The Energetics of Obesity: A Review

Monitoring Energy Intake and Energy Expenditure in Humans

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Writing about obesity research is a challenging task. While the rising obesity epidemic drastically raised public awareness of the problem, the causes behind the epidemic are still poorly understood. The etiology of obesity is a subject of ongoing scientific debate with widely varying views and strong opinions. Is it mostly genetic or environmental in nature? Is obesity caused by changes in our diet or changes in lifestyle and physical activity or both? Modern research literature quite often offers conflicting findings. Publications in popular media like the one in *Time* magazine [1] add to the controversy by making quick and strongly worded summaries of academic research. Although the root causes of obesity remains a topic of active research, this review concentrates on the fundamental components of weight regulation in humans and their relative contribution to the energy equation. A better understanding of the energetics of obesity may provide some insight into the etiology of the obesity epidemic. The energetics of obesity also showcases an engineering challenge: development of techniques to accurately measure individual components of the energy equation.

Digital Object Identifier 10.1109/MEMB.2009.935470

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Being overweight and obesity [which in adults is defined as the body mass index (BMI) greater than 25 and 30, respectively] result from a persistent positive energy gap, the difference between energy intake and expenditure. The energy intake is provided by the digestive system, which releases the chemical energy of food. The energy expenditure consists of three major components: basal metabolic rate (BMR), thermic effect of food (TEF), and activity energy expenditure (AEE) (Figure 1). Under normal conditions, our body maintains a steady body weight through a process known as weight homeostasis. Any long-term changes in body weight are caused by a persistent energy imbalance, the energy gap, which leads to a new increase in weight. The change in body mass in overweight or obese adults is mostly due to an increase in the mass of white adipose tissue commonly known as fat tissue. The white fat cells play the role of a high-capacity buffer that provides energy on demand during substantial variations in intake and expenditure. Therefore, the first fundamental question is the amount of energy gap leading to weight gain.

Early estimates of the energy gap were based on population statistics accumulated over past decades. An average American adult gains 9 kg (20 lb) between 25 and 55 [2]. Assuming that all this weight gain comes from adipose tissue with an energy density of 3,500 kcal/lb, the equivalent energy storage is worth 70,000 kcal. Food intake of an average nonobese adult is about 900,000 kcal/year. The weight gain over the period of 30 years signifies a difference of $70{,}000\ \text{kcal}/(30\ \text{years} \times 900{,}000\ \text{kcal/year}) = 0.259\%$ the total calorie intake. Since ingested food requires energy costs of about 35% to be stored inside adipose cells, this is equivalent to excess intake of 97 kcal of food per day. Results obtained by Hill et al. [3] suggest that increasing energy expenditure or decreasing energy intake on an average by 100 kcal/day may be sufficient to close the energy gap in 90% of the population. Other studies [4] associated weight gain with the energy gap as small as 10 kcal/day! These estimates show that the weight gain in the majority of population may be caused by a relatively small daily imbalance. For example, not drinking a standard 330-mL can of sugar-sweetened soda (100–160 kcal) or not eating a cookie (50–200 kcal) could potentially lead to a zero gap in the majority of the population. However, such low estimates of the energy gap are derived from simplified models that do not account for increased energy demand in a body with higher BMI. As an example, if a weight-stable individual cuts the energy intake by 50 kcal daily, this individual would not eventually disappear into the thin air as suggested by the simple model. Rather, the weight loss would lead to a lower energy demand from the body and eventual weight stabilization at a new equilibrium point. Similarly, increasing one's energy intake by a small number of calories per day will lead to a small weight gain and reaching a new equilibrium weight. Recent studies question the size of the energy gap and suggest more sophisticated models of the energy balance. In a recent article, Swinburn et al. [5] suggested that the gap of 382 kcal/day could explain the weight gain in the U.S. population since the 1970s. Another insight into the dynamics of weight gain was given by a publication of Bouchard [6], which identified the energy gap of 300–400 kcal for individuals with a BMI of 30 and almost of 1,000 kcal for individuals with a BMI of 40. These numbers are 4–40 times higher than was previously thought!

Estimation of the energy gap in children adds another level of complexity. Unlike weight-stable adults, children need additional energy for growth, which implies a need for persistent positive energy balance. Using the previously discussed methodology of Hill et al., Butte and Ellis estimated that the median energy gap in overweight children was 288 kcal/day, while normal-weight children maintained a positive energy balance of 150 kcal/day [7]. Both of these estimates are substantially higher than those for adults; however, they are also based on a simplified model. Using a model that accounted for the energy demands of a heavier body, Wang et al. [8] estimated that energy gap in overweight adolescents was as high as 700–1,000 kcal/day. Other studies produced estimates from 46–72 kcal/day [9] to 100–450 kcal/day [10]. Similar to adults, the current understanding about the amount and dynamics of energy imbalance leading to overweight and obesity in children is far from perfect.

