Effects of carbohydrates on satiety: differences between liquid and solid food

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Purpose of review
To examine the satiety effect of carbohydrates with a focus on the comparison of liquid and solid food and their implications for energy balance and weight management.

Recent findings
A number of studies have examined the role of dietary fiber, whole grains, and glycemic index or glycemic load on satiety and subsequent energy intake, but results remain inconclusive. Intake of liquid carbohydrates, particularly sugar-sweetened beverages, has increased considerably across the globe in recent decades in both adolescents and adults. In general, liquid carbohydrates produce less satiety compared with solid carbohydrates. Some energy from liquids may be compensated for at subsequent meals but because the compensation is incomplete, it leads to an increase in total long-term energy intake. Recent studies also suggest some potential differential responses of satiety by characteristics of the patients (e.g., race, sex, and body weight status). These differences warrant further research.

Summary
Satiety is a complex process influenced by a number of properties in food. The physical form (solid vs. liquid) of carbohydrates is an important component that may affect the satiety process and energy intake. Accumulating evidence suggests that liquid carbohydrates generally produce less satiety than solid forms.

Keywords
added sugar, carbohydrate, gut peptides, satiety, sugar-sweetened beverages

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Introduction

Obesity has emerged as a major public health issue in the USA [1] and globally (http://www.who.int/mediacentre/factsheets/fs311/en/index.html). It has been well established that obesity is an important risk factor for type 2 diabetes, cardiovascular disease, cancer, and premature death [2]. Therefore, prevention of weight gain and the maintenance of a healthy body weight have significant public health implications. Obesity is mostly caused by a combination of excessive dietary (food) intake, lack of physical activity, and genetic susceptibility, whereas food intake is regulated by the complex interaction of psychological and physiological events associated with ingestion.

In addition to the energy content of foods, a number of other properties also have important roles in determining the amount we eat, including palatability, macronutrient composition, cooking methods, food quality, energy density, and form (solid vs. liquid). This review highlights the impact of carbohydrates on energy intake and weight status, with a focus on the satiety effects of solid and liquid forms of carbohydrates.

Background

Appetite, which plays an important role in the regulation of food intake, includes at least two components: satiation and satiety [3••]. Satiation results from a series of neural and humoral signals, mostly produced in the gastrointestinal tract in response to food stimulation. It is defined as the process that evokes meal termination. Satiety refers to the postprandial state that influences the interval between meals. Several peptides secreted by small and large intestine epithelial cells – including ghrelin, cholecystokinin, glucagon-like peptide 1 (GLP-1), and peptide YY (PYY) [3••] – are involved in the process of satiety. Postprandial glucose and insulin levels may also play certain roles in the regulation of satiety [4]. Thus far, the sweet-sensing receptor, T1R2/T1R3, is expressed in both the taste buds of the oral cavity and throughout the gastrointestinal tract [3••,5•].

Impact of carbohydrates on satiety

Carbohydrates are a major source of energy in our daily diets. A hierarchy of macronutrient satiating effects has been observed for protein, carbohydrate, and fat, with protein being the most satiating and fat the least [6,7]. However, before a recent long-term clinical trial in 811 overweight adults that compared weight loss diets with different compositions of fat, protein, and carbohydrate did not find any significant differences in satiety at 6 months and 2 years [8]. Lack of adherence to the assigned intervention may partially explain the results. But more importantly, factors other than the macronutrient content may also influence the satiety process.

Fiber is a major component of carbohydrate that is generally considered beneficial for health. Epidemiological studies show that intake of dietary fiber and whole grains is associated with a lower risk of overweight or obesity [9,10]. One possible mechanism for this association is prolonged satiety from lower-energy foods that are rich in dietary fiber compared with highly processed foods [11,12•]. However, a recent study on varying doses of fiber consumed in breakfast muffins failed to find differences in the effects on satiety, gut hormone levels, and subsequent food intake in 20 healthy, normal weight men and women [13•]. The results from medium-term clinical trials have also been mixed on the effects of a high-fiber or whole-grain diet on weight loss [14–16,17••]. Tighe *et al.* [18••] recently studied 233 volunteers who substituted three portions of whole grains for refined grains for 12 weeks and did not demonstrate any significant differences in energy intake and body weight. Further research is needed to determine whether dietary fiber and whole grains influence satiety and energy intake, or whether other dietary components or accompanying lifestyle factors are responsible for the beneficial effects associated with fiber intake.

Glycemic index, which is determined by the effect of foods on postprandial glucose response, is an alternative system for classifying carbohydrate-containing foods. Glycemic load is a product of glycemic index and carbohydrate content. Consumption of lower glycemic index or glycemic load foods is associated with less likelihood of being overweight or obese; the satiating effect of glycemic index or glycemic load might be a possible mechanism [19].

Short-term feeding studies in adolescents [20] and adults [21] show that ingestion of test meals with high glycemic index content increases food intake during subsequent meals, suggesting that low glycemic index meals might prolong satiety [22]. However, some long-term interventions did not find significant differences between low and high glycemic index foods on energy intake and satiety [23,24]. This disparity may be due to the effects of other macronutrients in the diet, overall diet quantity, and the effect of the foods on satiety hormone secretion, and energy intake [25]. Together, glycemic index and glycemic load have an impact on short-term satiety and energy intake but the long-term effect remains inconclusive.

A recent study conducted in a multiracial sample of normal weight and obese women found no effect of glycemic load on postprandial PYY secretion. However, postprandial PYY secretion was significantly lower in obese black women compared to the other group [26•]. This ethnic difference in PYY secretion has also been previously reported [27,28] and deserves further investigation.

