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Plenary Lecture 1
Dietary strategies for the prevention and treatment of obesity

Barbara J. Rolls
Department of Nutritional Sciences, The Pennsylvania State University, University Park, PA 16802–6501, USA

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Obesity is a rapidly-growing public health problem that is related in part to the foods available in the eating environment. Properties of foods such as portion size and energy density (kJ/g) have robust effects on energy intake; large portions of energy-dense foods promote excess consumption and this effect starts in early childhood. Studies show, however, that in both adults and children these food characteristics can also be used strategically to moderate energy intake, as well as to improve diet quality. Dietary energy density can be reduced by increasing intake of water-rich foods such as vegetables and fruits. Their high water content allows individuals to eat satisfying portions of food while decreasing energy intake. Filling up at the start of a meal with vegetables or fruit and increasing the proportion of vegetables in a main course have been found to control hunger and moderate energy intake. Data from several clinical trials have also demonstrated that reducing dietary energy density by the addition of water-rich foods is associated with substantial weight loss even though participants eat greater amounts of food. Population-based assessments indicate that beginning in childhood there is a relationship between consuming large portions of energy-dense foods and obesity. These data suggest that the promotion of diets that are reduced in energy density should be an important component of future efforts to both prevent and treat obesity.

Portion size: Energy density: Energy intake: Obesity

Obesity with its associated comorbidities is rapidly becoming the most challenging public health problem in many countries. Despite the known health consequences, the prevalence of obesity has surged in recent years. A likely reason for this increase is an obesogenic environment that encourages excess energy intake and inactivity. Proposed solutions encompass those that depend on government policy such as food taxes or labels that direct the public towards healthier choices, as well as those that aim to change food intake behaviours through early exposure to healthy choices and nutrition education. Another possibility is to modify the food environment so that it encourages appropriate levels of energy intake. The effectiveness of this approach will depend on understanding how characteristics of foods influence the overconsumption of energy. Historically, the study of energy intake regulation has emphasized the influence of variations in the macronutrient composition of foods on energy intake, hunger, and satiety. This focus has led to the hypothesis that there is a hierarchy for satiety such that protein is the most satiating macronutrient, followed by carbohydrate, with fat being the least satiating[1,2]. While the macronutrients have distinct effects on biological determinants of hunger and satiety, energy intake also depends on a number of other characteristics of food that can override the maintenance of energy balance. For example, the overall appeal, cost and availability of foods affect food choices. Once food items have been selected, energy intake can be influenced by their palatability, variety, portion size and energy density[3]. The present review focuses on how two of these attributes, portion size and energy density, affect energy intake in both adults and children and discusses the implications of these findings for the prevention and treatment of obesity.

Portion size and energy intake in adults

Since the 1970s the portion sizes of many foods and beverages have increased, a trend that has been observed in a variety of settings including restaurants, supermarkets and

Corresponding author: Professor Barbara J. Rolls, fax +1 814 863 8574, email bjr4@psu.edu

homes[4–7]. These increases in portion size have occurred in parallel with the rise in the prevalence of obesity, suggesting that portion size could play a role[6,8]. A crucial first step in establishing a relationship between portion size and body weight is to investigate the influence of portion size on energy intake.

Several laboratory-based studies have shown that energy intake is related to portion size. When adults are served four different portions of macaroni and cheese on different days, the results show a clear relationship between the amount served and the amount consumed[9]. This effect is seen both when the portion on the plate is determined by the investigator and when the participants serve themselves from bowls containing different portions. The influence of portion size is not limited to foods amorphous in shape, such as macaroni, for which it is difficult to judge the size. Variations in the portion size of foods with clearly-defined shapes or units, such as sandwiches, also have a systematic and marked effect on intake[10]. As the size of a sandwich served at lunch increases, energy intake increases. Similarly, the bigger the portion, the more men and women eat when offered potato crisps in five different commercially-available sizes[11]. Studies in more natural eating environments confirm that food portions influence energy intake[12]. For example, a study in a cafeteria-style restaurant has shown that increasing the portion size of a pasta entrée by 50% while keeping the price the same is associated with a 43% increase in energy intake for the pasta and a 25% increase for the entire meal. A customer survey shows no difference in ratings of the appropriateness of the two portion sizes.