The next logical question is how does each part of the energy equation contribute to the energy gap? On the energy intake side of the equation, the ingested calories come from food. Do we simply eat more now than before? Historic reports of the United States Department of Agriculture (USDA) and modern-day reports of the National Health and Nutrition Examination Survey (NHANES) show that daily caloric intake of an average

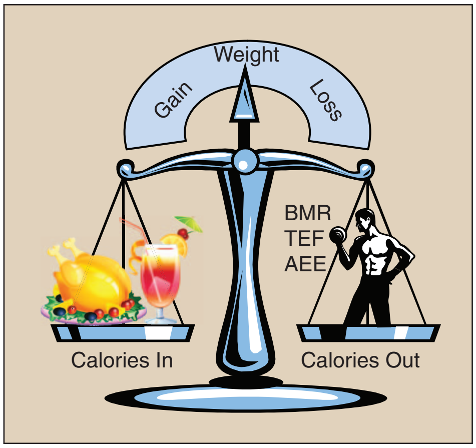

Fig. 1. The energy balance is defined as the equilibrium point between food intake and energy expenditure. The energy gap is the difference between the energy intake from food and energy expenditure, which consists of three major components: BMR, TEF, and AEE.

American has steadily declined from 1965 (2,060 kcal) to 1988 (1,785 kcal) [11] and in the past 20 years rose back to 1960 levels (2,157 kcal) [12]. This obviously does not give a clear picture of what is happening with the daily food intake. The obesity epidemic started when the caloric intake was on a decline, which makes a simple "eating more" hypothesis less likely. Could it be that the composition of food is what matters? Dietary fat has the highest energy density at approximately 9 kcal/g, alcohol is 7 kcal/g, while proteins and carbohydrates have an energy density of approximately 4 kcal/g. It is obvious that eating fatty foods would satisfy the daily energy requirement far faster than a diet rich in carbohydrates and protein. Again, using the data from the USDA and NHANES surveys, we can see the diet composition at the beginning of the obesity epidemic and present. Here is how daily intake from 1978 compares to 2005: proteins 74/82 g, fats 83/82 g, carbohydrates 194/265 g. It seems that the diet composition has not changed much since the 1970s. Obviously, food is a key ingredient of the energy balance. Nevertheless, researchers are struggling to pinpoint changes in intake patterns or changes in the diet that may explain the rise in overweight and obese populations.

On the energy expenditure side of the equation, the major contributor (~60%) is BMR (also known as resting energy expenditure). BMR is the energy that is spent to maintain the body's temperature, cardiovascular, nervous, and respiratory functions, and other vital functions of cells, tissues, and organs. BMR depends on body weight, height, age, and gender and thus varies among individuals. Although such variations can potentially lead to weight gain in individuals with relatively low metabolic rate, several studies have shown that BMR at best may provide only a small contribution to the energy gap [13].

The next component of energy expenditure is the TEF, which is comparably minor (10–15% of daily energy expenditure). TEF is the energy cost associated with processing of the food for utilization and storage in the body. The composition of food matters: proteins have much higher TEF than fat, and there are some indications that diets high in protein help in regulating weight [14].

AEE includes exercise energy expenditure (EEE) and nonexercise activity thermogenesis (NEAT), which is the energy spent on daily chores, occupational activity, maintaining posture, and fidgeting [15]. The energy expenditure from low-intensity exercise is rather low. For example, an average 190-lb man will expend about 100–150 kcal per half an hour of walking. The Center for Disease Control recommends at least 150 min/week of moderate-intensity aerobic exercise, such as brisk walking and muscle-strengthening 2 days/week [16]. However, some studies [17] suggest that this level of exercise may not be enough to close the energy gap. Exercises like jogging and weight lifting will burn 450–600 kcal/one-half hour and can compensate for the positive energy balance more easily. Overall, the U.S. population seems to exercise more: the number of people who reported no leisure-time physical activity has decreased from 30.5% in 1988 to 23.9% in 2007 [18]. So if we exercise more, why are we still getting larger?

One possible explanation is NEAT, which has steadily declined with advances in technology and spread of a sedentary lifestyle [19]. For example, each hour of watching TV or playing video games is associated with a net energy gain of approximately 100 kcal [20]. Historically, NEAT of activities of daily living was the major source of energy expenditure. A very interesting study conducted by Egger et al. [21] compared the physical activity level of authors playing the role of early settlers to Australia with that of sedentary office workers. The difference in energy expenditure between two groups was equivalent to 8–16 km walking per day or approximately 480–960 kcal/day! Such levels of energy expenditure are comparable even with largest estimates of the energy gap.

