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Dietary energy density: Applying behavioural science to weight management

B. J. Rolls

The Pennsylvania State University, University Park, PA, USA

Abstract

Studies conducted by behavioural scientists show that the energy density (kcal/g) of food provides effective guidance for healthy food choices to control intake and promote satiety. Energy density depends upon a number of dietary components, especially water (0 kcal/g) and fat (9 kcal/g). Increasing the proportion of water or water-rich ingredients, such as vegetables or fruit, lowers a food's energy density. A number of studies show that when the energy density of the diet is reduced, both adults and children spontaneously decrease their *ad libitum* energy intake. Other studies show that consuming a large volume of a low-energy-dense food, such as soup, salad or fruit, as a first course preload can enhance satiety and reduce overall energy intake at a meal. Current evidence suggests that energy density influences intake through a complex interplay of cognitive, sensory, gastrointestinal, hormonal and neural influences. Other studies that focus on practical applications show how the strategic incorporation of foods lower in energy density into the diet allows people to eat satisfying portions while improving dietary patterns. This review discusses studies that have led to greater understanding of the importance of energy density for food intake regulation and weight management.

Keywords: energy density, food choice, obesity, portion control, satiety, weight management

In debates about optimal diets for weight management, the dominant emphasis has been on the proportion of macronutrients (Sacks *et al.* 2009; Fogelholm *et al.* 2012; Hooper *et al.* 2012). Popular diets often encourage people to think that simply cutting carbohydrates or fat, or eating more protein, will promote weight loss. However, current evidence-based guidance focuses on healthy dietary patterns rather than prescriptions around fat, carbohydrate and protein (US Department of Health and Human Services & US Department of Agriculture 2015). We eat foods that contain a mix of nutrients and we need to learn how to enjoy a healthy variety while eating amounts that match energy needs. Research shows that applying the concept of food energy density can help to guide choices and control hunger while being flexible enough to encompass preferences. The suggestion that attention should be given not only to the macronutrient composition but also to the overall caloric or energy density of diets has developed from studies in the behavioural sciences. This review will highlight discoveries and insights that have led to an understanding of the

Correspondence: Barbara J. Rolls, Ph.D., Professor and Helen A. Guthrie Chair in Nutritional Sciences, The Pennsylvania State University, 226 Henderson Building, University Park, PA 16803, USA.
E-mail: bjr4@psu.edu

significance of dietary energy density for the regulation of food intake and bodyweight.

Defining energy density

Energy density is the amount of energy in a particular weight of food (calories per gram) and, depending upon the food's mix of nutrients, ranges from 0 to 9 kcal/g. The macronutrient with the greatest influence on energy density is fat at around 9 kcal/g. Carbohydrate and protein are more moderate in energy density and each provides around 4 kcal/g. A food's energy density depends not only upon the macronutrients but also upon its water content. Indeed, the largest influence on the energy density of the most commonly consumed foods is water, which contributes weight and volume without supplying any energy (0 kcal/g). Variations in the water content of foods can be used to systematically dissociate energy density from the proportions of macronutrients. This understanding of the impact of water has led to innovative studies that demonstrate the critical role of energy density in intake regulation. Before reviewing studies demonstrating such independent effects of energy density, the historical context of current thinking will be considered.

Seminal studies on the effects of energy density on energy intake

A role for dietary energy density in the regulation of energy intake emerged from studies on effects of dietary fat on energy intake. In 1978, in an unusual study, van Stratum and colleagues tested the impact of variations in the fat content of the diet on daily energy intake in 22 Trappist nuns living in a convent (van Stratum *et al.* 1978). In a crossover design consisting of two 2-week periods, the fat-to-carbohydrate ratio of a liquid formula diet was varied (24% fat and 58% carbohydrate vs. 47% fat and 35% carbohydrate, with constant protein). The energy density of the high-fat liquid formula was matched to the low-fat formula by dilution with water; the taste and appearance were also similar. This liquid formula, which was consumed *ad libitum,* comprised approximately 75% of daily energy intake, while standardised snacks accounted for the remaining 25%. Despite the substantial difference in fat content, daily *ad libitum* energy intakes were consistent across the two 2-week periods. The authors considered that this lack of effect of diet composition on energy intake could relate to the controlled energy density, but dismissed this explanation as several previous studies had failed to find that energy density affected the intake of infants (Fomon *et al.* 1969) or adults (Campbell *et al.* 1971).

