

## Energy Balance: Through the Looking Glass

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### Introduction

Human metabolic energy balance has been an area of intrigue and confusion for decades. An imbalance between energy intake and energy expenditure is considered the primary etiology for weight changes. Behavioral interventions, however, have generally resulted in a smaller than expected weight loss, which in part has been attributed to compensatory adaptations in other components contributing to energy balance [1,2]. Conversely, physically active individuals can exhibit negative energy balance without weight loss [3-5].

Energy balance is commonly used for understanding weight change and can be represented numerous ways, frequently by the equation [6]:

$$\text{change in energy stores} = \text{energy intake} - \text{energy expenditure}$$

Despite its use as the prevalent equation for energy, it lacks consideration regarding additional factors. Hence, simplistic notions based on “energy in and energy out” are largely ineffective. Human energy homeostasis is complex and there are many unanswered questions. This commentary reviews assumptions related to energy balance, especially emphasizing weight maintenance in exercising individuals. Additionally, paths for further studies are presented that may address some of the discrepancies in the current research literature.

### Thermodynamics and Estimates

A common belief is that reducing one’s caloric intake or increasing caloric expenditure should create an energy deficit, resulting in weight loss, thus complying with the first law of thermodynamics, which states that energy can be transformed from one form to another but cannot be created or destroyed. This accordance with the first law of thermodynamics is that energy within a closed system remains constant. As appealing as this ideology is, human physiology is not that simple, as humans are an open system within the biosphere.

Part of the noncompliance of data to support a simple energy equation is related to the ubiquitous measurement errors. Often, energy intake is estimated by food records or recall [7-10]. Underestimation of energy intake is a common finding. Redman and colleagues reported individuals significantly under reported energy intake (350 kcal/d; 15%), and underreporting by overweight individuals (~400 kcal.d<sup>-1</sup>; 16%) was greater than that of normal-weight individuals (~270 kcal.d<sup>-1</sup>; 12%) [9]. However, Ptomey and colleagues have reported on a new methodology for energy intake estimated by digital photography, which closely matched (6.8% ± 28%) with the energy expenditure gold standard of doubly labeled water [8].

The other aspect of the energy balance determination is energy expenditure. Although calorimetric chambers and doubly labeled water are state-of-the-art techniques, they are not always available [9,11]. Thus, indirect calorimetry can be used for resting metabolic

rate (RMR) or during exercise, while accelerometers and metabolic equivalents (METs) of physical activity are methods used during physical activity [12,13]. The value equating 1 MET to 3.5 ml O<sub>2</sub> Kg<sup>-1</sup>.Min<sup>-1</sup> or 1 Kcal.Kg<sup>-1</sup>. hr<sup>-1</sup> was derived from the resting O<sub>2</sub> consumption of one person, a 70-kg, 40-yr-old man. The MET value has come under scrutiny during rest and a set walking workload in 642 women and 127 men, 18-74 yr, 35 kg to 186 kg in weight, who were weight stable and healthy [13]. Resting values measured by indirect calorimetry were significantly lower than the commonly accepted 1 MET value. Body composition accounted for 62% of the variance.

Daily energy expenditure is the more difficult of the contributors to energy balance to obtain accurate measurements due to variability in putative compensatory effects [14]. These inconsistencies may be related to differences in RMR, exercise-related appetite changes, and reduced spontaneous physical activity. There is a large variability in resting energy expenditure (~250 kcal.d<sup>-1</sup>) that is not explained by differences in body composition [1]. In “The Biggest Loser” weight loss competition, RMR decreased significantly more than expected based on measured body composition changes. The magnitude of this metabolic adaptation was correlated with the degree of energy imbalance (r=0.55) [15]. Exercise programs consistent with public health recommendations may promote modest weight loss (~2 kg) however responses are highly heterogeneous [16]. Lower energy compensation occurs with short-term exercise, and a much higher level of energy compensation accompanies long-term exercise interventions [14]. Longer duration studies are obviously needed. Additionally, in many studies, the energy deficit produced by the prescribed exercise may be far less than that produced by dietary restriction [17]. Further, it was reported that subjects increased 24 h energy expenditure by 209 ± 555 kcal over baseline as assessed by doubly labeled water, yet lost no weight. Although energy intake was measured periodically and did not increase, some compensatory change in calorie intake must have occurred for body weight to remain stable.

