Proceedings of the Nutrition Society (2011), **70**, 145–154 doi:10.1017/S0029665110004763

First published online 28 January 2011

A meeting of the Nutrition Society hosted by the Irish Section was held at the University of Ulster, Coleraine on 16–18 June 2010

Symposium on 'Nutrition: getting the balance right in 2010'

Session 1: Balancing intake and output: food *v*. exercise
Satiety: have we neglected dietary non-nutrients?

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Proceedings of the Nutrition Society

Satiety, which is the inhibition of eating following the end of a meal, is influenced by a number of food characteristics, including compositional and structural factors. An increased understanding of these factors and the mechanisms whereby they exert their effects on satiety may offer a food-based approach to weight management. Water and gas, which are often neglected in nutrition, are major components of many foods and contribute to volume, and to sensory and other characteristics. A review of previous short-term studies that evaluated the effects of water or gas in foods on satiety showed that while satiety was generally increased, effects on subsequent intakes were not always apparent. These studies were diverse in terms of design, timings and food matrices, which precludes definitive conclusions. However, the results indicate that solids may be more effective at increasing satiety than liquids, but gas may be as effective as water. Although increased gastric distension may be the main mechanism underlying these effects, pre-ingestive and ingestive impacts on cognitive, anticipatory and sensory responses also appear to be involved. Furthermore, there is limited evidence that water on its own may be effective at increasing satiety and decreasing intakes when drunk before, but not with, a meal. Longer-term extrapolation suggests that increasing food volumes with water or gas may offer weight-management strategies. However, from a practical viewpoint, the effects of water and gas on satiety may be best exploited by using these non-nutrients to manipulate perceived portion sizes, without increasing energy contents.

Food gas: Food water: Food volume: Energy intake: Portion size

Obesity is a major public health issue, which occurs when energy intake exceeds energy expenditure, leading to a chronic positive energy balance. However, energy balance is under complex control, and over 100 interacting factors have been identified and described in a series of obesity system maps, which have energy balance at their core[1]. A key variable in energy balance is the degree of primary appetite control, which has physiological, psychological and behavioural determinants[1]. Drugs that suppress appetite and increase satiety offer one strategy to combat obesity[1]. However, compositional and structural variations between foods can lead to substantial differences in their effects on satiety[2]. An increased understanding of these compositional and structural factors and the mechanisms whereby they exert their effects on satiety may offer an alternative, food-based approach to weight management. Water and gas, which are the focus of this review, are major components of many foods, where they contribute to structure and texture, and also to sensory characteristics. However, as non-nutrients, water and gas are often neglected in nutrition. Following an overview of the assessment of satiety and the role of physiological and food factors in satiety, the water and gas contents of a range of foods are presented. Short-term studies that have assessed the effects of water and gas on satiety are reviewed in relation to variations in study designs, food characteristics and putative mechanisms of action, and the potential for exploiting these effects to provide foods that may assist in weight management is discussed.

Abbreviation: RTE, ready-to-eat.
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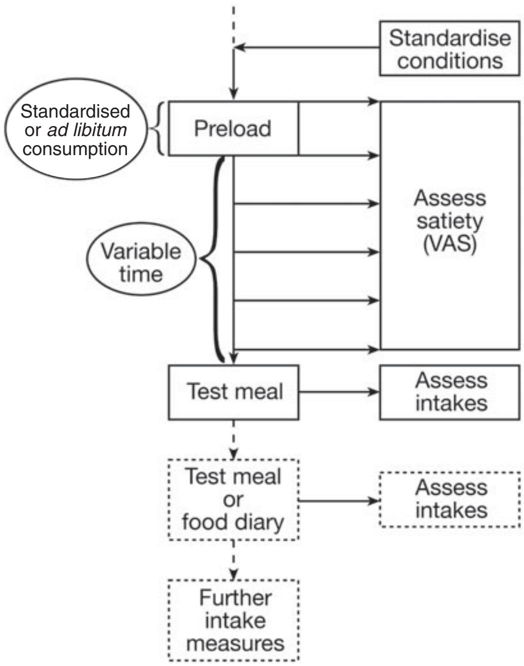

Fig. 1. Generalised design of preload studies. VAS, visual analogue scales.

The assessment of satiety

Satiety, also known as post-ingestive satiety or inter-meal satiety, is the state of inhibition over further eating that follows at the end of a meal and that arises from the consequences of food ingestion[3]. A wide range of potential objective biomarkers of satiety have been identified[3–5]. However, satiety is generally assessed by recording the participant's subjective satiety responses following consumption of the food, and the subsequent assessment of the amount consumed at the next meal[3,6].