Understanding of the importance of energy density for managing hunger and bodyweight took root with studies from Roland Weinsier's group in the early 1980s (Duncan *et al.* 1983). Rather than following the typical emphasis on the macronutrient composition of the diet, they proposed that lowering dietary energy density was critical in that it allowed patients to consume a satisfying volume of food even when restricting energy intake. They tested this over two 5-day periods, during which participants were allowed to eat to satiety either a diet high in energy density (high in fat, meat, desserts) or low in energy density (low in fat, high in fresh fruit, vegetables and wholegrains). They found that with the lower-energy-dense diet participants felt full, energy intake was nearly halved and there was no compensatory increase over the 5 days. The authors proposed that prolonged eating time was at least part of the explanation for the reduction in energy intake. We now know that while prolonged eating time is likely to be part of the explanation for the diet's efficacy, energy density can affect intake even when eating rate is controlled (Rolls *et al.* 1999b). The main insight from these studies was the recognition that consumption of a diet low in energy density was satiating even though energy intake was reduced; however, the experimental diets varied in a number of parameters so the influence of energy density was not dissociated from that of the fat content.

Several years later, scientists proposed a role for energy density independent of other dietary factors. In a 1992 review article on the influence of dietary fat on *ad libitum* food intake, we observed that energy density must play an important role because the amount of food consumed appeared to be controlled more precisely than the amount of energy (Rolls & Shide 1992). If a person eats a consistent weight of food, then even modest changes in energy density will have an impact on energy intake. Several provocative reviews from the Dunn Clinical Nutrition Centre also proposed a role for energy density in intake regulation and suggested that weight loss could be achieved on a low-energy-dense diet (Poppitt 1995; Poppitt & Prentice 1996). These reviews provided hypotheses that facilitated a number of studies.

Systematic studies on the effects on energy density on ad libitum intake

During the 1990s, several laboratories systematically tested the independent effects of dietary fat and energy density on satiation or *ad libitum* intake (Rolls & Bell

1999). Some studies manipulated the amount of fat while holding the energy density constant. This was carried out by varying the proportion of water or water-rich vegetables or fruit. In one of the longest controlled studies (14 days), the test diets were 20%, 40% or 60% energy from fat (Stubbs *et al.* 1996). Results showed that across conditions people ate a consistent weight of food and as energy density was matched, energy intake was similar despite the differences in fat content. Several additional studies from other laboratories found that changes in the proportions of macronutrients in foods did not affect energy intake if the energy density was controlled across conditions (see Table 1). It appears that the effects of dietary fat on intake are related to its high energy density.

More support for the importance of energy density came from studies in which it was varied while holding the proportions of macronutrients constant. One such study showed that with a 30% difference in energy density between test meal conditions, participants ate a consistent weight of food over 2 days so that energy intake varied directly with the food's energy density (Bell *et al.* 1998). The higher the energy density of the diet, the more energy participants consumed over the 2 days. That study and several others (see Table 1) add support to the suggestion that the weight of food eaten is more consistent than energy intake. It is of particular interest that children as young as 3–5 years of age showed a similar response in that they ate a consistent weight of food over several days even as the energy density was varied (Leahy *et al.* 2008). This body of evidence reinforces the critical role that energy density plays in the regulation of intake. That is, if the weight of food eaten remains constant, the density of calories in that food will determine energy intake.

