The energy balance equation: looking back and looking forward are two very different views

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The energy balance equation has served as an important tool for the study of bioenergetics. It is based on one of the most fundamental properties of thermodynamics and has been invaluable in understanding the interactions of energy intake, energy expenditure, and body composition. Recently, however, the obesity epidemic has extended the use of the equation to the creation of public health messages for preventing or even reversing secular trends in body mass index. This usage often fails to consider how changes in any one term of the equation can lead to accommodations in one or both of the other two terms. It is concluded that research and public health messages should not simply consider how interventions affect just energy expenditure or energy intake, but rather how they affect the balance or gap between energy intake and expenditure.

INTRODUCTION

The prevalence rates of overweight and obesity in the United States have increased so dramatically that healthy-weight adults are now in the minority.[1] The increased prevalence in the United States, while one of the highest in the world, is by no means a problem in the United States alone. Obesity has been increasing in emerging and industrialized countries. Because of the negative health consequences associated with obesity, there has been a parallel increase in public health campaigns aimed at preventing obesity. Among these has been an increased emphasis on individual and community efforts to alter energy balance.

ENERGY BALANCE

According to the first law of thermodynamics, energy can be neither created nor destroyed; thus, for any system, the following equation applies:

$$\text{Energy in} = \text{energy out} + \text{change in energy stores} - \text{work performed} \quad (1)$$

For the human, energy input is the amount of chemical energy entering the body that can be liberated via metabolism and thus is measured as metabolizable energy.[2] This is the difference between gross energy of the foods we consume and the unabsorbed energy that is excreted as feces plus the potential energy in compounds excreted in urine due to incomplete metabolism. Energy output is the heat released by the body through resting metabolism, the thermic effects of meals, and physical activity.[2] Energy storage is the potential chemical energy mostly stored as fat, but also as glycogen and protein. It can also include stored heat energy due to changes in body temperature, but this term is generally negligible except for time intervals of less than a few hours.[3] Work, as defined by physicists, is also a generally negligible term.[4] Thus, for most cases, equation 1 can be reduced to:

$$\text{Energy intake} = \text{energy expenditure} + \text{change in body stores} \quad (2)$$

This simple concept of energy balance in the human, as shown in Figure 1, helps us to understand the development of overweight and obesity, which, by definition, is an excessive accumulation of energy stored as body fat. Consider a male who is 1.77 m tall and a healthy weight of 70 kg. If this individual were to gain 10 kg, his body mass index (BMI) would increase from 22.3 (healthy range) to

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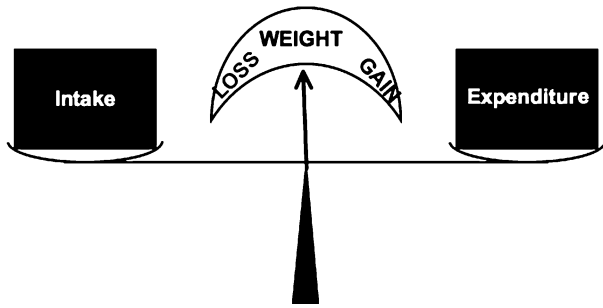
Figure 1 **A common conceptualization of the energy balance equation as it applies to the regulation of body weight.**

25.6 (overweight). If body composition were to be measured and the excess weight gain found to be 70% fat and 30% fat-free mass,[5] then equation 2 could be easily applied to determine that this individual had accumulated a positive balance of about 70,000 kcal of excess (metabolizable) energy intake.

An energy imbalance of 70,000 kcal is large, but the daily imbalance that leads to this accumulation depends upon the period over which this theoretical male gained that excess mass. If he gained the excess mass in 1 month, it corresponds to a large daily imbalance of 2300 kcal/day; but if the 10 kg was gained over 1 year, it equates to an average daily imbalance of 200 kcal/day; and if the excess weight was gained over 10 years, then the imbalance is an average of only 20 kcal/day. Thus, the calculation is simple and valid because energy is conserved; but interpretation of this application of the energy balance equation for the development of overweight and ultimately obesity (an additional 14 kg gain yielding a BMI of 30), is dependent on the timeframe over which the weight was gained.