The final question is why these studies result in such drastically different conclusions? Accurately measuring components of energy balance remains an open problem in medicine and bioengineering. First of all, a possibly very small imbalance needs to be measured for a long period of time, challenging the precision of available methods. Second, controlled laboratory tests confining the subjects to an artificial environment create substantial changes in behavior affecting the results. Taking the study outside of the laboratory and into free-living environments poses a further challenge to the required precision of measurement.

The most accurate measurement of energy balance can be performed by a room calorimeter in laboratory conditions (Figure 2). The subject is confined inside the calorimeter,

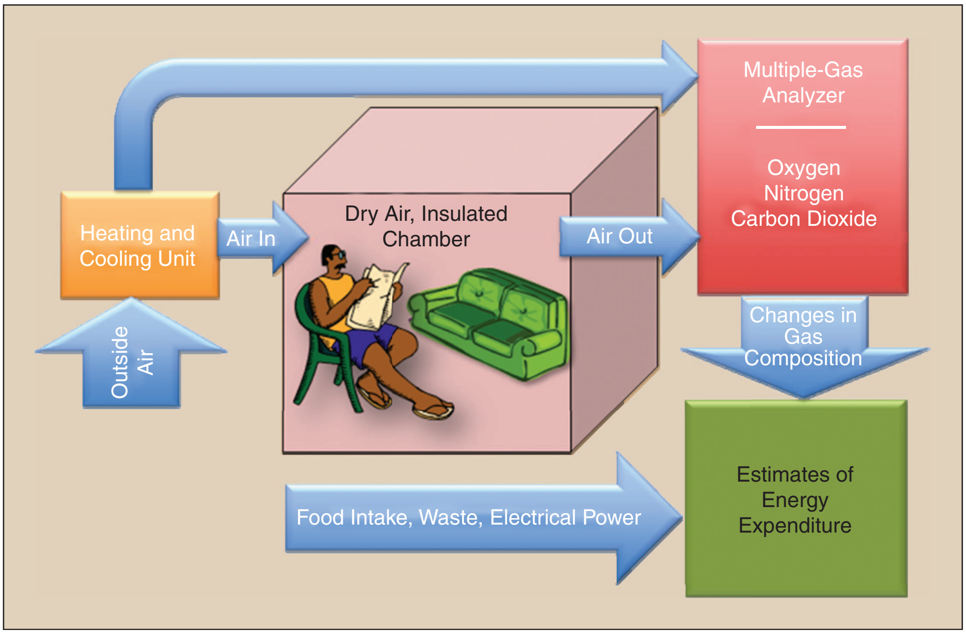

Fig. 2. Indirect room calorimetry is based on the measurement of oxygen consumption and carbon dioxide and methane production to estimate energy expenditure. Subjects typically spend at least 24 h in a controlled room where gases in the inlet and outlet air are carefully measured and controlled. The room contains a small sitting area with entertainment, a table for eating meals that are passed through a window, an exercise machine, and a bed for sleeping.

which uses direct heat-loss measurements (direct calorimetry) or oxygen consumption and carbon dioxide production (indirect calorimetry) to continuously monitor energy expenditure. The most significant advantage of room calorimeters is the ability to accurately (0.5–2%) measure BMR, TEF, and AEE components of energy expenditure. The response time may vary between 5 and 30 min. The energy intake can be specified by serving meals of known energy content with waste-plate measurements or estimated using the weight-equilibrium assumption.

For the free-living conditions, the most accurate method of assessing energy intake and expenditure for periods of 1–3 weeks was developed in the 1950s. This method uses doubly labeled water and is available only on a limited basis because of high costs. The subjects are administered water in which both hydrogen and oxygen atoms have been replaced with uncommon isotopes such as deuterium and oxygen-18. Measuring the elimination rate of the isotopes through blood or urine samples allows the estimation of carbon dioxide production by the body and thus measuring the total energy expenditure (TEE) over a period of time. If the subject is weight stable over this period of time, then the total energy intake from food is equivalent to the measured energy expenditure. Doubly labeled water cannot measure individual components of energy but rather provide an estimate of TEE with an accuracy of several percent. In addition, it does not provide insight into when the actual food consumption takes place or about the size and composition of the meals.

Methods of monitoring energy intake from ingested foods traditionally rely on self-report. Methods such as diet history, 24-h food recall, etc., as well as newer methods such as multimedia or personal digital assistant (PDA) diaries suffer from underreporting, which could be as high as 400 kcal/day [22]. It is obvious that such accuracy is not sufficient to satisfy the needs of measuring the energy gap over a long time. There are several reasons for such low accuracy. A food diary used in research may look like a checkbook in which each page contains fields describing what was eaten, at what time, what was the size, and location. First, the respondents may underestimate the size of what was eaten or do not report some parts of the meal altogether (so-called reporting effect). It was shown that people usually disregard and do not report small snacks that may contribute a significant part to the daily intake. Second, some individuals change their eating behavior to reduce the reporting burden (observation effect). Accurate capture of energy content of food ingested throughout the day is still one of the big challenges facing obesity research, although there are attempts to use objective measures to evaluate periods of intake and mass of ingested food [23], [24]. For example, we developed a method [23] that can accurately detect food intake, differentiate between ingestion of liquids and solids, and estimate ingested mass. The principle of operation is based on a simple observation that the frequency of swallowing at rest is at least half of that during ingestion. Thus, a sudden increase in swallowing frequency can serve as a reliable predictor of food intake that is not influenced by common activities such as talking (Figure 3). This technique can potentially be used to create a noninvasive wearable device for objective monitoring of eating behaviors.