Satiety is most often assessed in short-term studies, using a preload study design (Fig. 1). Conditions are standardised before consumption of the preload, typically by providing the preload as a breakfast after an overnight fast, or later after the consumption of standard meals. Preloads may be consumed *ad libitum* or over a standardised time. Satiety is measured before and after the preload, and at regular intervals until the test meal using visual analogue scales to assess factors such as 'hunger', 'fullness' or 'desire-to-eat'[3,6]. The time between the preload and the test meal can vary from a few minutes to several hours. When the period is very short, the preload may be considered as a surrogate for a starter course for a main meal; when the period is longer, the test meal may be considered as a surrogate snack or main meal. Very short intervals between the preload and test meal may only assess pre-ingestive, sensory and immediate post-ingestive effects. However, longer intervals may also elicit a range of post-absorptive mechanisms. After the assessment of subjective satiety, intakes are covertly assessed at the test meal, which is provided in very large amounts for consumption *ad libitum*. Intakes at the test meal are generally reported in terms of energy. In some studies the persistence of effects, or compensatory responses, are assessed using further test meals, or food diaries.

Most preload studies use a randomised within-participant cross-over design with balanced treatment order in order to minimise the effects of inter-participant variation and potential period or carry-over effects[3,6]. It is also generally important that the foods used are similar in all respects except for the factor under evaluation since differences in energy, composition or sensory characteristics may confound the results. Foods are often specially prepared to in order to attain this. However, this may not be feasible, for example, when consumer foods are compared. Thus, the studies, such as those reviewed later, tend to use either rigorous designs where only one food factor is varied but which do not represent habitual eating conditions, or which utilise consumer foods but do not control all variables.

Physiological and other factors involved in satiety

Fig. 2 gives an overview of the physiological, psychological and other responses underlying the onset and persistence of satiety. Responses are often initiated before consumption by cognitive, anticipatory and sensory factors related to the food type or its presentation (eating environment, familiarity, aroma, meal size and appearance). The rate of ingestion and time taken to consume, which may depend on the eating environment or cognitive factors, are also related to food textural factors and the degree of oral processing, and will vary with serving size, and influence the degree and persistence of oropharyngeal sensory stimuli. The stomach distends in response to food ingestion, and distension increases as the meal proceeds, leading to increased sensations of fullness[5]. Gastric emptying, which is a complex process, can start rapidly, but this will depend on the nature of the meal[5,7]. Liquids generally empty more rapidly than solids, and the rate of emptying of liquids increases exponentially as the volume increases[7]. The emptying of solids is dependent on their particle size, and solids are retained in the stomach until the size is reduced to <2 mm[5,7]. Thus, the time course of gastric emptying will vary considerably depending on the foods ingested. The rate of gastric emptying will influence the rate of absorption of nutrients from the small intestine, and the accompanying glycaemic, insulinaemic and gut hormone responses that may influence satiety[5]. Food components that are not digested may be fermented by the colonic bacteria, eliciting the further secretion of gut hormones that can impact on satiety in the longer term[5].

Food factors that influence satiety

A comparison of isoenergetic portions of consumer foods showed wide variations in satiety[8]. However, foods are very diverse in chemical composition, physical structure and sensory characteristics and no clear-cut relationships were found between macronutrient composition and satiety[8]. On the other hand studies, often using model or simplified food systems, have shown that macronutrients generally vary in their effects on satiety in the order