NATURAL HISTORY OF BODY MASS GAIN

The question regarding the timeframe for the development of overweight and obesity can be addressed using national survey data and several small, longitudinal studies. Based on United States' population averages from the NHANES data, the average weight for a 40–year-old adult male between the periods 1976–1980 and 2002–2004 increased by 7.4 kg or 0.5 kg/year; this timeframe reflects the period of the obesity epidemic during which the prevalence of obesity in the United States increased from 15% to 32%.[1] Assuming 80% of the gained weight was fat, the gain of 0.5 kg over 1 year would correspond to a daily imbalance of 10 kcal/day, which is even smaller than in the example above. The longitudinal study conducted in the United States by Yanovski et al.,[6] however, does not support the use of a simple daily average. That

study reported an average annual weight gain of 0.5 kg/year, which is identical to the population average, but reported that two-thirds of the gain occurred during a 12-week period between the Thanksgiving and Super-bowl weekends, which are times of celebration related to the nation's history and a football event, respectively. This corresponds to a 54 kcal/day imbalance for that 12-week period. In order to increase the time resolution, Racette et al.,[7] measured body mass daily in 48 adults. They found that the daily gain averaged 3 g/day, or equated to an average energy imbalance of 21 kcal/day. Interestingly, however, they found that the average weekend daily gain was 60 g/day compared to a weekday average loss of 20 g/day. The higher weekend rate of gain corresponds to an energy imbalance 420 kcal/day. Again, all of these calculations assume the increase in body mass is 70% fat and it must also be pointed out that the averages include individuals with larger changes in body mass. It can be concluded from a retrospective population point of view that the energy imbalance driving the obesity epidemic in the United States is quite small on an annual basis, and is probably due to short bouts of modest imbalance that are not negated by subsequent negative energy balance.

COMMON PUBLIC HEALTH MESSAGE

Based on this retrospective application of the energy balance equation, many investigators and public health officials have used the same energy balance equation in a prospective manner to predict that the obesity epidemic can be addressed by initiating changes in energy expenditure or energy intake as small as 25–50 kcal/day. From the energy expenditure side of the equation, 25–50 kcal/day can be spent by walking an additional 750–1500 steps per day. From the energy intake side of the equation, energy intake can be reduced by 25–50 kcal/day or by eating one less cookie, or forkful of food each day. Although this use of a valid retrospective application of the energy balance equation to a prospective prediction appears quite valid, it is not an equivalent situation. The prospective application of the energy balance equation for a single change in energy intake assumes that energy expenditure will not change in response and that a simple change in energy expenditure assumes that energy intake will not change in response. Evidence, however, does not support this assumption.

CHANGES IN ENERGY EXPENDITURE IN RESPONSE TO CHANGES IN ENERGY INTAKE

Any change in energy intake will also be accompanied by a change in the thermic effects of meals, which will mediate the energy balance in response to a change in

intake. Decades of research have shown that the thermic effect of meals is proportional to energy intake and varies among individuals, but averages almost 10% of energy intake when mixed meals are consumed by subjects under conditions of near energy balance.[8] There is more controversy regarding the value for the thermic effect of meals during periods of significant energy imbalance due to significant variation between studies.[9] Despite the study-to-study variation, the average across studies employing large energy imbalances indicates that the thermic effect of meals remains small compared to the size of the meal.[8,9] Regardless of any controversy regarding the thermic response to large changes in energy balance, however, the effect of changes in the thermic response to meals for a 50 kcal/day reduction in energy intake is likely to be 5 kcal/day or less; consequently, it will only slightly moderate the change in energy balance.

A decrease in energy intake will thus result in a negative energy balance and loss of body mass and that will act to moderate the ultimate weight loss. When body mass is lost, there will be, on average, a reduction of energy expenditure. As mass is lost, some fat-free mass is expected to be lost and this is associated with a reduction in resting metabolic rate;[10] loss in body mass will also reduce the energy costs of physical activities of daily life.[11,12] Using cross-sectional data (Figure 2) from multiple doubly labeled water measurements of energy expenditure in adults (OPEN), we find that energy expenditure will decrease by 21 kcal/day and 15 kcal/day for each 1 kg loss for the average male and female, respectively, once they end their energy-restricted diet. Longitudinal data has provided similar results. Among women who lost body mass and then stopped energy restriction, we reported an average decrease in total energy expenditure (TEE) of 54 kcal/day after a 9 kg wei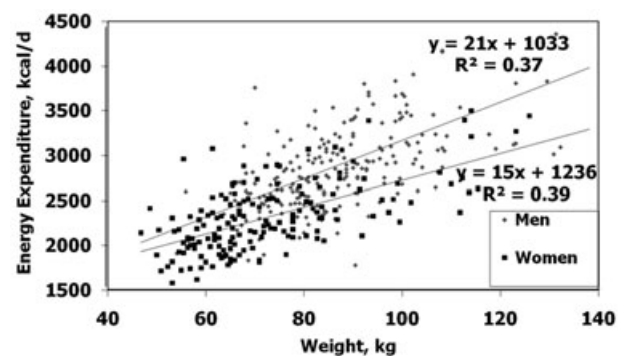ght loss, which equates to a value of 6 kcal/kg.[12] Simi-larly, Amatruda et al.[13] reported a decrease in TEE of 231 kcal/day for a 22 kg loss, which equates to a value of 10 kcal/kg. Combining these estimates without weighting gives an average weight-related change in energy expenditure of 13 kcal/kg. This weight effect alone would limit weight loss from a decrease in daily energy intake of 50 kcal/day by eating one less cookie per day to 4 kg. That is not an insignificant weight loss, but it is not sufficient to return an overweight or obese individual to a healthy weight and is thus an insufficient dietary change to reverse the obesity epidemic of the last two-and-one-half decades. Based on this same 13 kcal/kg estimate, the 24 kg weight loss required to reduce the BMI of a 1.77 cm tall male from 30 to 22 kg/m^2 would have to reduce his habitual energy intake by 310 kcal/day (24×13). Moreover, it is estimated that intake would have to be decreased and maintained at that level for several years to attain the 24 kg weight loss.[14]