Table 1 The effects of dietary fat and energy density on satiation were separated in a number of studies. These findings support the suggestion that dietary fat affects energy intake through its impact on energy density

	n	Length of study	Effect on energy intake
Fat content decreased and energy density held constant			
van Stratum *et al.* (1978)	22	2 phase, 14 days each	None
Stubbs *et al.* (1996)	6	3 phase, 14 days each	None
Saltzman *et al.* (1997)	14	2 phase, 9 days each	None
Rolls *et al.* (1999a)	34	4 weeks, 4 days each	None
Raben *et al.* (2003)	19	4 weeks, 1 day each	None
Energy density decreased and fat content held constant			
Stubbs *et al.* (1998)	6	3 phase, 14 days each	Decrease
Bell *et al.* (1998)	18	3 weeks, 2 days each	Decrease
Rolls *et al.* (1999a)	34	4 weeks, 4 days each	Decrease
Bell and Rolls (2001)	36	6 weeks, 1 day each	Decrease
Kral *et al.* (2002)	40	3 weeks, 1 day each	Decrease

Energy density and satiety

At the same time as studies established that energy density affects *ad libitum* energy intake, others used the traditional preloading technique to determine the influence of the energy density of a compulsory first course (the 'preload') on satiety as assessed by intake at a subsequent test meal (Benelam 2009). In one study, decreasing the energy density of a milk-based preload by adding water and thus increasing the volume led to a significant reduction in test meal energy intake (Rolls *et al.* 1998). In another study, we determined whether drinking water as a beverage along with a preload had a similar effect on satiety as incorporating an equivalent amount of water into the preload to lower its energy density. We found that water had a greater impact on satiety when included in a food than when consumed as a beverage along with a food (Rolls *et al.* 1999b). Part of the explanation is that water blended into foods has been shown to slow stomach emptying more than consuming the water separately (Marciani *et al.* 2012). In addition, other studies have found that with the infusion of preloads directly into the stomach, the volume infused enhanced satiety and reduced subsequent intake more than the energy content (Rolls & Roe 2002).

Studies of mechanisms

Slowed gastric emptying and enhanced gastric filling are only part of the explanation for the effects of energy density on intake regulation (Keller *et al.* 2013). There is a complex interplay of cognitive, sensory, gastrointestinal, hormonal and neural influences. The effect of cognitive or visual cues was demonstrated by studies where the volume of foods was altered either by aeration or by altering the shape of food pieces. Aerating a milkshake pre-load to increase its volume enhanced satiety and reduced subsequent intake (Rolls *et al.* 2000). Aeration also reduced the amount eaten *ad libitum* of a savoury snack food (Osterholt *et al.* 2007). Altering the shape and size of the flakes in a breakfast cereal affects how it fills a bowl such that smaller flakes pack down more. When offered smaller flakes, people served and ate more cereal so their breakfast intake was significantly increased

(Rolls *et al.* 2014). It is of interest that these effects were seen in people who were familiar with the foods. In our complex eating environment, foods vary in many ways that make it difficult to judge how much to take and to eat; thus, the volume of a food is one cue that guides consumption.

There are other possible explanations for the influence of energy density on intake. One is that intake is limited by the declining hedonic response to the sensory properties of a food as it is consumed (sensory-specific satiety), and this decline is affected more by the amount of food eaten than by its energy content (Bell *et al.* 2003). Another is that learning related to previous experiences could prompt people to eat a consistent weight of foods differing in energy density. It makes sense to rely on previous experience (Stubbs & Whybrow 2004); however, when the sensory properties of foods are dissociated from the energy density, expectations and previous experiences with foods can provide unreliable guidance to consumers on amounts to eat (Hogenkamp *et al.* 2012). To understand further what affects food choices, some current research aimed to use functional magnetic resonance imaging to determine how energy density affects brain responses and whether individual variation in responsivity is related to eating behaviour and bodyweight (Fearnbach *et al.* 2016; English *et al.* 2017). Longitudinal studies are needed that examine how individual differences in response to food energy density affect bodyweight.

Strategies to reduce dietary energy density

Studies conducted by behavioural scientists have not only demonstrated the role that dietary energy density plays in food intake regulation but have also suggested specific strategies that can help to manage hunger, reduce food intake and facilitate weight management. The ultimate goal of such research is to provide sustainable strategies to moderate energy intake while emphasising diet quality. An advantage of using energy density to guide dietary patterns is that it can be modified in a number of ways; for example, by varying the quantity of fat and sugar, or water-rich components such as fruit and vegetables. Although the sensory and biological effects of these approaches differ, they are all associated with decreased energy intake. A recent study compared three methods of energy density reduction (decreasing fat, increasing fruit and vegetables and adding water) and found that all three decreased daily energy intake (Williams *et al.* 2013).