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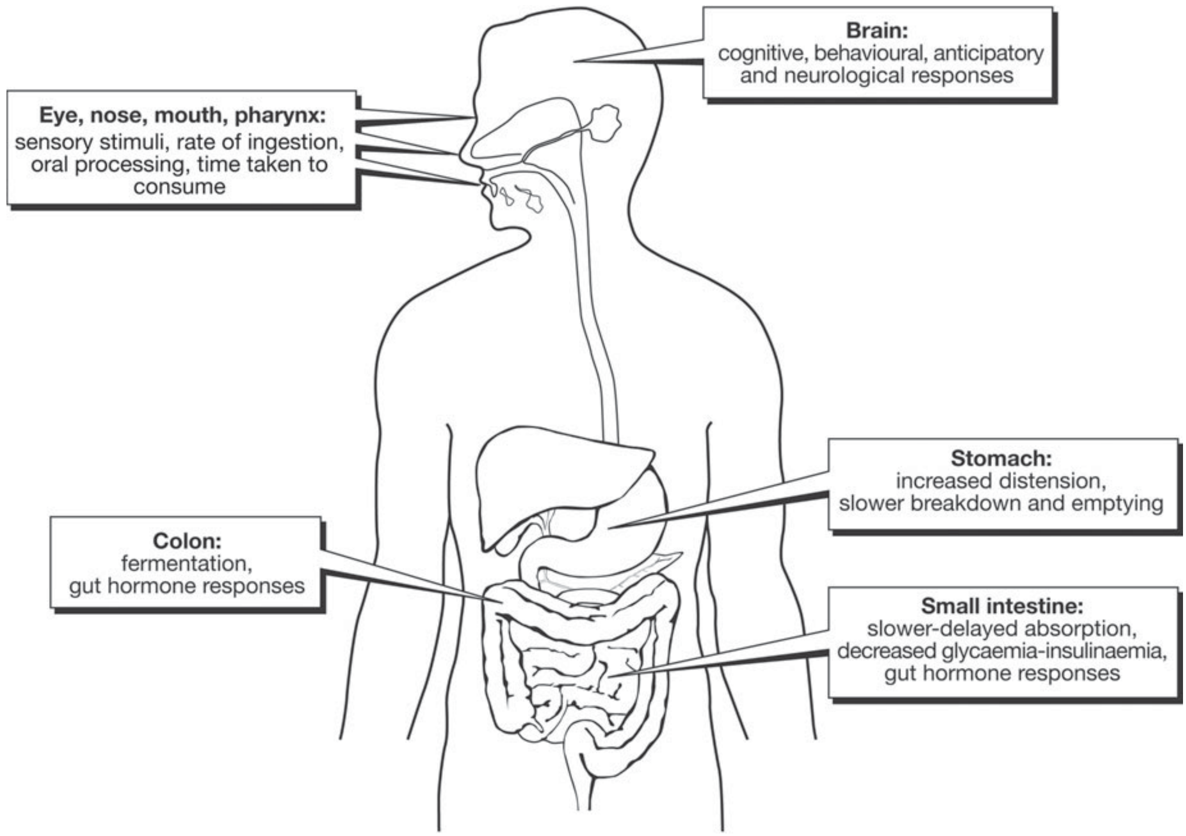

Fig. 2. Physiological and other responses involved in satiety.

protein > carbohydrate > fat[9]. Nevertheless, proteins from different sources vary in their effects on satiety[9,10], and fats can vary in effects on satiety due to differences in chain length, degree of unsaturation and configuration of the fatty acids and differences in the composition and stability of emulsions[11–15]. Dietary fibre components are also very variable in chemical and physical characteristics and can influence satiety by a range of mechanisms. Viscous polysaccharide gums can decrease the rate of gastric emptying and slow the delivery of digesta to the small intestine, where effects on viscosity can decrease the rate of nutrient uptake[16–18]. Highly fermentable non-digestible carbohydrates such as fructans can stimulate the production of gut hormones involved in appetite[19]. Furthermore, in foods such as fruits and vegetables, dietary fibre components associated with the cell wall structure, will influence satiety in a number of ways, for example, by increasing the time taken to consume and modulating the uptake of nutrients[20,21]. However, fresh fruits and vegetables are complex foods with distinct morphological and cellular structures, which contain substantial amounts of water, and may also contain gas.

Table 1. Water, gas contents and densities of a range of foods*

Food	Water (g/100 g)	Gas (ml/100 ml)	Water + gas (ml/100 ml)	Density (g/ml)
Cucumber†	96	12	98	0·90
Puffed wheat‡	5	95	95	0·08
Strawberry†	93	13	95	0·89
Onion†	88	9	93	0·95
Pear†	83	11	93	0·98
Cornflakes	5	92	93	0·12
Apple†	85	20	92	0·85
White bread	38	79	89	0·28
Shredded wheat‡§	4	87	88	0·20
Bagels	26	78	86	0·32
Banana†	72	20	85	0·91
Chocolate mousse	59	49	83	0·56
Steak (beef, grilled)	62	12	72	0·97
Biscuits (digestive)	2	62	63	0·51
Sausage (pork, grilled)	46	11	57	1·02
Cheese (Brie)	49	11	56	0·94
Cheese (Cheddar)	37	2	40	1·05
Chocolate wafer bar	2	37	38	0·84

*Derived from data in PA Irvine (unpublished results).
†Fresh, raw.
‡Gas and density on a bulk volume basis.
§Bite-size.

Water and gas in foods

Water and gas are major components in many foods (Table 1). Although these non-nutrients are often neglected in nutrition, adequate daily intakes of water from all dietary sources have recently been set in the EU at 2–2·5 litres per day for adults[22]. On a weight basis, water is the major component of most unprocessed foods such as fruits, vegetables and meats, and many processed foods including meat products and desserts (Table 1). Gas is also a major

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Table 2. Summary of studies that have evaluated the effects of varying water or gas in foods on satiety and energy intake