While it is clear that portion size can influence intake at a single eating occasion, for it to play a role in the development of obesity the effect must be sustained over time. In adults studies have indicated that portion size effects persist for periods of 2–4 d[13–15]. However, these studies may have been too short to fully engage physiological adjustments to the increased intake associated with larger portions. A recent analysis of self-reported food intakes over 2 weeks has shown that corrective responses to deviations from average energy intakes occur with a lag time of 3–4 d[16]. In order to determine whether adjustments to large portions occur when there has been sufficient time for such compensation, the effect of increasing the portion size of all available foods has been examined over 11 d[17]. Men and women were provided with all their foods during two 11 d periods, which were separated by a 2-week interval. During one period standard portions of all foods and beverages were served and during the other period all portions were increased by 50%. It was found that the larger portions are associated with a 16% increase in mean daily energy intake. Furthermore, this effect is sustained for 11 d and does not decline significantly over time, resulting in a mean cumulative increase in intake of 19·4 MJ (4636 kcal; Fig. 1). Another study conducted at a work site has indicated that doubling the portion size of a lunch provided to workers increases intake with no indication of a compensatory reduction in intake over a 1-month intervention[18]. These data demonstrate that portion size can have persistent effects over multiple days, resulting in substantial increases in energy intake. Thus,

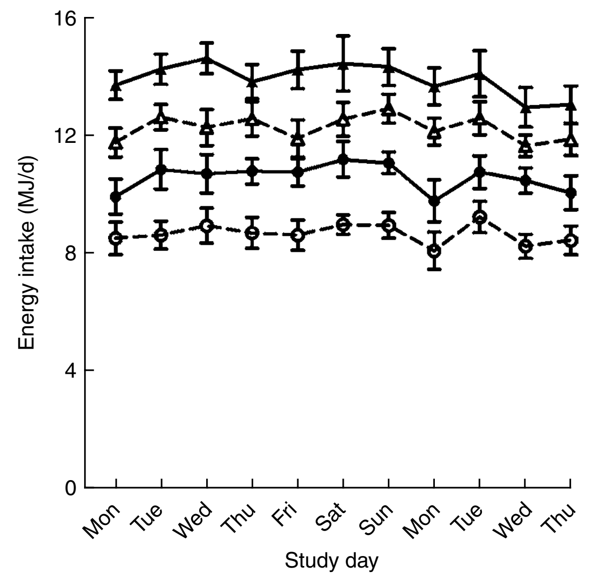

Fig. 1. Daily energy intake for ten women (○, ●) and thirteen men (△, ▲) who were served baseline (100%; ○, △) and large (150%; ●, ▲) portions of all foods over 11 d. Values are means with their standard errors represented by vertical bars. Serving large portion sizes led to a significant increase in daily energy intake ($P<0·0001$), which did not differ by participant gender and showed no evidence of change over time. (From Rolls *et al.*[17]; reprinted with permission from Macmillan Publishers Ltd; copyright 2007.)

characteristics of the eating environment such as the ready availability of large portions of energy-dense foods can override the regulation of energy balance over prolonged periods.

Portion-size effects in children

While there are probably individual differences in the susceptibility to the influence of large portions on energy intake, studies to date have failed to clearly identify them. Men and women, overweight and normal-weight, as well as restrained and unrestrained individuals all respond to portion size[9–12,14,15,17]. It is not clear, however, that individuals start life responsive to portion size. An analysis of food survey data over a 20-year period has indicated that, despite changes in the eating environment, there has been a remarkable stability in the average portion size of foods consumed by children in the second year of life in the USA[19]. Before the age of 2 years children may attend more to biological cues than to those in their eating environment. After that age some population studies show a relationship between portion size and energy intake[20]. For example, a recent analysis of 7 d food records in France has estimated portion sizes for twenty-three food categories and has found that the prevalence of overweight in 3–6 year olds is associated with consumption of large portions of energy-dense foods such as pastries[21]. Although such observational data cannot show causality, the findings support the suggestion that consuming large portions of energy-dense foods could play a role in the aetiology of obesity.

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Several experimental studies have tested the responsiveness of young children to increases in portion size. The first study suggests that 3 year olds are unaffected by portion size, but 5 year olds eat more as the portion size increases[22]. Additional studies have failed, however, to clearly demonstrate such developmental changes in the susceptibility to portion size[20]. Indeed, one study has shown that doubling the portion size of a main dish increases intake in children as young as 2 years[23]. However, it is not clear that children are as responsive to portion size as adults. A recent study has failed to find an effect of a 25% decrease in the size of a main course of pasta on energy intake by 3–5-year-old children[24]. A similar decrease in portion size has a robust and marked effect on adult's energy intake[14,25].

If susceptibility to large portion sizes is not firmly established in young children, strategies might be found that can diminish its development. One study has shown that when children are allowed to serve themselves, they eat 25% less of a large main course compared with when they are served the large portion by an adult[26]. Although more studies are needed, these data suggest that allowing children to serve themselves and to determine their own portions may help them to learn appropriate amounts to satisfy their hunger. It is also possible that the response to external cues such as portion size can be shaped by early experiences. This suggestion is supported by the finding that 4-year-old children who are taught to focus on satiety cues, indicated by the fullness of their stomachs, show better self-regulation of energy intake than those who are rewarded for cleaning their plates[27]. Thus, the response to portion size by children could be a learned behaviour that leads to a shift away from internal hunger and satiety cues toward food cues in the external environment. In an environment in which children are growing up surrounded by huge portions of energy-dense foods, there is a need for more studies that will suggest simple strategies with the potential to moderate the effects of portion size.