High-intensity exercise has a beneficial impact on 24 h energy balance, as measured in a calorimetric chamber, resulting in spontaneous decrease in energy intake [11]. In normal-weight and overweight men, increasing physical activity while keeping energy ad libitum over an 8-week period produces a prolonged negative energy balance [18]. In a longer study, over a 10-month period, exercise training did not significantly alter energy intake in young adults [19]. Energy intake drops upon initiating an increased exercise volume. Subsequently, intake begins to increase in order to provide compensation for about 30% of the energy expended in activity. This compensation is partial and incomplete over short term studies [20]. Exercise-induced alterations in appetite may be driven by complex changes in appetite-regulating hormones [21], among other factors. Conversely, it can be demonstrated that when active individuals are

forced into a sedentary state, energy intake does not decrease to match the reduced energy expenditure.

There is minimal evidence to support that exercise training results in decreased non-exercise energy expenditure in healthy adults [12]. A 10-month aerobic exercise training program in previously sedentary, overweight and obese young adults was not associated with compensatory decreases in non-exercise energy expenditure. Results suggest that individuals do not become less physically active or spend more time in sedentary pursuits in response to exercise [22]. Generally, humans seem to be better equipped to defend against weight loss than avoid weight gain, but results also show a large individual variability. Therefore, individual differences should be explored to identify specific characteristics of compensator and non-compensators [23]. Dynamic energy imbalances definitely need further exploration [24].

### Athletes' Defense to Weight Loss

Athletes have been reported to have energy imbalances. Discrepancies between energy intake and expenditure in physically active women was described in the 1990s in weight stable runners [3]. Daily energy intake equaled energy expenditure in non-runners, but energy expenditure in women runners significantly exceeded intake, a deficit of approximately 650 kcal.d<sup>-1</sup>. The runners showed no evidence of compensating with decreased non-exercise energy expenditure. The findings suggest that women adapted to high levels of activity may possess mechanisms to maintain body weight without significantly increasing energy intake. Further, energy balance in weight stable athletes with and without menstrual disorders was assessed [25]. A small energy deficit was observed in runners with irregular menstrual function but not in a comparable group of runners with normal menstrual function. Thyroid hormone was also measured with significantly lower levels of free thyroxin in runners demonstrating irregular menstrual function, which may indicate an adaptive lower RMR in these athletes.

Male endurance athletes may also exhibit energy imbalances, though they are weight stable. When RMR was assessed in low-energy intake and adequate-energy intake male endurance athletes who had been weight stable for 2 years, RMR was significantly lower in low-energy intake athletes. The difference between groups was about 158 kcal.day<sup>-1</sup> [26]. The researchers postulated that lower RMR is one mechanism that contributes to weight maintenance when energy intake is less than energy expenditure. In another study that evaluated energy balance during high-volume and low-volume training periods among male endurance athletes, significant differences were reported in lower energy intake [27]. During the course of the study, there was no difference in body weight or composition. There was no compensation of increasing energy intake to match energy expenditure during the increased volume training.

### Sex Incongruity

One major source of variability in energy balance might be sex. The studies on athletes demonstrated a reduced RMR in both females and males [25,26]. In comparison of non-athletic and athletic women, RMR per kilogram body weight was wide for nonathletic, but narrow for athletic women. The researchers postulated metabolic efficiency was highly variable in both lean and obese nonathletic women [28]. If higher efficiency is present, then it would predispose those women to developing body fat. However, the mean lower RMR in athletes may have some compensatory mechanism that defends against weight gain.

Conflicting evidence exists on RMR findings in response to variable energy expenditure. Long term exercise training studies have shown both that training increases RMR while other studies have failed to support these findings [5,29]. Intense exercise training may induce reductions in RMR, in spite of the increased lean tissue mass, similar to the changes observed in animals in response to flight [5]. There may be sex differences to account for the observed energy imbalances, as well. In 24 h energy expenditure, females had 5% to 10% lower values compared with males after adjusting for differences in body composition, age, and activity [30]. RMR was approximately 120 kcal.day<sup>-1</sup> lower in females than males. Assessed spontaneous physical activity was not significantly different between males and females in that study. In another study, total daily energy expenditure was about 20% higher in men than in women, which equated to 580 kcal.day<sup>-1</sup> [9]. Noting the differences in RMR and total daily energy expenditure from these studies, there must be some metabolic efficiency changes that contribute to the energy imbalance with stable weight.