		Preload							
Food matrix	Variable	Contrast (ml)†	Range (ml)†	Energy (kJ)	Time to consume (min)	Time to test meal (min)‡	Effect on satiety§	Effect on intake‖ (kJ)	Reference
Water and milk-based drinks	Water	500¶	250 *v.* 750¶	0–2510¶	5–6¶	120	↑*	300↓*	de Graaf & Hulshof[34]
Milk-based drinks	Water	300	300 *v.* 600	2088	15(S)	30	↑*	560↓*	Rolls *et al.* [24]
Milk-based drinks	Water	250	250 *v.* 500	716	10 (S)	30	↑*	134–179↓NS	Latner *et al.* [29]
Milk-based drinks††	Water	200	200 *v.* 400	837‡‡	15 (S)	30	N	322↓*	Rolls & Roe [28]
Soups	Water	300	150 *v.* 450	629	NR	30	↑*	76↓NS	Gray *et al.*[25]
Soups	Water	300	150 *v.* 450	629	9, 13 (A)§§	9, 13§§	↑*	35↑NS	Gray *et al.*[26]
Soups	Water	300‖‖	300 *v.* 600‖‖	1121‖‖	15 (S)	30	↑*	32↓NS	Norton *et al.*[35]
Casserole or soup	Water	356¶¶	263 *v.* 619¶¶	1128	12 (S)	17	↑*	430↓*	Rolls *et al.*[30]
Milk-based shakes	Gas (air)	300	300 *v.* 600	2088	15 (S)	30	↑*	402↓*	Rolls *et al.*[27]
Milk-based gel and solid foam	Water or gas	100	200 *v.* 300	786	4,5 (A)§§	19–20	↑*	875↓*	Moorhead *et al.*[31]
Carbonated drinks	Dissolved gas	800†††	680 *v.* 1480†††	639	6 (S)	18	↑*	725↓*	Moorhead *et al.*[36]
Bread rolls	Gas	144	214 *v.* 358‡‡‡	1897‡‡‡	7, 8 (A)§§	180	↑*	131↓*	Irvine *et al.*[32]
Ready-to-eat cereals	Gas	380	197 *v.* 577‡‡‡	1532‡‡‡	6, 10 (A)§§	180	↑*	223↓*	Irvine *et al.*[33]
Aerated snacks§§§	Gas	0	1250§§§	2391, 5258§§§	12 (S)	12§§§	N	293↓*	Osterholt *et al.*[37]

↑*, significant increase ($P<0{\cdot}05$); ↓* significant decrease ($P<0{\cdot}05$); S, time-to-consume standardised; ↓NS, non-significant decrease; N, no effect; NR, not reported; A, *ad libitum* consumption; ↑NS, non-significant increase.
†Contrast and range due to differences in water or gas, the lower limit of the range is the baseline preload volume.
‡Time from start of preload until start of *ad libitum* test meal; total duration for aerated snack.
§Subjective satiety assessed from the finish of the preload to the start of the test meal.
‖Difference in intake attributable to preload contrast.
¶Contrast and range in g, there were also treatments at 500 g and 1260 kJ, not clear if consumed *ad libitum*, main effects shown only for weight contrast.
††Infused via nasogastric tube.
‡‡An additional treatment at 400 ml, 1674 kJ not included.
§§Times for smaller and larger preloads respectively.
‖‖For men; data for women, 240 ml, 240 *v.* 480 ml and 894 kJ respectively.
¶¶Contrast and range in g.
†††Contrast between lowest and highest volumes tested.
‡‡‡Ranges for cereal products, energy values for total breakfasts.
§§§Not a preload study.

component of many foods on a volume basis. Foods with relatively high gas contents include some fruits, ice cream, mousses, breads and ready-to-eat (RTE) cereals, as well as a wide range of carbonated beverages (Table 1)[23]. In processed foods, this gas is often air that has been entrapped by mechanical agitation, or in processes such as extrusion. However, food gases also include CO_2, nitrogen and nitrous oxide[23]. CO_2, for example, is the product of leavening agents in a wide range of baked foods, and dissolved CO_2 provides effervescence in carbonated beverages[23]. Thus, water and gas impart texture and other sensory characteristics and contribute substantially to the volume of a wide range of foods (Table 1).

Effects of water on satiety: earlier work, the satiety index

There were indications that the water content of foods may be an important determinant of satiety in a study that compared isoenergetic servings of thirty-eight diverse foods, and which developed the concept of the satiety index. The satiety index was calculated as the area under the 2 h satiety curve for each food, relative to white bread, whose value was set at 100[8]. Foods included fresh fruit, baked products and RTE cereals. Wide variations were found in satiety index, which ranged from forty seven for croissants, to about 200 for apples, oranges and oatmeal porridge, to a maximum of 368 for boiled potatoes. Correlations between the satiety index and various food characteristics showed that the best predictors of satiety were serving weight (r 0·66; $P<0{\cdot}001$; R^2 0·44) and water content (r 0·64; $P<0{\cdot}001$; R^2 0·41). However, serving weight is largely determined by water content, which suggests that water content was the major determinant of satiety. However, gas, which would have contributed substantially to the volumes of many of the foods, was not measured.