While energy density can be reduced in a variety of ways, research shows that some approaches have a greater impact on intake than others. Much of the emphasis in recent studies has been on the most effective ways to add water or water-rich dietary components to reduce energy density and moderate energy intake. For example, we found that simply adding more vegetables to a meal did not reduce overall meal energy intake, while substituting a bigger portion of vegetables for the more energy-dense meat and grain did (Rolls *et al.* 2010). The substitution can be done overtly or covertly if individuals dislike vegetables. The covert incorporation of puréed vegetables into entrées served at all meals across a day significantly reduced daily energy intake in preschool children (Spill *et al.* 2011) and adults (Blatt *et al.* 2011). While substituting lower-energy-dense meal components for those higher in energy density can moderate energy intake, it is important to ensure that this substitution does not affect acceptability.

Another approach derived from behavioural studies of satiety is to encourage consumption of low-energy-dense foods at the start of a meal, when hunger is elevated and there are no competing foods. 'Filling up first' by consuming a large portion of a low-energy-dense food such as salad (Rolls *et al.* 2004), fruit (Flood-Obbagy & Rolls 2009) or soup (Flood & Rolls 2007) has been shown to reduce meal energy intake. However, studies demonstrating the benefits of low-energy-dense foods for satiety enhancement need to be carefully interpreted if they are to have broad utility for weight management. The low-energy-dense first course needs to be low in calories and the foods served at the rest of the meal should be managed strategically. For example, if a low-energy-dense salad is followed by large portions of high-energy-dense palatable foods, people are still at risk of overconsumption (Williams *et al.* 2014).

Studies in the behavioural sciences demonstrate the advantages of a diet low in energy density in that it is not restrictive and can be tailored to accommodate individual preferences. These studies have shown that decreases in energy intake can be achieved by substituting lower-energy-dense foods for those higher in energy density, incorporating lower-energy-dense ingredients into mixed dishes to reduce energy density, and 'filling up first' with a low-energy-dense first course. As a range of eating patterns can be reduced in energy density, this type of diet has wide applicability and thus can be a key component of a lifestyle that encourages a healthy, well-balanced diet for weight management.

Dietary energy density and weight management

Studies testing the role of energy density in weight management began in the early 1980s when Weinsier's group extended their studies on satiety. They found that a low-energy-dense diet, consisting of relatively large volumes of low-energy complex carbohydrates, was associated with significant weight loss over 6 months of active treatment and with maintenance of weight loss 17 months post-treatment. The authors proposed that an energy-restricted diet of large quantities of high-bulk, complex carbohydrates would result in prolonged eating time, a greater sense of satiety, decreased energy absorption and a large enough volume to displace intake of more energy-dense foods (Weinsier *et al.* 1982). Before his untimely death, Weinsier worked with his colleagues to develop a weight management programme based on energy density that is still utilised in clinical practice (University of Alabama at Birmingham 2017).

The utility of a diet reduced in energy density for weight management has been confirmed in several trials (Rolls 2009). In a year-long randomised controlled trial, women with obesity who were counselled to increase intake of vegetables and fruit and reduce fat intake had a larger reduction in dietary energy density and greater weight loss than those who were advised only to reduce fat intake (Ello-Martin *et al.* 2007). In another multicentre trial that included three different lifestyle interventions, dietary changes that led to a lower-energy-dense diet were correlated with greater weight loss after 6 months (Ledikwe *et al.* 2007). Several clinical trials report that lowering dietary energy density helped patients maintain their weight loss (Raynor *et al.* 2011). Greene and colleagues (Greene *et al.* 2006) examined energy density values 2 years after participation in a weight loss programme based on Weinsier's advice (Weinsier *et al.* 1982). They found that individuals who maintained weight loss reported eating a diet lower in energy density than those who regained 5% or more of their bodyweight. In another trial, instruction on reducing dietary energy density led to sustained weight loss 36 months after the start of the intervention (Lowe *et al.* 2014).

