stomach that acts as a reservoir so that eating does not need to be continuous throughout the day; body fat and glycogen stores that buffer meal-to-meal and day-to-day variability in dietary energy intake (the CV for day-to-day variation in energy intake is ∼10% in children and ∼25% in adults) (3); and intestinal microbiota that ferment some indigestible food components into absorbable energy. In extreme situations where no dietary energy intake occurs, the body can typically survive for 1–3 mo by slowing its metabolic rate and physical activity and utilizing available energy stores (4). In less extreme situations, physiologic adaptations involve compensatory responses that decrease energy expenditure acutely (and perhaps over a longer period) and subsequently increase energy intake. One mechanism by which energy intake is increased after energy deficiency is increased hunger, which in addition to being perceived as sensations in the stomach also manifests rather strangely as nonspecific changes in mood (e.g., level of anger and irritability) (5). Through such mechanisms, a fall in energy intake is partly or fully accommodated to attenuate loss of body energy.

Undernutrition occurs when energy intake is lower than energy requirements for a prolonged period and is common worldwide, especially in infants and children in low- and middle-income countries. As defined by the WHO (6), undernutrition for children includes moderate acute malnutrition (i.e., wasting; weight-for-height z score –2.0 to –3), severe acute malnutrition (weight-for-height z score <–3.0), stunting (height-for-age z score <–2.0), and underweight (weight-for-age z score <–2). Deficiency states are also defined for adults: underweight is a BMI (kg/m^2) of 17.0 to <18.5, and thinness is a BMI < 17.0. Underweight and thinness are also common in adults of all ages in low-income

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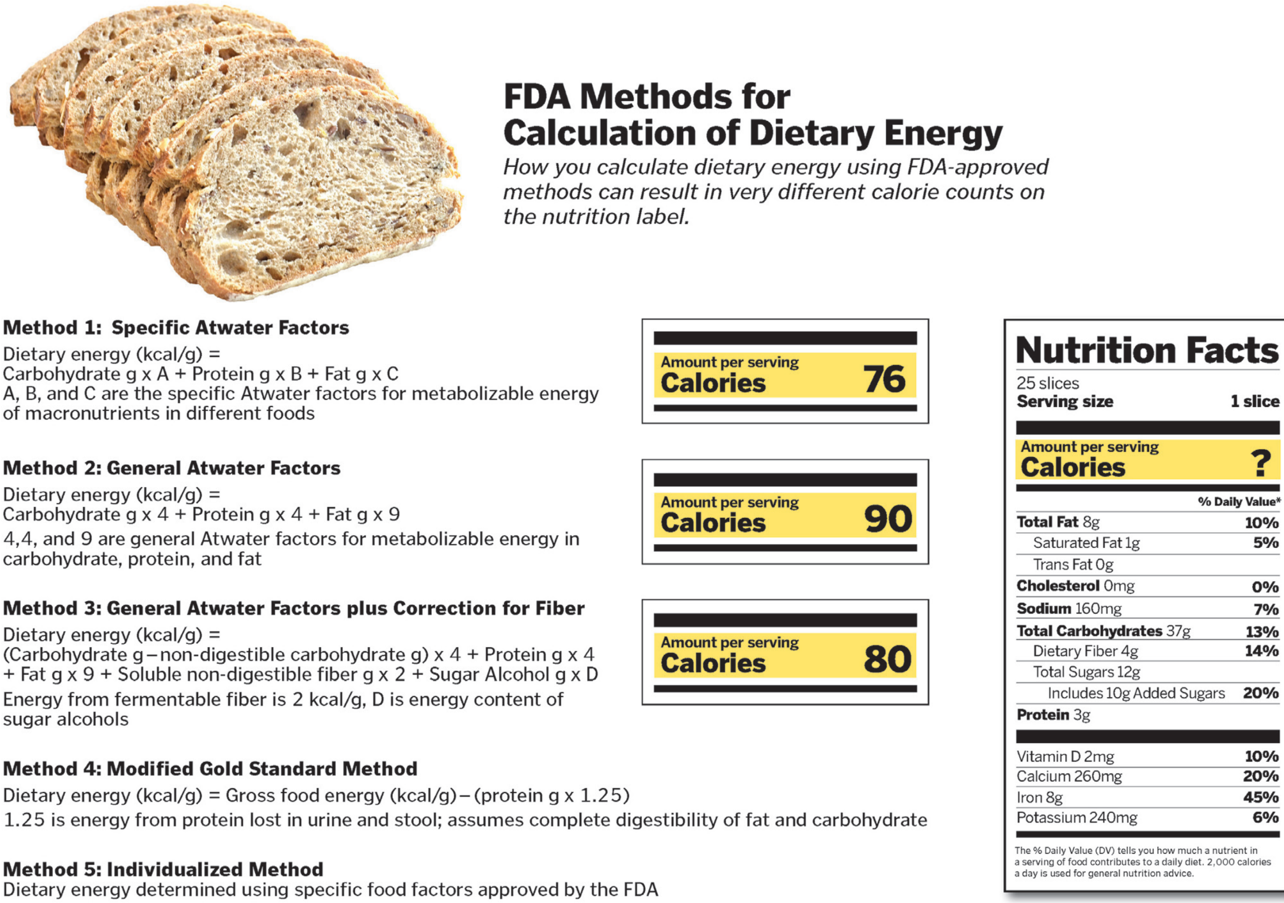