Studies that evaluated the effects of water and gas on satiety

Previous studies which assessed the effects of water and gas on satiety are summarised in Table 2, which gives the main experimental conditions and results. Eight studies varied water content, four varied gas content, one compared water and gas, and one varied dissolved gas. All but one of these studies used a preload study design. Food matrices included liquids, semi-solids and solids, with volume contrasts of 100–500 ml, which led to significant

https://doi.org/10.1017/S0029665110004763 Published online by Cambridge University Press

differences in satiety and in subsequent energy intakes ranging from 131 to 875 kJ (Table 2). However, some studies did not show significant effects, which may be due to variations in study design or the type of preloads. The study design characteristics and preload variables are reviewed below, in relation to the outcomes and the potential mechanisms whereby water and gas may influence satiety and intakes.

Participant characteristics

Most of the studies were with young adults. Four studies were with only men[24–27], six with only women[28–33] and four had both men and women participants[34–37]. As expected, intakes were generally lower for women than for men, but there were no significant gender differences in responses in the studies that included both men and women. Non-obese (BMI<30) participants were used in all but two studies, where comparisons of lean and obese women[28], and women with and without binge-eating disorder[29] showed no significant differences in response to variations in water content. Overall, this indicates that participant characteristics did not influence responses, and that the conclusions may be generally applicable.

Standardisation of preload characteristics

Variations in the energy, nutrient or fibre contents or the sensory characteristics and hedonic responses to the preloads have the potential to confound results. Thus, most studies took steps to ensure that these variations were small. However, standardising preload characteristics presents particular challenges when the proportions of water or gas are varied substantially. Ideally, preloads should use the same amounts of identical ingredients to provide the same energy and nutrient contents and give sensory and hedonic responses that are not significantly different. This appears to have been achieved in the study that compared a casserole and a soup made by adding water to the casserole[30]. Variable amounts of thickeners were added to maintain sensory characteristics in some studies[24–26,29,35], but this appears unlikely to have confounded the results. However, when consumer foods such as RTE cereals or extruded snacks are used as preloads it is unlikely that the products can be closely matched for all characteristics, and thus, the potential effects of any differences need to be considered when interpreting results.

Participant blinding

Notwithstanding the standardisation of the composition and sensory characteristics of the preloads, it is difficult to blind the participants to treatments that involve large manipulations in the amounts of water or gas present, and which may not only influence the perceived serving size, but also the time taken to consume, and the duration or intensity of sensory responses. However, participants were effectively blinded when liquid preloads were administered intragastrically via a nasogastric tube[28]. In comparison with a previous study by the same group, where similar preloads were drunk[24], increasing preload volume with water did not affect satiety, but similar significant effects on subsequent intakes were maintained (Table 2). This suggests that pre-ingestive visual and cognitive responses and oropharyngeal sensory responses are involved in effects on subjective satiety, but not on intakes[28].

Preload volumes, volume contrast and preload energy

Significant effects on both satiety and intakes were found with baseline preload volumes that ranged from about 200 to 300 ml, and with preload volume contrasts of ranging from 100 to 500 ml (Table 2). However, significant effects on satiety, but not energy intake were found when the baseline volumes were 150 ml (Table 2)[25,26], which suggests that a baseline intake of at least 200 ml may be needed before effects on subsequent energy intakes are apparent.

Preloads with energy contents ranging from 786 to 2088 kJ led to significant effects on both satiety and intake, whereas significant effects on satiety, but not intakes were found with preloads which ranged from 629 to 1121 kJ (Table 2). This indicates that preloads with higher-energy contents may be more effective, and which may explain the differences in responses found between the milk-based drink preload (2088 kJ)[24] and the soup preloads (629 and 1121 kJ)[25,26,35]. However, effects of preload energy do not appear clear-cut and may be confounded by other factors, such as time to the test meal or the food matrix. Furthermore, there is some evidence that water on its own can increase satiety and decrease intakes (see later).

Settings and timings

The setting refers to the environment in which the studies were conducted, whereas timings refers to the time of the day when the preload was served, the time taken to consume the preload and the time between the preload and the test meal.

All the studies in Table 2 were either carried out in North America or in Europe and most studies were conducted in specialised facilities where the participants were isolated, or where social interaction was restricted. However, some studies were conducted in metabolic suites where social interaction with other participants was not constrained. The social setting has been shown to affect intakes[38], but there is no evidence that there is an interaction between the setting and satiety responses. While isolation of the participants may confer greater experimental control, those studies that facilitate social interaction may more closely resemble habitual eating environments. Furthermore, significant effects on satiety and intake were found with preloads served as part of breakfast meal, as a surrogate starter to a lunch meal and as an afternoon snack, indicating that differences in eating patterns, or the time of the day, did not influence outcomes (Table 2).