While a 310 kcal/day decrease in energy intake is greater than the oft-quoted 50 kcal/day suggested to reduce the weight of an obese individual, it is still smaller than the 500–1500 kcal/day energy restrictions prescribed in most weight-loss treatments. Evidence from multiple weight-loss studies indicates that a slow, steady weight loss over a period of 1 year, much less 3 years, however, is difficult to sustain.[15] Moreover, there have been some recent studies that have not placed emphasis on energy restriction per se, but instead focused on long-term dietary or behavioral changes and, in so doing, encouraged this smaller deficit for large periods of time. These dietary changes often lead to a modest energy restriction, which produces weight losses of 1–8 kg at 12 months of intervention.[16] Unfortunately, the few studies that perform weight follow-up beyond 1 year, find that further weight loss is not common and that weight regain can occur.[17] This lack of continued weight loss cannot be explained by the reduction in energy requirement due to weight loss and smaller body size. Based on the above relationship between energy expenditure and body size, a 310 kcal/day reduction in energy intake, should allow a weight loss of 15 kg in men and 21 kg in women. Thus, the smaller average weight losses of 2–10 kg seen in the above studies must have another explanation. In a recent review, it was reasoned that this lack of continued weight loss or even weight loss maintenance after 6–12 months of energy restriction is not due to decreases in energy expenditure secondary to weight loss; instead, the slowing of weight loss and later regain was likely due to a loss of dietary adherence.[18] The loss of dietary adherence is thought to reflect an increase in hunger resulting in greater energy intake.[19] Thus, the return to an upward weight trajectory appears to be driven by the body's hunger and satiety system as it interacts with food and food cues in the environment.[20]

Figure 2 **Cross-sectional relationship between total energy expenditure and body weight in 40–69-year-old US adults.**
Drawn using data from the OPEN study in Tooze et al. (2007).[31]

CHANGES IN ENERGY INTAKE IN RESPONSE TO CHANGES IN ENERGY EXPENDITURE

Because of the difficulty in obtaining sustained negative energy balance and weight loss through energy restriction, it has been suggested that changing energy expenditure may be an effective approach to obtain sustained weight loss. As described above, the amount of physical activity required to increase energy expenditure by 50 kcal/day is about 1500 additional steps. For most people, this can be accomplished by walking a little less than an additional mile each day, an activity that requires only 15–20 min of time. Because of this, numerous trials have been performed to determine if increasing exercise levels can increase energy expenditure, producing a beneficial energy balance and weight loss. Most of these trials have been short-term trials of 12 weeks in length. As reviewed by Garrow and Summerbell,[21] the addition of exercise to an individual's daily activities does result in a 12-week weight loss averaging 1.4 kg in 12 weeks (0.12 kg/week) in women and 3 kg in 30 weeks (0.10 kg/week) in men. While small, the weekly weight loss is close to that predicted using the energy balance equation. The interventions used in the many studies varied, but they generally consisted of either three sessions of aerobic exercise per week or five or more sessions of walking per week. Performing aerobic exercise for 60 min at 7 METS (one metabolic equivalent is an activity energy expenditure of 1 kcal/kg/h) can be calculated to increase energy expenditure by 420 kcal/session or an average of 150 kcal/day, assuming there are three sessions per week. Similarly, walking for 60 min at 4 METS for 5 days out of the week should increase energy expenditure by an average of 130 kcal/day. A simple application of the energy balance equation predicts a weight loss of 0.11–0.16 kg/week, respectively, assuming the loss is composed of 80% fat.

