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Energy Homeostasis and the Law of Thermodynamics

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

With the increasing prevalence of obesity and associated morbidity, research continues to investigate the associated factors as well as approaches for effective bodyweight management. While there is consensus that obesity is characterised by an energy imbalance, the interactions between the various components of energy components and the implications of the homeostatic determinants remain controversial. This review critiques the existing theories on energy balance in relation to the law of thermodynamics and proposes the inclusion of important determinants in the energy balance equation.

Keywords: Energy homeostasis; dietary intake; obesity; thermodynamics; energy expenditure.

1. INTRODUCTION

Energy is the ability to do work, and the study of energy is known as thermodynamics. Through the subject of thermodynamics, nature, characteristics, and forms of energy can be understood. Also, through the subject, the working principles and mechanisms of bodies that utilise energy can be understood [1]. The human body is a typical example, it requires energy for the perpetuation of biological functions and gains energy primarily through food intake. The energy contained within the food is metabolised through complex processes and

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regulated within healthy limits by homeostatic mechanisms [2]. The roles of various homeostatic variables in the regulation of energy are well documented, collectively participating in regulating energy intake, expenditure, and storage in keeping with the laws of thermodynamics [3]. This review critically considers energy homeostasis with the first law of thermodynamics and proposes some interpretations of the energy balance equation. The propositions in this paper have significant implications for the management of obesity.

2. ENERGY HOMEOSTASIS AND THERMODYNAMICS

Compliance of the body's energy regulation to the first law of thermodynamics is of unanimous consensus. However, the interpretation of this law as regards energy balance in the body has remained controversial [2]. The first interpretation of the law with regard to energy homeostasis is typified by the classical equation which states that the body energy store equates with the difference between the energy intake and expenditure (energy burned) {Energy stored= Energy intake – Energy expended}. This interpretation appears insightful and simple, however, may be critiqued for being static thereby misleading, in view of undermining the influence of the component metabolic homeostatic mechanisms in the regulation of energy. Also, it has been demonstrated to be unsuitable for predicting energy balance in living organisms since it does not account for increasing energy expenditure due to increasing fat-free mass [4], thereby expressing energy intake and expenditure as independent variables [5]. More so, it is said to promote the "calories-in-calories-out" ideology, which implies that energy consumed in the diet is only consciously expendable through physical activity.

Based on these criticisms, another equation was proposed incorporating "rates"- a time dependency factor permitting the influence of changes in energy stores on energy expenditure [4]. The equation is represented thus:

> Rate of Change of Energy Stores = Rate of Energy Intake – Rate of Energy Expenditure

Accordingly, energy stores (body fat) increase when the rate of intake exceeds the rate of expenditure, and vice-versa. The equation attempts to demonstrate a non-linear relationship, changes in energy stores and energy fluxes. Such that small initial increases in energy intake will not lead to large body fat changes over the long term since a mechanism of increasing energy expenditure is eventually triggered. However, the triggered energy expenditure does not necessarily counterbalance the increased energy store but results in the establishment of a new balance with larger energy stores. A major strength of this postulate is that it acknowledges the presence of a built-in feedback mechanism for energy balance. Notwithstanding, since it makes no claim on re-establishing of body fat to the initial level by the said mechanism, a theoretical basis for the suggested mechanism can be argued. In other words, it raises obvious questions. For instance, why does the mechanism allow some proportion of the energy intake to be stored rather than restore energy balance to the initial level? Also, is the operation of this mechanism normal or due to inefficiency? Also, this postulate [4] fails to address the possible determinant factors of how much energy is stored. These questions ought to be resolved for the interpretation to be valid for the development of mathematical models capable of simulating changes in energy storage and expenditure due to energy intake for an individual.

The research argues that a more fruitful approach towards understanding how energy intake is balanced against expenditure, and how changes might occur would involve dissecting energy balance into its various macronutrient components such as protein balance, carbohydrate balance, fat balance and alcohol balance [6]. This view urges for a single energy balance equation for each macronutrient to determine if an imbalance occurs between intake and utilisation. This is a reductionist approach that seems simpler than is feasible, as the energy derived from each macronutrient is not separately regulated and stored in its compartment. Also, it might become problematic to reconcile all equations to produce a unified equation for energy balance. Hence, how can the first law of thermodynamics be interpreted as pertains to energy balance in the body?

The first law of thermodynamics pertains to the transfer of matter (mass) and energy and applies only to bodies known as "thermodynamic systems." Thermodynamic bodies could either be open, closed, or isolated. A closed system can exchange energy (in form of heat or other), but cannot exchange matter with its environment, whereas an isolated system can neither exchange energy nor matter with its surroundings. An open system can exchange both matter and energy with its environment (for instance, the human body) [7]. Despite these differences, all of them (isolated, closed, and open systems) are said to obey the first law of thermodynamics with respect to energy and matter. Hence, a clear interpretation of this law is, "in any given thermodynamic system, the energy or matter gained may be transformed but remains constant (or can neither be created nor destroyed)." If this law is limited to energy for the context of this paper (energy balance), the following equations will suffice.