The time taken to consume the preloads was standardised across treatments in most studies (Table 2) which was probably to mask the differences in the amounts consumed, and/or to ensure that differences in the rate of ingestion did not influence gastric or post-gastric responses. However, standardising the time to consume is likely to influence the degree of oral processing and to disrupt habitual eating patterns. This may influence any effects due to the duration or intensity of oropharyngeal stimulation. In those studies where the preload was consumed *ad libitum* and the time to consume was recorded, as expected, the preloads with higher volume took significantly longer to consume (Table 2)[26,31–33].

The time from the preload to the test meal was typically 20–30 min, but this varied from 9 min to 3 h. With shorter times, the preload may represent the first course of a meal, whereas with longer times, the preload may act as a surrogate for a meal. Shorter times may accentuate potential effects of pre-ingestive and oropharyngeal stimuli, while longer intervals may engage post-gastric events.

The food matrix, and solids v. liquids

In most of the studies that varied water contents, the food matrices were liquids served as milk-based drinks or soups. With the exception of the study where the milk-based drink was administered intragastrically[28], increasing the water content of milk-based preloads significantly increased satiety, and led to significantly lower intakes at the test meal in all but one study, where consistent trends were found (Table 2)[29]. On the other hand, three studies with soups found significant effects on satiety, but not on intakes (Table 2)[25,26,35]. The volume contrast (300 ml) in these three soup studies was the same as that used in a previous study with milk-based drinks[24]. However, there were no effects on intake even when the time from the preload to the test meal was minimised[26] or the baseline preload volume was increased from 150 to 300 ml[35]. It was suggested that this lack of effect may have been due to the lower-energy contents of the preloads[26,35].

However, an alternative explanation for the differences observed between soup and milk-based drinks may be the nature of the food matrices. Although some studies have found that milk exerts similar effects on satiety to water-based drinks[39–41], a recent study showed that, compared to an isoenergetic fruit drink, a skimmed milk preload increased satiety over 4 h, and decreased subsequent energy intakes[42]. Differences in protein or carbohydrate may underlie these effects[42]. However, another possible explanation is that milk coagulates on contact with gastric secretions. Thus, the milk-based drinks may be handled more like solids in the stomach, whereas the soups tested, which were blended commercial varieties, were handled more like liquids.

Potential interactions between the food matrix, satiety responses and gastric handling is also suggested in the comparison of a casserole of chicken, vegetable and rice, with a soup that was made by adding water to the casserole, and where the soup led to significantly ($P<0·05$) increased satiety and decreased intakes[30]. Unlike the previous studies that used blended soups[25,26,35], the casserole and the soup included unblended rice, chicken and vegetables, which may have influenced gastric handling and gastric emptying. This suggestion is supported by a comparison of soups with vegetables that were either 10–20 mm or <1 mm in size, which showed that the soup with the larger particles was more satiating and led to lower energy intakes[43].

Overall, the above studies indicate that the addition of water to liquid or semi-liquid foods will increase satiety, but that effects on subsequent intakes are variable, and may depend on the underlying food matrix. However, significant effects on both satiety and energy intakes were found in the four studies that utilised semi-solid or solid food matrices, and where volumes were increased by either water or gas (Table 2). Furthermore, effects on satiety and intake persisted for up to 3 h with bread and RTE cereal preloads, which suggests that increased volumes of these solid foods may have decreased the gastric emptying rate.

Water v. gas

In contrast to the variable effects on intakes when preload water contents were varied, all six studies in Table 2 that evaluated the effects of variations in gas contents showed significant effects on both satiety and energy intakes. Interestingly, the first study specifically to evaluate the effects of gas (air) on satiety[27] used very similar milk-based liquid preloads, with the same energy contents, volume contrasts and timings as a study that evaluated the effects of water[24]. Although a direct comparison is not possible, similar decreases in energy intakes were found with water and air, suggesting that the effects of the two non-nutrients are of a similar order of magnitude. This was also indicated in the study with semi-solid milk-based gels, where the addition of water or the incorporation of air were equally effective at increasing satiety and decreasing subsequent intakes[31] (Table 2).