Methods of monitoring energy expenditure in free-living populations are better developed [25]. Indirect calorimetry systems that sample composition and flow rate of expired gases have been implemented as portable systems that can be worn for hours. The obvious downside is the use of a face mask, which interferes with normal activities. A variety of methods estimate energy expenditure from measurements or observations of various physiological indicators. One of the most popular approaches is kinematic measurement through use of pedometers or accelerometers. The gross levels of motion activity captured by a triaxial accelerometer attached to a limb or the body have been shown to correlate reasonably well with TEE measured by the doubly labeled water [26]. Other physiologic indicators include heart rate, ventilation volume, and electromyographic activity. Overall, modern methods allow estimation of TEE on the error of 10–15%, which may not be accurate enough for energy-gap measurements.

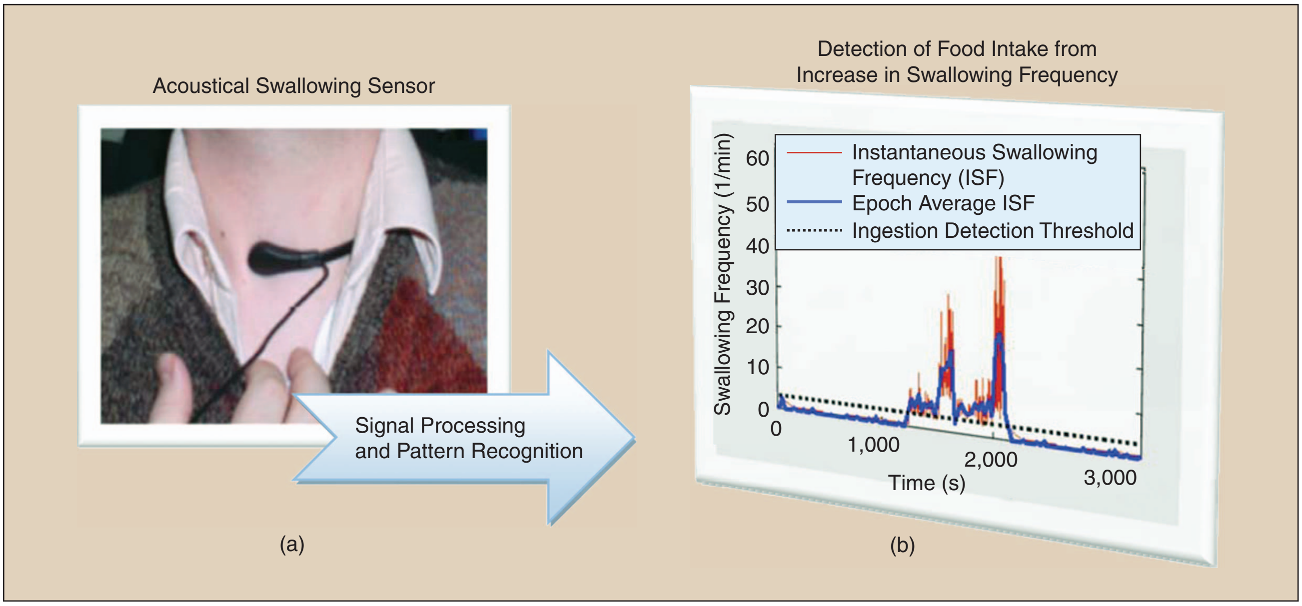

Fig. 3. (a) An acoustical sensor for swallowing detection. (b) An increase in swallowing frequency corresponds to a period of ingestion.

In summary, the energetics of maintaining body weight is defined by several key components that should remain in balance under normal conditions. The size of the persistent energy imbalance that feeds the growing waistlines of the population is not completely understood, with estimates varying from tens to several hundreds of kilocalories per day. The question of "what is more responsible for the obesity epidemic: reduced physical activity of the population or increased energy intake?" remains hotly debated. However, there is a growing agreement that the challenges of the obesity epidemic require addressing both the energy intake and energy expenditure sides of the equation. Better understanding of the contribution of all parts of the energy equation is needed for a better understanding of the etiology of obesity. Development of more accurate technologies for measurement of energy balance in free-living individuals may be an enabling factor for obesity research.

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