Portion-size effects on intake of healthy foods

Studies of the effects of portion size have focused on intake of palatable energy-dense foods since these foods are most likely to contribute to excess consumption. Since the effects of portion size are robust and persistent, it is possible that they could be used to increase intake of nutritious low-energy-dense foods such as vegetables. In a study in which the portions of all available foods were increased by 50% over 11 d it was found that larger portion sizes lead to greater energy intakes for nearly all types of foods, the most notable exception being vegetables, whether served at meals or as a snack[17]. A key question is whether the portion size of such low-energy-dense foods affects intake when their size is varied relative to the other available foods. Popular dietary advice stresses the importance of increasing the proportion of vegetables served at a meal, but it is not clear whether this factor would influence intake or whether the vegetables should be added to the meal or substituted for other components. In two separate studies the proportion of a low-energy-dense vegetable (broccoli) served on a plate with beef and rice was increased, either by substituting broccoli for the more-energy-dense meal components or by adding more broccoli to the meal[28]. Both strategies were found to increase vegetable intake. In addition, energy intake at the meal was found to be reduced when the extra vegetable was substituted for other meal components rather than added to the meal. These studies support the suggestion that variations in portion size can be used beneficially to influence the types and amounts of foods consumed at a meal.

Strategies to moderate the effect of portion size

While there is convincing evidence that portion size has persistent effects on energy intake, the data do not prove that portion size plays a role in the aetiology of obesity; indeed it is difficult to know how such causality could be established. Nevertheless, recent population-based studies support an association between portion size and weight status[29]. Of particular interest is the indication from these analyses that it is large portions of foods high in energy density that are related to excess body weight[21,29].

While many strategies have been proposed to counter the effects of portion size, there are few data indicating which are likely to be both acceptable and effective[30,31]. Interventions to modify children's susceptibility to portion size show potential, but it is not clear whether these interventions will lead to sustained behavioural changes. For adults accustomed to large portions, getting portions back in synchrony with energy needs will be difficult. Possible approaches include education and consumer awareness campaigns, food labels that provide clear information about portion size, more point-of-purchase nutrition information and incentives to the food industry to reduce portion sizes or to offer a greater variety of portions[8]. The impact of these suggestions needs to be established since it is difficult to anticipate consumer responses in the prevailing obesogenic eating environment.

A response by the food industry to help consumers eat more appropriate amounts of energy-dense snacks has been to offer small portion-controlled packages. While research on the utility of such packaging is limited, several studies of consumer behaviour indicate that this approach can lead to a lapse in self-control and increased consumption, particularly in individuals trying to restrain their intake[32,33]. The marketing of these products as diet foods may give dieters license to lower control over their energy intake. These findings emphasize the complexity of eating behaviour and the need for more studies to determine how to translate basic research on determinants of eating behaviour to the consumer world.

Although small portions of energy-dense snacks have not been demonstrated to moderate energy intake in consumers concerned about their weight, a number of studies suggest that portion-controlled meals can be a useful tool for weight management. Providing patients with pre-portioned liquid meal replacements is associated with better compliance and greater weight loss compared with self-selected diets for periods as long as 4 years[34]. While provision of pre-portioned meals reduces the influence of

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environmental food cues by limiting uncontrolled eating opportunities, little is known about how variations in the characteristics of these meals, such as total energy content, energy density and macronutrient composition, affect their efficacy.

In the current environment of huge portions of energy-dense foods it is difficult for many individuals to eat appropriate amounts of food. Getting intake back in synchrony with energy needs will be challenging since consumers equate large portions with good value and they have a distorted idea of how much food is appropriate. If individuals were to heed the frequently-offered advice simply 'to eat less' and were to reduce the portion size of all the foods consumed, they would probably feel deprived and would not sustain this eating pattern. A promising approach that would allow individuals to eat satisfying amounts would be to reduce the energy density of the diet or at least of selected foods.

Dietary energy density and satiety

Energy density is the amount of energy in a particular weight of food (kJ/g). Foods with a low energy density provide less energy relative to their weight than foods with a high energy density. Thus, for the same amount of energy a larger more-satiating portion can be consumed when the energy density is low. Energy density is influenced by the moisture content and macronutrient composition of foods. Of the components of foods, water has the greatest influence on energy density since it adds substantial weight without adding energy. Fat, because of its high energy content (37·7 kJ (9 kcal)/g), has a greater influence on the energy density of a food than either carbohydrates or protein (16·7 kJ (4 kcal)/g). Not all high-fat foods have a high energy density; the incorporation of water lowers the energy density even of high-fat foods. A growing body of evidence indicates that lowering the energy density of foods by increasing the water content or decreasing the proportion of fat or sugar can reduce energy intake.