Gas may be incorporated into drinks by agitation[27]. However, gas in drinks is more commonly encountered as dissolved gas in carbonated beverages, where it is present in very substantial amounts in terms of volume. Conventionally, beverage carbonation is expressed as the volume of (vol) CO_2 per volume of liquid. For example, the level of carbonation ranges from 2 to 3 vol CO_2 in colas[44]. Thus, the volume of dissolved CO_2 often greatly exceeds the volume of liquid. Although the fate of ingested dissolved CO_2 is unclear, it may impact on gastric function[45,46]. A comparison of fruit drink preloads [36] showed that, relative to low carbonation (1·7 vol), high-carbonation preloads (3·7 vol) significantly ($P<0·05$) increased satiety, and led to significantly lower energy intakes at the test meal served 18 min later (Table 2). Although not all the gas is likely to have been ingested, this suggests that dissolved gas can exert effects on satiety and intake, in the short term at least.

Three studies evaluated the effects of varying the gas contents in solid, cereal-based food matrices. When bread rolls made with identical ingredients, but proofed for different times to give different volumes, were consumed as part of a breakfast, satiety was significantly ($P<0·05$) higher after the higher volume rolls, and this difference persisted for 120 min, and energy intakes at the lunch test meal were significantly ($P<0·05$) lower[32]. However, a comparison of four breads varying in volume did not show consistent relationships between gas content and satiety, but some breads appear to have been very dense, which may have affected palatability[47]. Furthermore, satiety was assessed at the same time as blood sampling, which may have confounded results. This was not a preload study and intakes were not assessed.

Puffed wheat and bite-size shredded wheat, which are wholegrain RTE cereals with very similar nutrient profiles, but which differ substantially in bulk density and gas contents, were served in 40 g portions, as part of a breakfast meal[33]. Results showed that compared to shredded wheat (87 % (v/v) gas), consumption of puffed wheat (95 % (v/v) gas) led to significantly ($P<0·05$) greater satiety until the lunch test meal 180 min later, when intakes were significantly ($P<0·05$) lower.

Two corn-based snack foods, which differed in the degree of aeration, were compared in a study where participants were offered equal volumes, but different energy levels, for consumption *ad libitum* over 12 min[37] (Table 2). Satiety levels were similar after the two snacks, but participants consumed significantly ($P<0·0003$) less energy from the more aerated snack. However, the volume of the more aerated snack consumed was greater than that of the less aerated snack (578 *v.* 332 ml), which may have been due to differences in structural or textural factors.

Although it is difficult to generalise from a relatively small number of studies, these results suggest that increasing the gas content of foods may be at least as effective in enhancing satiety and decreasing energy intakes as increasing the water content.

Potential mechanisms for the effects of water and gas on satiety

Cognitive, anticipatory and pre-ingestive sensory responses

Water and gas both increase food volume and thus, the perceived serving size, which may influence pre-ingestive anticipatory and cognitive responses. When the cognitive, anticipatory, visual responses and the oropharyngeal stimuli were bypassed by administering preloads of varying volumes via a nasogastric tube, there were no subsequent effects on satiety, but effects on energy intake persisted[28]. However, since all pre-gastric events were eliminated, it is not possible to dissociate the effects of pre-ingestive responses and oropharyngeal stimuli. In the studies where breads or RTE cereals were served as part of the breakfast meal, participants rated the meals with the higher-volume preloads as significantly ($P<0·05$) larger than the lower-volume preloads[32,33]. This difference was particularly large for the RTE cereals and has implications on portion size, which are discussed later.

Effects on rate of ingestion, time taken to consume, oral processing and sensory stimuli

In addition to appearing larger, foods with greater water and gas contents will increase the time taken to consume and the amount of oral processing required, and prolong the oropharyngeal stimuli. Although most studies standardised the time to consume, in the four studies where the preloads were consumed *ad libitum* and the time to consume was recorded, as expected, the preloads with higher volumes took significantly ($P<0·05$) longer time to consume[25,31–33]. Furthermore, in the satiety index study, satiety scores were strongly associated with time to consume ($r=0·68$; $P<0·001$; $R^2=0·46$)[8]. Thus, under the *ad libitum* conditions encountered in habitual eating environments, higher-volume foods are likely to increase time taken to consume, and to prolong oropharyngeal stimulation. Furthermore, this effect is likely to be greater with semi-solid, particulate or solid foods that require more oral processing, and will consequently have slower rates of ingestion. However, the prolonged ingestion of a large volume of a single food leads to a decline in perceived pleasantness, and to the onset of sensory-specific satiety[48] which may inhibit consumption under habitual eating conditions.

Effects on gastric distension and gastric emptying

Gastric distension can play an important role in satiety[5,49,50] and, in many of the studies in Table 2, the effects of increased preload volume on satiety and energy intake were attributed to increased gastric distension. Early work showed that distending the stomach with a balloon, significantly ($P<0·01$) decreased intake when the balloon volume was $\geq$400 ml[51]. A study using non-invasive methods showed that gastric volumes were about 200 ml when fasting and about 700 ml after prolonged ingestion of a liquid food to extreme fullness[52]. Furthermore, intragastric balloons, which are used to treat obesity, can vary in volume from 400 to 700 ml[53]. Thus, it appears that baseline volumes and volume contrasts used in many of the above studies are adequate to impact on gastric distension.