Again, however, these rates of weight loss are not typically sustained over longer periods of time. A more recent review reported that rates of weight loss over the first 6 months of treatment using only exercise and no prescribed energy restriction, averaged a smaller 0.07 kg/week loss and that by 12 months, weight loss from baseline was even smaller because body weight trended back toward baseline.[15] The two potential explanations for the smaller weight loss than that predicted from the simple application of the energy balance equation are that energy expenditure decreases at other times of the day to compensate for the exercise energy expenditure or that energy intake increases to compensate for the exercise energy expenditure. The former can be tested by measurement of total energy expenditure using doubly labeled water. There are, however, only a small number of such studies, including five studies reviewed by Westerterp[22] and one study published since that review.[23] Of these, four reported that total energy expenditure increased and that the increase was twice that estimated for the energy costs of the exercise sessions. In the fifth study, performed in an elderly cohort, total energy expenditure did not increase much, indicating a compensatory decrease in non-exercise energy expenditure. However, in the final study, men exhibited an increase in total expenditure that was only a little lower than the energy costs of the excess sessions, while women exhibited an increase in total energy expenditure that was only about half of the energy costs of the exercise sessions. Thus, evidence is mixed with regard to the effects of added exercise on total energy expenditure. In all cases, however, the weight losses still averaged less than the measured increases in total energy expenditure. By deduction then, the other portion of the explanation must be increased energy intake. This, however, is difficult to measure because of the limitations on the accuracy of self-reported energy intake.[24]

PROSPECTIVE USE OF THE ENERGY BALANCE EQUATION

Retrospective use of the energy balance equation is based on sound scientific principles.[2] Measurement of any two terms of the equation allows for solution of the third, although random measurement errors will introduce an error into the estimate of the third term. Prospective use of the energy balance can also be scientifically valid, but again, it does require knowledge of two of the three terms. The purpose of the above discussion is to illustrate not that the equation is invalid, but rather, that its application when only a single term is known is open to error. This is because a prospective application of the energy balance equation is not valid when only one term, or even a component of one term, such as exercise energy expenditure, is known. This is because there are three terms in the energy balance equation and if only one term is known, the equation cannot be solved. Stated another way, using the energy balance equation to predict weight change when only energy intake is known or when only energy expenditure is known is not valid because that calculation makes the assumption that the other term will not change. The above discussion illustrates that this assumption is rarely true and thus the prediction is rarely correct. This is because changes in any one term often are met with a response that counters some of the effect of that change on energy balance, leading to the better representation of the energy balance in the equation (Figure 3).

This is not to imply that prevention or reversal of obesity should not be attempted through interventions aimed at energy intake or energy expenditure, or that both should not be attempted. Just as the above examples demonstrate that the simplistic application of the energy balance equation for the prediction of weight loss is
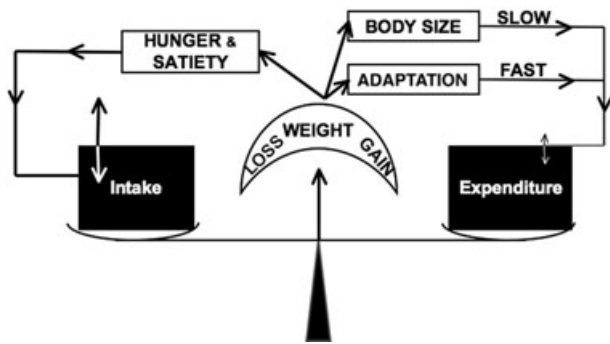
Figure 3 **A more mechanistic conceptualization of the energy balance equation that incorporates some of the feedback mechanisms interrelating energy expenditure, energy intake, and body weight.**

usually a quantitative failure, they also demonstrate that weight can be lost and the loss can be maintained.[25] Recent studies have also demonstrated that comprehensive interventions aimed at the dietary and physical activity environment can be successful in preventing pediatric weight gain.[26]

CONCLUSION

In summary, many of the prospective applications of the energy balance equation are over-simplified and often the wrong way to think about obesity prevention or reversal.[27] In a prospective application of the equation, one should not consider energy intake or energy expenditure as the independent variable, but instead consider interventions that influence fat balance and energy balance. Thus, the search should not be simply for interventions that can alter energy intake or energy expenditure, but rather for interventions that can alter body fat.

The principle behind a consideration of energy balance rather than energy intake or energy expenditure as the independent variable can be illustrated. Several decades ago, public health messages suggested that individuals reduce their intake of nuts by substituting less energy-dense snack foods. This advice was based on the fact that nuts are energy dense and that a substitution of a less energy-dense snack would reduce energy intake. More recently, research has demonstrated that nuts have multiple effects on energy absorption, energy consumption, and possibly even energy expenditure, and more importantly, they have been shown to result in negative energy balance and weight loss when included as part of a healthy diet.[28] A second example is the use of the supplement CLA (conjugated linoleic acid). This supplement is usually taken in the form of 4 g of triglyceride. From a purely prospective point of view, adding capsules containing 36 kcal of oil to the diet would appear to be

prescription for weight gain. CLA supplementation, however, increases fat oxidation and results in modest weight loss.[29,30] Both examples thus illustrate that research on weight maintenance and weight loss should first consider the effects of the intervention on energy balance and not energy intake or energy expenditure alone.

Acknowledgment

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