The energy density of food influences satiety or the feeling of fullness that occurs after the food has been eaten. To study satiety a fixed amount of a defined food (a preload) is consumed and the effect of the preload on subsequent intake of a test meal is measured. Energy density has been shown to influence satiety even when the macronutrient content and the palatability of the preloads are matched. One study has shown that decreasing the energy density of a milk-based preload by adding water, and thus increasing the volume, leads to a reduction in subsequent energy intake[35]. Other water-rich foods that are low in energy density, such as soup, can substantially reduce energy intake at a meal when consumed as a preload[36–40]. Of particular interest is that drinking water as a beverage along with a food does not have the same effect on satiety as incorporating it into the food to lower the energy density[39].

Thus, consumption of a food low in energy density at the start of a meal can be an effective strategy for reducing energy intake. This reduction depends not only on the energy density of the preload, but also on the portion size. This inter-relationship has been demonstrated in a study in which on different days participants consumed salad preloads that were varied across three levels of energy density and two portion sizes[41]. The salad was followed by a main course of pasta consumed *ad libitum*. It was found that compared with having no first course consumption of a low-energy-dense salad leads to a decrease in total energy intake at the meal. Furthermore, this reduction in intake is greater when the participants eat the larger rather than the smaller low-energy-dense salad. Consuming either portion of the higher-energy-dense salad increases energy intake at the meal. This finding suggests that the effects of energy density and portion size combine to influence satiety and energy intake. When translating this advice to consumers, it is important to emphasize that while eating large portions of foods low in energy density at the start of a meal can help to lower their energy intake, this strategy is dependent on the first course being low in energy content.

Variations in both the energy density and portion size of foods served at the start of a meal affect satiety. While these properties of foods can markedly affect intake at a meal, few studies have explored the utility of 'high-satiety' foods over multiple meals or as a tool for weight management. This position is surprising in view of the interest shown by the food industry in making claims that their products enhance satiety. The impact on body weight of strategically varying portion size and energy density to affect satiety should be investigated.

Energy density and satiation: effects on *ad libitum* energy intake in adults

Energy density can influence energy intake not only by enhancing satiety, but also through effects on *ad libitum* intake. *Ad libitum* intake is an indicator of satiation, or the processes leading to the termination of eating during a meal. A groundbreaking study conducted in 1983 has suggested that dietary energy density could affect satiation[42]. Obese and non-obese participants were confined to a hospital ward for two separate 5 d periods. During one period a lower-fat lower-energy-dense diet was provided, which included substantial amounts of fresh fruits, vegetables, whole grains and beans; the other diet included large amounts of high-fat meats and desserts. Comparable weights of food were consumed by the participants during each 5 d period, resulting in a 50 % reduction in energy intake on the lower-fat lower-energy-dense diet.

It is not clear from the study whether it is the reduction in the fat content or the energy density that affects energy intake. It is possible, however, to separate these effects by adjusting the water content of foods[43–45]. The adjustment can be achieved either by diluting foods or by adding low-energy water-rich vegetables. In a study to test whether energy density has effects independent of changes in fat normal-weight women were provided with all their meals during three different 2 d periods[43]. Across the periods the amount of vegetables in the mixed dishes was varied, which changed the energy density of the meals but not the

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fat content. Although the women could eat as much as they liked, similar amounts of food were consumed over the 2 d sessions, showing that, a 25 % reduction in the energy density of the diet leads to a 20 % reduction in energy intake. Despite this substantial reduction, participants rated themselves as equally full. Thus, when individuals continue to consume their usual amount of food, reducing the energy density of the diet by adding water-rich ingredients such as vegetables is an effective way to lower energy intake while managing hunger.

Dietary influences on satiation in children

Most of the understanding of the effects of dietary energy density comes from studies in young to middle-aged adults. Responses to changes in energy density may be different in children, since it has been reported that young children are better at responding to variations in the energy content of foods than adults. This suggestion is based on studies showing that children make some adjustments to their energy intake at a test meal following preloads of different energy densities[46–49]. However, until recently there have been no studies indicating how children would respond to foods varying in energy density that are consumed *ad libitum*.

Satiation has been studied in several recent studies by offering children foods of different energy densities and allowing them to eat as much or as little as they like. In these tests of satiation young children behave similarly to adults. In a study in 5- to 6-year-olds the energy density of a main course of macaroni and cheese was lowered by reducing the fat content[50]. Despite the difference in energy density children, like adults, were found to consume a consistent weight of food so that they consume less energy. Comparable findings have been reported in a younger sample of children (2–5 years old) using a similar protocol[51].