Confirmation that lower-energy-dense diets are associated with lower bodyweight comes from several systematic reviews (Perez-Escamilla *et al.* 2012; Karl & Roberts 2014; Rouhani *et al.* 2016) and a meta-analysis (Stelmach-Mardas *et al.* 2016). In addition to weight loss, reductions in energy density are associated with improved diet quality, indicating that this is a healthy strategy for weight management (Ledikwe *et al.* 2006b; Murakami & Livingstone 2016). Nevertheless, it is clear that more data on the role of energy density in weight management are needed and could be obtained from secondary analyses of existing data. Many studies in which variations in the proportions of macronutrients are the focus do not provide information about dietary energy density (Sacks *et al.* 2009; Fogelholm *et al.* 2012; Hooper *et al.* 2012; Astrup *et al.* 2015), perhaps assuming that a high-fat diet is high in energy density. While this can be true, an analysis of population-based reported intakes demonstrated that the energy density of a high-fat diet (>30% of energy) rich in vegetables and fruit (>5 daily servings) was lower than that of a lower fat diet (<30% of energy) with fewer than five servings of vegetables and fruit per day (Ledikwe *et al.* 2006a).

More data are also needed on how to leverage the effects of dietary energy density to prevent overweight and obesity (Rolls 2010). Part of the challenge is to establish dietary patterns early in life that promote preferences for foods lower in energy density. It is not clear that such patterns would persist into adulthood and, if they did, whether there would be compensation for reductions in energy intake associated with lower-energy-dense foods. Biological regulatory systems may sense an accumulating energy deficit that leads to increased hunger and energy intake. Research should investigate the long-term effects of lowering dietary

Table 2 Foods can be divided into four categories of energy density (ED; kcal/g) to guide food choices and portion sizes. As energy density increases portion management becomes more critical (Rolls 2012, reproduced with permission from Harper Collins Publishers)

Energy density (ED) categories				
Category	ED description	ED range (kcal/g)	How to eat	Examples
1	Very low ED	<0.6	'Free' foods to eat any time	Almost all fruit and non-starchy vegetables, and broth-based soups
2	Low ED	0.6–1.5	Eat reasonable portions	Wholegrains, lean proteins, legumes and low-fat dairy
3	Medium ED	1.6–3.9	Manage your portions	Breads, desserts, fat-free baked snacks, cheeses and higher-fat meats
4	High ED	4.0–9.0	Carefully manage portions and frequency of eating	Fried snacks, candy, cookies, nuts and fats

energy density in a person's everyday eating environment. Even small reductions in energy density of frequently consumed foods could influence daily energy intake. Such research will likely identify new strategies that will help consumers to more successfully navigate the current obesogenic environment and maintain a healthy bodyweight.

Dissemination of advice to focus diets on energy density

With the accumulating body of evidence indicating that dietary energy density encourages healthy eating patterns that facilitate weight management, resources have become available on how to implement this approach. A series of consumer books that provide practical advice on how to use dietary energy density to guide food choices and to manage bodyweight is available (Rolls & Barnett 2000; Rolls 2005, 2012). These books divide foods into four categories of energy density and provide guidance on appropriate amounts to eat (see Table 2). The British Nutrition Foundation (2016), the Centers for Disease Control and Prevention, Division of Nutrition, & Physical Activity and Obesity (2008), and The American Institute for Cancer Research (2017) have been among the first organisations to develop web-based educational materials to help consumers understand the importance of energy density. In addition, a report from The Institute of Grocery Distribution introduces food businesses to using energy density in formulating new foods that help promote healthy choices (Hackett 2012).

In summary, studies from the behavioural sciences have advanced our understanding of the role of dietary energy density in the control of energy intake and how this knowledge can be applied to weight management. These studies indicate that the strategic incorporation of low-energy-dense foods into the diet can promote satiety and help control hunger. If individuals adopt a lower-energy-dense eating pattern, they can eat satisfying amounts of food that meet their energy and nutrient needs so that they can avoid weight gain or lose excess weight. As a range of eating patterns can be accommodated, a diet reduced in energy density has wide applicability and thus can be a key component of a lifestyle that encourages a healthy well-balanced diet for weight management.

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