FIGURE 1 The FDA of the US government allows dietary energy in Nutrition Fact panels on commercial foods to be calculated by any 1 of 5 methods. As illustrated for a single food example (a whole grain bread), these methods can give substantially different dietary energy values for the same micronutrient content.

countries, in humanitarian disasters, and in older adults after mechanisms of energy regulation decay, including loss of sensations of hunger (7). An important qualification of energy deficiency states in all age groups is that when energy is inadequate, other nutrients are likely to be deficient because energy-containing foods are the primary vehicle in which all nutrients are consumed.

Diet Recommendations

The Food and Nutrition Board of the Institute of Medicine, National Academies of Science, convenes a panel of subject experts to define DRIs for dietary energy. The recommendations from the most recent committee (2002) (8) were generated using the following general principle: that energy requirements are equal to total daily energy expenditure, as determined during approximate energy balance using the gold-standard doubly labeled water method, plus any additional allowance for tissue deposition as needed in specific groups (e.g., weight gain in infancy). The DRIs are provided in the form of equations to estimate energy requirements from weight, height, age, sex, and activity level; there is no RDA or tolerable upper level for dietary energy, in recognition of the considerable person-to-person variability in energy requirements due to differences in body weight and height, age, gender, and individual factors. The 2020–2025 US Dietary Guidelines (9), which are supposed to be harmonized with DRIs, suggest typical ranges of dietary energy to meet the energy requirements of individuals: 2000–3200 kcal/d for adult men, 1600–2400 kcal/d for adult females, and 1000–2000 kcal/d for male and female children aged 2–8 y. The FAO of the UN has recommendations for dietary energy that are generally somewhat lower than US dietary recommendations. The AHA recommendations for dietary energy intake, as endorsed by the American Academy of Pediatrics, include 900 kcal/d for 1-y-old infants and 90–105 kcal/kg/d for preterm infants.

Food Sources

Recognizing the centrality of dietary energy in nutritional health, Nutrition Fact panels on packaged food in the United States require that dietary energy has the largest and boldest font. Information on dietary energy must also be available for menu items sold in large US restaurant chains (≥20 outlets), and dietary energy is listed in every food in the US Department of Agriculture's standard reference database for the composition of different foods. This public information is used as an essential underpinning of national recommendations on healthy portion sizes from birth to old age; weight loss programs; and food rations used in schools, nursing homes, prisons, and other public institutions.

As noted, there are 5 approved FDA methods for calculating dietary energy, which give variable results. The FDA recommends that energy values be rounded to the nearest 5 kcal for foods ≤50 kcal and to the nearest 10 kcal for foods >50 kcal. Foods containing <5 kcal are labeled 0 kcal (10). There is no required oversight of Nutrition Fact information for packaged food prior to distribution for sale, and food companies are encouraged but not required to submit nutritional labeling to a database. However, the FDA can perform inspections of packaged food (typically a small percentage of available foods; e.g., <1% imported foods); measured energy content must not be >120% of that stated on the Nutrition Fact panel in 12 food samples collected at the point of consumer purchase; and weight must not be < 99% when 48 samples are measured. These relatively large ranges to define acceptable accuracy in dietary energy reporting may enable misreporting. We and others have noted considerable inaccuracy in dietary energy values reported in Nutrition Fact panels and by restaurants even when using methods that do not account for variability introduced by the different FDA calculation options (10). These inaccuracies have important ramifications in public health, making it harder for individuals to engage in the nationally promoted self-monitoring of dietary energy for healthy weight management.

Clinical Uses

Since energy-containing food is the vehicle in which almost all essential nutrients are consumed and is itself essential for life, it is used widely in clinical practice for disease prevention and treatment. Food as medicine is an increasingly accepted concept that recognizes food as being foundational for prevention and treatment of a range of disease states. A usual tenant of clinical uses of dietary energy is that energy provided in foods or supplements should ideally contain a comprehensive selection and balanced amounts of protein, essential fatty acids, and essential micronutrients.

For children, adequate intake of dietary energy (as part of a nutritionally balanced diet) is the fundamental underpinning of healthy growth and brain development. A major public health focus has been on improving nutrition during the first 1000 d, from conception to the second birthday, but evolving evidence suggests that adequate dietary energy throughout childhood is critical for ensuring optimal skeletal and nervous system maturation. Unwell children may have high metabolic needs with suppressed appetite, making adequate energy intake difficult; supplementary dietary energy may be needed in these cases. Preterm infants in particular are exquisitely vulnerable to fluctuations in dietary intake because brain glucose needs are high whereas energy reserves in the form of body fat are low.