Thus, reductions in energy density lower the energy intake of preschool children at a single meal. However, if children are sensitive to variations in energy content, they may compensate when the manipulation is extended over several days. This possibility has been tested in children who were provided with all their meals for 2 d in two experimental sessions[52]. During one session the foods and beverages served at breakfast, lunch and afternoon snack on both days were reduced in energy density using various strategies, such as reducing fat and sugar content and increasing fruit and vegetable content. Similar to findings from single-meal studies, the children were found to eat a consistent weight of foods and beverages over the 2 d in both sessions, therefore consuming less energy when served the lower-energy-dense versions (Fig. 2). The findings of the study suggest the possibility of using reductions in energy density strategically to prevent excess energy intake in young children. However, studies are needed to determine whether over periods >2 d children will sense an energy deficit or will learn that foods reduced in energy density are not satisfying and therefore will adjust their energy intake.

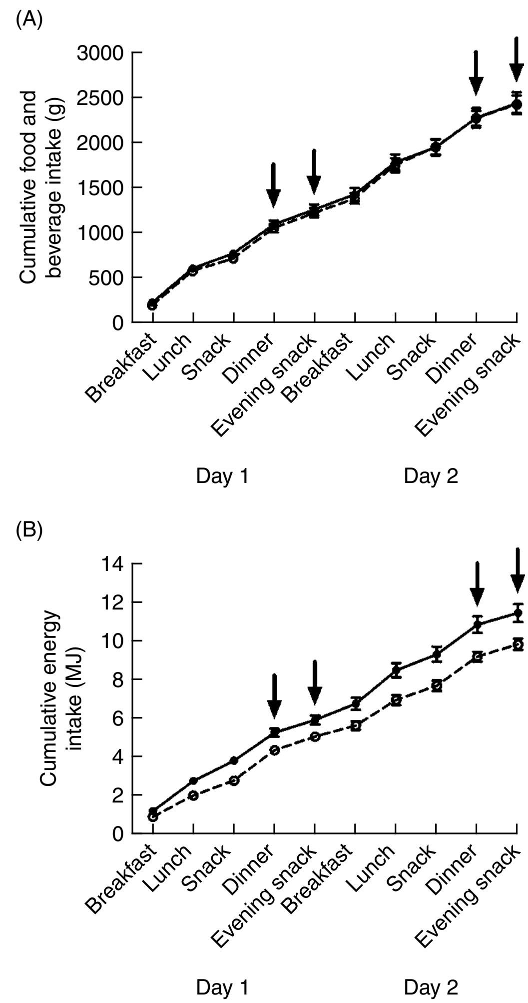

Fig. 2. Cumulative food and beverage intake (A) and energy intake (B) over 2 d in twenty-six preschool-age children who were served foods and beverages that were reduced in energy density at breakfast, lunch, and afternoon snack. Dinner and evening snack were not varied in energy density (↓). (●–●), Higher energy density; (○- -○) lower energy density. Values are means with their standard errors represented by vertical bars. There was no effect of energy density on the cumulative weight of food and beverages consumed over 2 d. There was a significant effect of energy density on cumulative energy intake starting at breakfast on day 1 and accumulating over the course of 2 d, as assessed by a mixed linear model ($P<0{\cdot}01$). (From Leahy *et al.*[52]; reproduced with permission from the *American Journal of Clinical Nutrition*.)

Combined effects of energy density and portion size

Both the portion size and the energy density of foods can markedly influence energy intake in adults and children[53]. Since individuals under free-living conditions have access to foods that vary simultaneously in portion size and energy density, it is important to understand how these factors work together to affect energy intake. As mentioned previously, both the energy density and the size of a preload influence satiety and total energy intake at a meal[41]. Portion size and energy density also combine to affect satiation or *ad libitum* consumption[14,25]. In a laboratory-based study women were served a variety of

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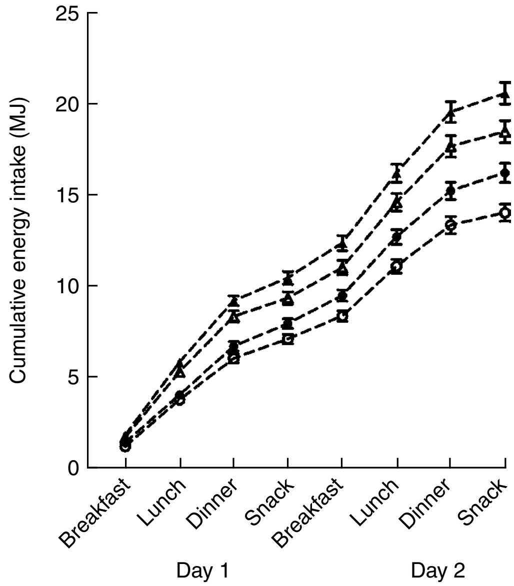