$U = Q - W$ (for an open thermodynamic system)

$U = Q - W$ (for a closed thermodynamic system)

$U = Q$ (for an isolated thermodynamic system) since work done (W) is 0

(Where; U= internal energy of the system, Q= energy supplied to the system, W= work done by the system on its surroundings).

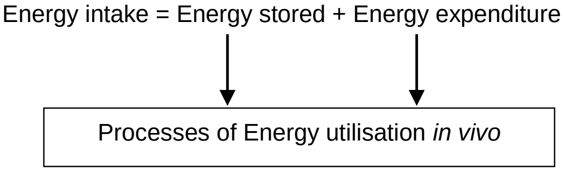
If the symbols are represented in terms of energy intake, energy storage, and energy expenditure, the energy balance equation will be given as;

Energy stored = Energy intake – Energy expenditure

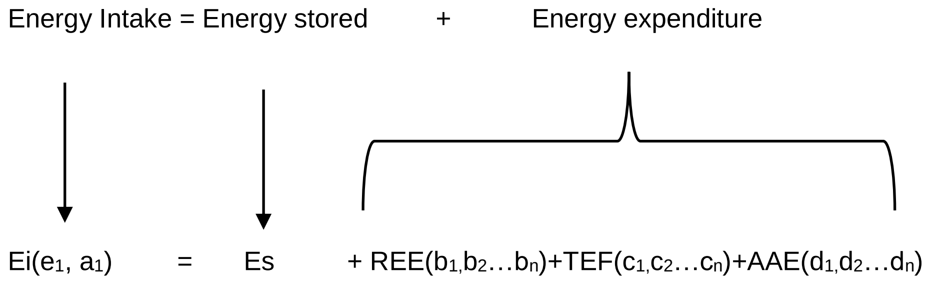
Or

Energy intake = Energy stored + Energy expenditure

The above equation simply infers that a thermodynamic system such as the human body cannot create its energy but can derive it from a source. This also means that it can only utilise energy for either storage or expenditure, in proportion to what is gained or derived from an external source.



The integration of a time dependency factor such as "rate" to the equation as proposed by Alpert [4], is originally not part of the law of thermodynamics and in actual terms becomes inconsequential since energy remains constant irrespective of the rate, provided a thermodynamic system (or body) is involved. This implies that at any point in the process of energy intake, the energy utilisable by the body is only equivalent to that gained via intake. This also means that energy intake expressed simply quantitatively (Ei) or as dependent on time (Ei x time) neither predicts which aspect of energy utilisation (either storage or expenditure) is favoured nor suggests any influence on the determinants of the process of energy utilisation. Consequently, one may decrease their energy stores (body fat) by decreasing energy intake, but this outcome is not guaranteed due to the influence of some determinants. Hence, an adequate application of the law of thermodynamics to the body's energy balance in consideration of the determinants or factors influencing each process should be:



$$Ei(e_1, a_1) = Es + REE(b_1, b_2 \ldots b_n) + TEF(c_1, c_2 \ldots c_n) + AAE(d_1, d_2 \ldots d_n)$$

Left side equation [$Ei(e_1, a_1)$]: Energy intake is expressed as a function of quantity (e_1) (the amount of energy), and quality (a_1) (form in which energy is consumed). Right side equation**:** Energy storage is expressed as Es, while energy expenditure is represented as a function of its components; resting energy expenditure (REE), diet-induced thermogenesis (TEF), activity energy expenditure (AEE), with each, also expressed as a function of determinants "$b_1, b_2 \ldots b_n$", "$c_1, c_2 \ldots c_n$" and "$d_1, d_2 \ldots d_n$", respectively.

2.1 Energy Intake ($Ei(e_1, a_1)$)

Energy intake mainly occurs through the intake of macronutrients- carbohydrates, fats and proteins, and a little proportion of alcohol. Once ingested, energy is supplied to the cells for functioning. The amount of energy available to the cells for normal biological functioning, known as the metabolisable energy is highest for fat (9cal/g, or 38J/g) and least for carbohydrates and proteins (4cal/g or 17J/g). Since fat is the source with the highest energy content, one may argue that increased intake of dietary fat increases utilisable energy. However, this does not necessarily predict the specific aspect of energy utilisation favoured- storage or expenditure. Rather, this factor appears dependent on the metabolic and hormonal responses evoked due to the quality of the energy-containing diet. Results from a 20-year prospective cohort study on the influence of diet on body weight involving 120, 877 participants showed that the dietary source of energy had a larger influence on their weight compared to the number of calories consumed or expended [8]. Furthermore, in 2012, a clinical trial on the effect of dietary composition on weight loss in which 21 individuals were tracked concluded similarly [9]. In the study, participants were placed on three varying dietary regimens but isocaloric; a high protein but low carbohydrate diet, a low-fat diet emphasising whole grains, fruits and vegetables, and a low glycaemic index diet. At the end of the experiment, each group recorded varying levels of energy expenditure, leading to the conclusion that the quality of energy in diet influenced its utilisation. Other researchers have similar findings in agreement that both quantity and quality of energy are important in predicting metabolic response [10].