In a 10-month study exercise intervention to promote weight loss, responders were defined as those who lost  $\geq 5\%$  of body weight. Men who were non-responders had higher energy intake and lower non-exercise energy expenditure when compared with men who responded to the exercise, which may account for not losing as much weight. No significant differences in any parameters assessed were observed between women who did not meet the threshold weight loss compared to those losing  $\geq 5\%$  of body weight. The researchers suggest that factors associated with the weight loss response to exercise in women warrant additional investigation [31].

### Microbiota

A flurry of research has emerged on intestinal bacteria and how the microbiota may influence body weight in addition to promising health effects. However, adverse effects can also occur such as reported in a case study in a woman who was treated with fecal microbiota transplantation [32]. The young woman had been normal weight with a BMI of 26. After 16 months, her BMI had increased to 33; she had received the transplant from an obese donor.

Exercise effects on the microbiota have been reported [33], and limited animal and human research findings imply that exercise may have a beneficial role on microbiome characteristics [34]. In mice, exercise has a strong influence on gut integrity and host micro biome [35]. Heterogeneity in energy derived from energy intake has been the main focus of many recent studies. However, from the few studies to date, effects of habitual exercise on the intestinal micro biota have demonstrated positive health effects and support further rigorous research concerning energy balance.

### Autonomic Influence

Some of the variance in energy balance may be related to autonomic system influences. A thermodynamic model demonstrates the sympathetic and parasympathetic nervous systems regulate energy [36]. The autonomic nervous system (ANS) plays a critical role in the control of energy balance and body weight [37]. The ANS is involved in the control through influences exerted on the production and loss of heat. Activation of the sympathetic discharge causes an increase in energy expenditure and a decrease in energy intake. Paradoxically, RMR is higher in the athletes than in sedentary women, despite the augmented parasympathetic activity that is usually related to lower energy expenditure.

Research shows enhanced resting metabolic rate (RMR) in trained athletes is an acute effect of prior exercise induced by catecholamines, and not due other factors such as thyroxin levels [38]. Conversely, adaptation to exercise training is associated with a relative enhancement of vagal dominance [39-41]. In both male and female subjects, high vagal influence is negatively correlated with BMI [41,42]. These results provide evidence for a prominent role of the vagal tone in the modulation of the energy expenditure of the human. Further, intensive training resets towards sympathetic dominance [43,44]. Under similar training strain, male athletes showed constantly higher markers of sympathetic activity than female athletes [45]. Sympathetic influence on reduced energy intake may contribute to observations during multi-stage exercise events of high volume and intensity, such as the Tour de France. Exercise effects on the ANS influence on energy balance needs to be explored more fully. Further studies should be addressed to reveal new aspects of the control exerted by the autonomic nervous system on body weight.

### Exercise Perspective on Energy Balance

Energy balance is a complex phenomenon. The thermodynamic equation for energy balance is an oversimplification. The body is not a closed system, since there are energy fluxes with the biosphere. In addition to the promising areas of research briefly presented in this paper, other influences include genetics and hormonal balances, among others. The list of peripheral anorexigenic and orexigenic physiological factors is intimidating and expanding. Exercise may modify responses in a direction expected to enhance satiety [46], and yet permit weight maintenance. The possibility of a threshold level beyond which increased exercise energy expenditure fails to produce a more negative energy balance and potential sex differences in the energy intake response to increased levels of exercise are potentially important. Much research focus has been on negative energy balance factors to address the expanding prevalence of obesity in society. However, in examining energy balance from the exercise perspective, through a looking glass, may provide understanding that otherwise may be not be achieved. This brief commentary emphasizes the need for more research with simultaneous measurements of all major components contributing to energy balance to enhance understanding of the complex regulation.

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