Fig. 3. Cumulative energy intakes by meal for twenty-four women who were served 2 d menus that were varied in energy density (ED; △, ▲, 100 %; ○, ●, 75 %) and portion size (▲, ●, 100 %; △, ○, 75 %). Values are means with their standard errors represented by vertical bars. All means at a given time point were significantly different ($P \leq 0{\cdot}003$). Data were analysed using a mixed linear model with repeated measures. (From Rolls *et al.*[14]; reproduced with permission from the *American Journal of Clinical Nutrition*.)

popular foods such as pizza and sandwiches to consume *ad libitum* at all meals over 2 d (Fig. 3)[15]. It was found that a 25 % decrease in portion size leads to a 10 % decrease in energy intake and a 25 % decrease in energy density leads to a 24 % decrease in energy intake. The effects are independent and when combined daily energy intake is reduced by 32 %. Of particular interest is that the effect of the energy-density manipulation is stronger than that of portion size and that the participants are more likely to notice the changes in portion size.

The suggestion that the effect of portion size is less robust than that of energy density is reinforced by a study in preschool children[24]. To test how portion size and energy density combine to influence children's intake pasta was served in two portion sizes and at two levels of energy density. Energy density was reduced by 25 % by adding extra vegetables and lowering the fat content. The change in energy density was not found to affect children's liking for the pasta and they ate similar amounts of both versions. As a result, the decrease in energy density reduces energy intake from the pasta by 25 %. Increasing the proportion of vegetables has the additional benefit of increasing vegetable intake. The 25 % reduction in the portion size of the pasta was not found to significantly affect intake in these 3–5-year-old children. In slightly older children (5–6-years-old) a two-fold difference in portion size of macaroni and cheese has been found to affect intake, with effects of variations in portion size and energy density combining to determine energy intake[49]. These studies in children lead to the same conclusion as those conducted in adults that the effects of energy density and portion size combine to influence energy intake and the influence of energy density is greater that of portion size.

Implications for the treatment of obesity

Large portion sizes are often targeted as an important influence on the increased incidence of obesity. In turn, while restriction of portions is an important element of many diet programmes, it is not clear that focusing on reduced portions is an optimal strategy for weight loss. A more effective approach may be to shift the emphasis from restriction to more-positive messages related to increasing intake of healthy low-energy-dense foods. Data from two year-long clinical trials in adults support this suggestion. In one trial overweight men and women were provided with controlled portions of either a low- or high-energy-dense food to be incorporated daily into a reduced-energy diet. The reduction in dietary energy density was found to be the main predictor of weight loss during the first 2 months of the study. Daily incorporation of the low-energy-dense food (soup) into the reduced-energy diet was found to increase the magnitude of the weight loss and help participants to maintain this loss[54].

A second trial has tested the effect of two strategies to reduce the energy density of the diet on weight loss in obese women[55]. One group was counselled to increase their intake of water-rich foods, such as fruits and vegetables, and to reduce dietary fat. A comparison group was counselled to restrict portions and to reduce dietary fat. Analysis of participants completing the study shows that both groups reduced the energy density of their diets and both groups lost weight. However, after 12 months the group counselled to eat more fruits and vegetables were found to have a greater reduction in the energy density of their diet and to have lost more weight than the group told to reduce fat and restrict portions (Fig. 4). Over the course of the year it was found that participants on the lower-energy-dense diet (higher in fruits and vegetables) report consumption of a greater weight of food, having less hunger and feeling greater satisfaction with the diet than those in the comparison group.

While additional data from large-scale clinical trials of dietary energy density are needed, a secondary analysis of the results from a multi-centre intervention (the PREMIER trial) indicates that changes in dietary energy density after 6 months are related to changes in body weight[56]. Participants received one of three lifestyle interventions to reduce blood pressure that included information on physical activity, diet and weight loss. Since each intervention group experienced a decline in dietary energy density and body weight, analyses were conducted by classifying participants into tertiles based on the magnitude of change in energy density after 6 months. Participants with a relatively large reduction in energy density were found to have reduced their energy intake and lost more weight than those with a modest reduction or those with a slight reduction or increase in energy density. In addition to weight loss, reductions in energy density were shown to be associated with improved diet quality, indicating that this approach is a healthy strategy for weight management.