Some researchers have argued otherwise, proposing that a unit of energy consumed (a calorie) has the same metabolic implication regardless of the diet composition or quality of dietary intake and that it is in consonance with the first law of thermodynamics [11]. However, this rather seems to be a misconception, as the law neither places any limits nor predicts the mechanisms or processes through which the energy gained by a thermodynamic system is transformed. Furthermore, a review [12] clarifies that undermining the influence of the quality of energy intake violates the second law of thermodynamics- which predicts a unique increase in entropy of a substance in a thermodynamic system over time. This implies that accepting that the metabolic implication of a unit of energy (a calorie) is independent of the source is synonymous with claiming that the microscopic configurations (entropy) that are assumed by two chemically dissimilar compounds as they undergo metabolic processing are identical. A clear understanding can be gained from glucose and fructose. Although these are almost chemically identical, they are metabolised differently and elicit varying responses in the body. Glucose metabolism, for instance, is insulin-dependent and once consumed, it stimulates insulin release, unlike fructose. Also, the increased presence of glucose in the liver results in the formation of glycogen, while in the case of fructose, it is channelled to the mitochondria where excess acetyl-CoA is formed. Excess acetyl-CoA then leaves the mitochondria to form fat [13]. Furthermore, the ability of almost all cells in the body to use glucose unlike fructose coupled with the distinct pattern of regional brain activation characteristic of each of them [14] bears evidence of their difference.

Additionally, a qualitative factor such as glycaemic index may also modify the metabolic response of energy intake. The glycaemic index defines the level of insulin response elicited by a given diet [15]. Research shows that foods of a higher glycaemic index promote weight gain compared to those of a low glycaemic index [16,17]. Put together, these arguments highlight the need to qualify energy intake to make sense of the influencing factors in energy balance. Hence, energy intake at the left side of the equation above may be incomplete without introducing the determinants (e_1, a_1), to indicate the quantity and quality of energy intake under consideration.

2.2 Energy Expenditure [REE($b_1, b_2 \ldots b_n$) + TEF($c_1, c_2 \ldots c_n$) + AAE($d_1, d_2 \ldots d_n$)], and Energy Storage (Es)

Once food is ingested, it is transformed into absorbable substrates which is either stored as body fat (Es, as in the equation) or is used as energy to perpetuate biological processes. The use of energy as fuel for metabolism is regarded as energy expenditure and varies through the life of an individual [2] Energy is expended through processes such as growth, digestion, reproduction, respiration, renewal or broken tissue, physical activity, lactation and more. Energy expenditure can be categorised into three based on the activities involved. These include resting energy expenditure (REE), thermic effect of food (TEF), and activity energy expenditure (AEE) [2]. Resting energy expenditure refers to the amount of energy expended by one when at rest and constitutes about two-thirds of the total energy expendable. It is dependent on factors such as one's energy status, body composition, and size. Regarding body composition, it increases in proportion to total tissue mass, with lean mass contributing more than fat mass. Inter-individual variability has also been noted and suggested to be due to hormonal differences [18]. Given the determinants, it is thus represented in the above equation as; REE ($b_1, b_2 \ldots b_n$).

Activity energy expenditure (AEE) describes the energy expended due to any bodily movement produced by muscles, which may be under conscious (during exercise) or unconscious conscious (non-exercise activity) and can be influenced by body movement and body mass [19]. Hence, it is represented in the energy balance equation above as; AAE($d_1, d_2 \ldots d_n$). The thermic effect of food (TEF) otherwise regarded as diet-induced thermogenesis is the energy expended in processing food once ingested. The amount of energy expended in this component varies with the component of the diet, especially macronutrients, increasing from fat to carbohydrate, to protein. It is influenced by other factors such as physical activity, meal size, one's previous diet, age, and determinants of food metabolism such as insulin sensitivity [20]. In consideration of the influencing factors, it is represented in the above equation as a function of its determinants; TEF($c_1, c_2 \ldots c_n$).

3. CONCLUSION

This paper makes two main propositions. First, the inclusion of qualitative and quantitative aspects of energy intake in the energy balance equation. Second, the inclusion of determinants of the various components of energy expenditure in the energy balance equation. The former emphasises that the amount of energy and the form in which it is ingested have metabolic consequences which moderate energy utilisation. Whereas the second proposes the inclusion of the determinants of energy expenditure such as physiological factors and other factors which serve as the indices by which homeostasis occurs. Understanding the determinants applicable under various conditions can support the development of mathematical models for simulating changes in energy storage and expenditure due to energy intake, beneficial for obesity research. More research is required to understand the full extent of the determinants of energy metabolism, and the compliance of the human body to the first law of thermodynamics.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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