In adults, diseases in which changes in dietary energy are the primary focus include obesity and the noncommunicable diseases that are promoted by obesity (11). A reduction in dietary energy to achieve a body weight loss of at least 10 kg can reverse diabetes in the majority of recently diagnosed cases (12), and weight loss ≥5% has broad medical benefits for cardiometabolic health in individuals with obesity, including reductions in blood pressure and cholesterol (11). In late life, clinical uses of dietary energy become more diverse. In addition to amelioration of cardiometabolic disease risk factors, dietary energy can be used to treat unexplained weight loss associated with unhealthy aging (7).

Toxicology/Health Risks

Acute health risks of very high-energy intake are minimal. However, long-term risks of excess dietary energy are pronounced. Overnutrition occurs when energy intake exceeds energy expenditure over a prolonged period, with resulting weight gain leading to overweight and obesity. The prevalence of obesity has been increasing worldwide for several decades (11) and, as noted, is the underlying driver of the increasing prevalence of noncommunicable diseases such as type 2 diabetes that are reducing population health and increasing disability and health care costs, especially in older adults (11).

Several levels of overnutrition are defined in adults using the BMI classification: overweight, 25–29.9; class I obesity, 30–34.9; class II obesity, 35–39.9; and class III obesity, ≥40.0 (11). In children, a healthy range for BMI varies by age, and BMI-based definitions of overweight and obesity at each age are now available (13). Although a few earlier studies suggested that excess energy intake could result in such profound accommodation in energy expenditure that weight gain was minimal, such results have not been the norm (14); on the contrary, the continuing increase in the prevalence of obesity worldwide demonstrates the relatively limited capacity of energy expenditure to adapt to increasing energy intake in most individuals.

Recent Research

Recent research has examined whether all food dietary energy sources have equivalent biological effects in the body—in popular terms, whether "a calorie is a calorie"—and what implications this may have for dietary recommendations and behavioral intervention approaches to weight management (15). In addition to the older studies that generally agree on protein being more satiating and increasing energy expenditure somewhat more than fat or carbohydrate (16), 4 newer lines of research support the contention that different dietary energy sources are not equivalent. This work does not invalidate the general principle that energy balance is determined by the difference between dietary energy consumed and energy expended.

Effects of fiber and food form on energy digestibility and metabolizable energy

Atwater factors for diets of a typical composition indicate that approximately 90% of gross food energy is available as metabolizable energy and 10% is lost in stool and urine. However, the Atwater factors were derived from studies on a small number of adult males. In more recent studies, the general Atwater factors appear to overestimate available metabolizable energy in higher-fiber diets, which also increase energy expenditure (presumably through a more abundant microbiota colony) (17). In addition, food form has a significant and currently underrecognized effect. For example, the measured metabolizable energy content of whole almonds is 32% lower than dietary energy calculated using Atwater factors (18), and further research is needed to define the effects of food form more broadly.

Effects of food form on ad libitum dietary energy intake

The energy density of foods (kilocalories per unit weight or volume) has short-term and potentially also longer-term effects on ad libitum energy intake (19). The reasons for this influence are not known but may relate to intrinsic mechanisms of energy balance and/or eating habits. In addition, foods that meet the relatively new and controversial classification of "ultraprocessed"—based on being commercially manufactured in multiple industrial steps usually involving the addition of synthetic chemicals—have been reported to significantly increase ad libitum energy intake as compared with similar foods that are not ultraprocessed (20). Additional controlled studies are needed to determine whether there is any specific effect of ultraprocessing on ad libitum energy intake over and above the effects of the typical dietary features of ultraprocessed foods (such as high energy density and low dietary fiber) that are not part of the definition of ultraprocessing.

Role of the microbiota in dietary energy availability

Gut microbiota narrow the gap between the gross energy content of food and the metabolizable energy available to the body by partially metabolizing some macronutrients otherwise indigestible to humans (21). Fermentable dietary polysaccharides interlinked in a manner too complex for digestion by human digestive enzymes pass into the large intestine (colon), where some are then fermented by colonic bacteria, with resulting production of free fatty acids that can be absorbed as an energy source. In addition, fermentation of pyruvate by gut microbiota generates butyrate, an important energy source for human intestinal epithelial cells. An estimated 50% of gross energy is made available in these ways, giving rise to the assumed dietary energy content of fermentable dietary fibers of 2 kcal/g. The relation between intestinal microbiota and dietary energy availability is being researched as a possible therapeutic target for obesity management.

Dietary energy sources in weight management interventions

Randomized trials and prospective epidemiologic studies continue to examine whether different dietary patterns are more beneficial for primary prevention of weight gain, weight loss, and weight loss maintenance. There is no consensus on this topic to date; meta-analyses point to significant albeit modest effects for some dietary parameters, including energy density, dietary fibers, and protein, with no information on whether the effects of different dietary factors may be additive in their effects (22). New precision nutrition initiatives will also be examining biological variability in response to different dietary patterns as a possible additional therapeutic approach to obesity management.

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