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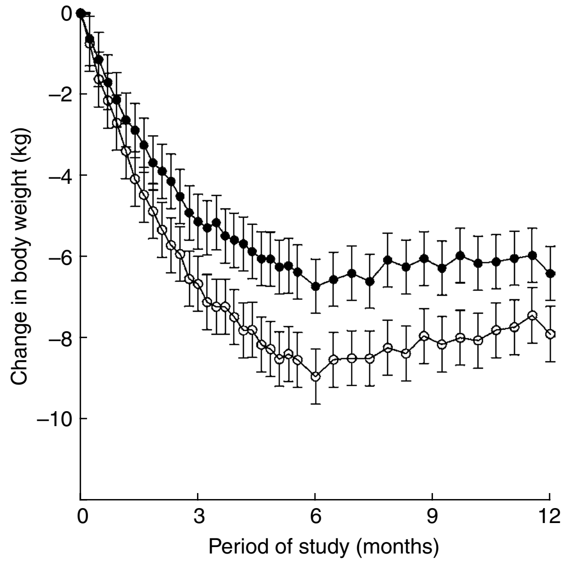

Fig. 4. Change in body weight over time for seventy-one obese women who completed a 1-year weight-loss trial. Women were randomly assigned to receive either advice to reduce dietary fat (●; *n* 36) or advice to reduce dietary fat and increase intake of water-rich foods including fruits and vegetables (○; *n* 35). Advice was provided in individual sessions in the first 6 months and in less-frequent individual and group sessions in the second 6 months. Values are means with their standard errors represented by vertical bars. Random coefficients analysis was used to model the longitudinal response over time, controlling for baseline values. The group × time interaction ($P = 0{\cdot}002$) indicates that the response over time differed between the groups. (From Ello Martin *et al.*[55]; reproduced with permission from the *American Journal of Clinical Nutrition*.)

Furthermore, participants with both large and modest decreases in energy density were found to increase the amount of food they consumed (Fig. 5). Increasing the amount of food consumed while decreasing energy intake could contribute to the long-term acceptability of a low-energy-dense eating pattern since it could help to control hunger.

Relationships between dietary energy density and the maintenance of lost weight have not been extensively investigated. In an examination of energy-density values 2 years after participation in a weight-loss programme that encouraged consumption of low-energy-dense foods it was found that individuals who maintain their weight loss report eating a lower-energy-dense diet than those who regain ≥5 % of their body weight[57]. In another study men and women with marked weight loss were taught the principles of low-energy-density eating. It was found that the participants do well at reducing the energy density of their diets and maintaining their weight loss while the energy-density lessons are ongoing; however, once treatment ends they have difficulty incorporating the strategies into their home environments[58]. Additional long-term interventions are required to understand the challenges associated with making sustainable changes in dietary energy density.

Despite the impact that dietary energy density can have on body weight, the emphasis in recent clinical trials has been on how variations in the proportions of macronutrients affect weight loss, with little consideration of how the intervention influences energy density[59]. Since dietary energy density depends on a number of dietary components, especially water and fat, it is not possible to simply infer how it will be affected by particular dietary advice. For example, a low-fat diet that includes few fruits and vegetables might have a higher energy density than a higher-fat diet that includes a number of water-rich foods[60]. The assessment of energy density should be an integral part of future studies of dietary treatments for obesity. In the meantime, more secondary analyses of completed dietary weight-loss trials are likely to provide a better understanding of the role of energy density in weight management.

Longitudinal and population-based studies

While data from clinical trials are limited, a relationship between dietary energy density and body weight has been observed in longitudinal and epidemiological studies that have tracked dietary patterns. One longitudinal study over a period of 6 years has found that the weight gain of young women who report a diet higher in energy density is two and a half times that of those reporting a diet lower in energy density (6·5 *v.* 2·5 kg)[61]. Consistent with previous research[62], the study also shows that diets lower in energy density are characterized by lower energy intake and consumption of a greater weight of foods of higher nutrient quality.

Population-based studies in adults provide additional support for associations between energy density and energy intake, the amount of food consumed, diet quality and weight status. Surveys of self-reported intakes by free-living adults have shown that those of normal-weight consume diets with a lower energy density than obese individuals[60,63]. Furthermore, increases in dietary energy density have been shown to be associated with greater weight gain in a prospective study of 50 000 middle-aged women over 8 years[64]. While these data suggest that dietary energy density could be a determinant of weight status, interpretation of epidemiological studies has been hampered by methodological considerations. The validity of self-reported intakes, especially those derived from FFQ, for the determination of dietary energy density has not been established. Furthermore, the significance of associations between energy density and energy intake and body weight depends on whether or not different types of beverages are included in the calculation of energy density[65,66]. As a result of their high water content beverages can have a disproportionate impact on energy density. Agreement is needed on the appropriate methods for exploring the influence of energy density on energy intake and body weight in free-living individuals. While the methods will probably depend on the population under investigation, all studies should include an assessment of energy density based on food alone. The impact of including different types of beverages on outcomes should also be explored; however, many data sets have incomplete