Gastric emptying is slower for solid than liquid foods, which suggests that increasing the volume of solid foods, such as the cereal products (Table 2) may prolong gastric distension, increasing the persistence of satiety[5,7]. However, studies with soups administered orally, intragastrically or into the small intestine have shown that orosensory factors such as anticipation or palatability play an important role in subsequent satiety, and that gastric mechanisms such as distension have much more influence than post-gastric events[5,54,55].

Is water effective on its own?

If water added to foods increases satiety and decreases subsequent intakes, can similar effects be attained by just drinking water? When 400 ml water was drunk with breakfast, satiety increased during the meal but this was not maintained after the meal[56]. Furthermore, in the study that compared soup and casserole preloads, a further condition where the casserole was served with a glass of water to give a similar total volume to the soup led to effects on intake that were not significantly different from the casserole, indicating that water alone has no effect[30]. However, when water was drunk 30 min before a lunch meal by younger and older men (500 ml) and women (375 ml), satiety increased and lunch energy intakes were decreased in the older, but not the younger participants[57]. Moreover, when older, overweight and obese men and

https://doi.org/10.1017/S0029665110004763 Published online by Cambridge University Press

women drank 500 ml water 30 min before breakfast, energy intakes at breakfast were significantly ($P = 0{\cdot}004$) reduced[58]. Thus, it appears that water on its own may be effective at increasing satiety and decreasing intakes for some population groups when drunk before, but not with, a meal.

Analogy with energy density

The energy density (kJ/g) of foods is mainly determined by water content[59,60]. Thus, increasing water is analogous to decreasing energy density, and the effects of water on satiety summarised here, are consistent with the inverse relationship observed between energy density (kJ/g) and satiety[60,61]. However, varying the gas contents of foods will not affect energy density (kJ/g) and, since many foods include large volumes of gas, it may be more appropriate to consider energy density on a volume basis (kJ/ml) rather than weight basis (kJ/g)[62].

Potential longer-term effects

A cumulative energy deficit in energy intake of 32·2 MJ is estimated to lead to a loss of 1 kg body weight[63]. Varying water or gas contents led to significant differences in energy intakes that ranged from 131 to 875 kJ (Table 2). A simplistic extrapolation of these differences in intakes would lead to a weight loss of 1·5–9·9 kg over the course of a year. However, many of the consumption patterns and the types and amounts of foods in these short-term studies are unrealistic for use in longer-term studies, or in practice. Thus, an alternative strategy to exploit the effects of water and gas on satiety may be by modifying portion sizes as outlined below.

Implications for portion size

The study that evaluated RTE cereal products used 40 g servings of the cereals[33]. Serving volumes, calculated using the density data in Table 1, were 203 ml for shredded wheat and 500 ml for puffed wheat. Thus, the puffed wheat serving appeared to be much larger than the shredded wheat, and this was reflected in the participants' responses. On the other hand typical portion weights for puffed wheat and shredded wheat are 15–20 g and 45–49 g respectively[64,65], which equates to volumes of 180–250 ml and 228–249 ml. This suggests that portion sizes are determined on a volume rather than weight basis. Thus, the effects of water and gas on satiety may be best exploited by the production and consumption of foods with relatively high proportions of water or gas, with similar portion volumes, but lower portion energy contents than comparable foods.

Food weight or food volume?

A recurring observation is that people tend to consume a constant weight or volume of food[3,6,60,66,67]. Although weight and volume are often conflated, a study that assessed the effects of variations in fat content and energy density on intakes over a day showed that, across conditions, the participants consumed a constant volume, but not constant weight of food[62]. However, volume data are not available for many types of foods, particularly those with substantial proportions of gas. Thus, the provision of data for the density of foods, such as in Table 1, may enable evaluation of the volume of food consumed in intervention and observational studies that investigate the relationships between dietary factors and body weight.

Conclusions

Although equivocal, there is evidence from a number of short-term studies with a range of liquid and solid foods that increasing food volume with water or gas increases satiety and decreases subsequent intakes. Limited data suggest that gas may be as effective as water in this respect, and that the effects may be more persistent in solid or semi-solid food matrices, as compared to liquids. These effects appear to be due to pre-ingestive, ingestive and post-ingestive effects, including increased perceived portion size, increased time taken to consume and increased gastric distension. From a practical perspective, these effects could be exploited by the production and consumption of foods where the portion size is manipulated by increasing water or gas, to provide portions that confer high levels of satiety but relatively low-energy contents.

Acknowledgements

The author thanks Dr P. A. Irvine for the unpublished data on which Table 1 is based. The author declares no conflicts of interest.

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