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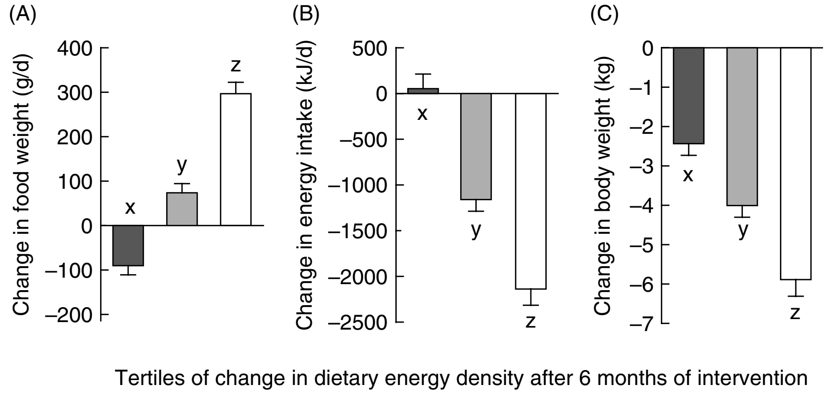

Fig. 5. Change in daily weight of food consumed (A), daily energy intake (B) and body weight (C) after 6 months in 658 participants in the PREMIER trial. Participants received one of several dietary interventions to reduce blood pressure and were classified into tertiles based on the magnitude of change in dietary energy density after intervention: tertile 1, increase or small decrease (+4·6 to −0·4 kJ (+1·09 to −0·10 kcal)/d; ■); tertile 2, medium decrease (−0·5 to −2·1 kJ (−0·11 to −0·51 kcal)/d; ▒); tertile 3, large decrease (−2·2 to −9·8 kJ (−0·52 to −2·35 kcal)/d; □). Values are means with their standard errors represented by vertical bars. [x,y,z]Means with unlike superscript letters were significantly different ($P<0·05$) using ANOVA with a general linear model adjustment for baseline values followed by a Tukey-Kramer adjustment for multiple comparisons. (From Ledikwe *et al.*[56].)

information on beverage intake, especially water, so that it is difficult to make accurate determinations.

Longitudinal and population-based studies show that dietary energy density can be related to energy intake, weight status and diet quality; however, the strength of these associations has been variable. This outcome could be related to true variability across populations or it could be a result of methodological considerations.

Lowering dietary energy density for the prevention of obesity

The potential impact of lowering energy density to prevent overweight and obesity needs to be explored. Prevention hinges on establishing healthy eating habits at an early age that influence energy intake[67], which will probably depend on children eating a diet rich in low-energy-dense foods such as vegetables and fruits that will lower the energy density of their diets. Children as young as 3 years of age, like adults, respond to reductions in energy density by consuming less energy over 2 d. Experimental data on how energy density affects preschool children's consumption over longer periods are not available.

Data from several clinical interventions in families indicate that encouraging children to eat more low-energy-dense foods could help to lower body weight[68,69]. In one of these studies participants were 8–12-year-old children who were either overweight or at risk for overweight and their parents[69]. Some families were given positive messages to increase intake of low-energy-dense foods such as fruits, vegetables and low-fat dairy foods. Others were given negative restrictive messages to reduce intake of high-energy-dense foods. Children in the positive-message group were found to have a greater reduction in BMI-for-age z-score compared with the children in the negative-message group at both 12- and 24-month follow-up appointments. These studies suggest that positive messages to increase intake of low-energy-dense foods such as fruits, vegetables and low-fat dairy foods may be more effective at improving children's eating behaviour and weight status than restrictive messages.

A relationship has also been found between reported dietary energy density and change in body fat as children (6–8 years of age) move into adolescence (13–17 years of age)[70]. Energy density of the foods consumed at baseline is associated with change in fat mass index (body fat normalized for height). Two additional larger-scale longitudinal studies of UK children have reported that consuming an energy-dense diet at ages 5 and 7 years is associated with excess body fat at age 9 years[71,72].

These data suggest that variations in dietary energy density have the potential to be used to prevent obesity in children. Developing strategic child-feeding policies for reducing energy density is a sensible step in countries in which childhood obesity has reached epidemic proportions. Even before such policies are enacted, parents and child-care providers concerned about children's weight and nutritional status may find energy-density-reduction strategies such as incorporating more vegetables and fruits into meals to be useful for moderating children's energy intake and improving their nutrient intakes.

Conclusion

In recent years notable progress has been made in understanding how characteristics of the food environment can affect energy intake. Both the portion size and the energy density of foods influence energy intake from an early age

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and show potential to be used either independently or in combination to counter overconsumption. Encouraging larger portions of foods low in energy density such as vegetables and fruits, while limiting portions of high-energy-dense foods, would not only improve diet quality but could also lower energy intake. The effectiveness of this strategy will depend on altering the current food environment so that lower-energy density choices are easily accessible, appealing and affordable.

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