Key points

- The physical form (solid vs. liquid) of carbohydrates is an important component that may affect the satiety process and energy intake.
- Accumulating evidence suggests that liquid carbohydrates generally produce less satiety than solid forms.
- In parallel with the growing obesity epidemic, global intake of liquid carbohydrates by adults and adolescents has dramatically increased.
- Incomplete energy compensation associated with sugar-sweetened beverages can contribute to positive energy balance and obesity.

Solid and liquid forms of carbohydrates on satiety

Various studies suggest that energy consumed in liquid form may induce less satiety than that from the same foods in solid form. It is possible that the rapid transit of liquids through the stomach and intestines may lead to reduced stimulation of satiety signals, differences in the regulation of thirst and hunger, and lower cognitive perception of energy content [29–31]. The effects of physical forms (solid or liquid) of carbohydrates on satiety and total energy intake have been an important focus of recent research [32].

Akhavan *et al.* [33••] built upon their previous research [34] and investigated the effects of 75 g of sucrose intake in solid or liquid form, with a monosaccharide mixture of 50% glucose and 50% fructose in 15 healthy, normal weight young adults (mean age 21.4 ± 0.4 years; BMI $22.1 \pm 0.5\,kg/m^2$). The addition of 6 g of gelatin and 0.13 g of sucralose to the treatment did not affect food and water intake 1 h after ingestion. Therefore, gelatin was added to the treatment to form the solid physical state and sucralose was added to mask the taste difference among treatments. Energy intake of the test meal 1 h after the administration of solid or liquid sucrose (matched in energy content, volume, and taste) did not differ, but the energy compensation was approximately 34% lower in both forms compared with the calorie-free sweetened water. Interestingly, patients in the treatment arm that received solid gelatin or sucrose reported a reduction in appetite, suggesting that solid food had a more satiating effect.

Aging is associated with changes in energy regulations due to alterations in the appetitive, metabolic, and hormonal processes that regulate energy balance [35]. Therefore, findings in young adults may not apply to the elderly. Leidy *et al.* [36••] examined appetite sensations and hormonal responses following consumption of solid and liquid foods matched for energy content, macronutrient, and fiber composition in 43 healthy, non-obese, older adults (age 72 ± 1 years; BMI 25.6 ± 0.3 kg/m^2). Participants in a fasting state were placed in two different portion size groups [12.5% ($n = 18$) and 25% ($n = 25$) of total daily needed energy] and consumed isocaloric food in solid or liquid form on 2 test days. Appetite questionnaires and plasma blood samples were collected every 30 min. After adjustment for age and accounting for between-patient effects of portion size, beverage consumption led to reduced postprandial satiety and greater hunger sensations, along with elevated ghrelin and reduced insulin responses for up to 4 h. Unfortunately, the energy intake of the subsequent meal was not tested. However, the test meals mimicked a standard breakfast and were comprised of three macronutrients instead of pure carbohydrate. The results from this study were also consistent with prior studies in healthy older adults [37,38].

Effects of liquid carbohydrates on satiety

The consumption of added sugar and sugar-sweetened, high-calorie beverages has increased dramatically in the last several decades and has been implicated in the obesity epidemic in both children [39] and adults [40]. Fructose and high-fructose corn syrup, commonly used by the beverage industry as sweeteners, may play an important role in the obesity epidemic [41]. Various studies have investigated the effects of fructose in beverages on satiety. The current literature has been comprehensively reviewed by Moran [42] and Bray [43].

Increasing evidence suggests that liquid carbohydrates are associated with less satiety and increased energy intake compared with solid food [42,43]. Another important consideration is whether caloric beverages are linked with more energy intake and long-term weight gain compared to calorie-free liquids, such as water or artificially sweetened beverages. Several feeding studies show that individuals who consume caloric beverages shortly before or with a meal eat the same amount of calories as individuals who have a calorie-free drink, thus increasing total energy intake [44–51].

A recent study by Anton *et al.* [52•] reported similar findings. The investigators tested the effects of three preloads (290 kcal of stevia or aspartame, and 493 kcal of sucrose) 20 min before lunch on subsequent food intake, satiety, and postprandial glucose and insulin levels in 19 healthy lean adults and 12 healthy obese adults. They found that participants did not compensate by eating more at either lunch or dinner when consuming stevia and aspartame preloads, despite reports of similar satiety levels. This suggests that replacing sucrose with non-caloric sweeteners (stevia and aspartame) is associated with reduced energy intake.

Another study by Ranawana and Henry [53•] investigated the impact of isocaloric (150 kcal, 300–350 ml) portions of three caloric beverages (sucrose-sweetened fruit drink, orange juice, and semi-skimmed milk) on subjective hunger and food intake at a subsequent *ad libitum* buffet, and compared their effects with an artificially sweetened calorie-free fruit drink control. The study enrolled 24 healthy women (mean age 23 years, BMI 22 kg/m^2) and 23 healthy men (mean age 24 years, BMI 24 kg/m^2), and tested each drink in duplicate within a randomized self-controlled paradigm. The investigators provided a standard breakfast, followed 3 h later by the preload beverage, and 1 h later by the test lunch. They found a significant difference between sexes on energy compensation at lunch. Men demonstrated calorie compensation (approximately 100%) at lunch following all three caloric beverages. Women who consumed the sucrose-sweetened fruit drink (about 140 kcal) significantly increased their total energy intake (energy at preload plus lunch) compared with those who had the calorie-free fruit drink. Furthermore, there was a larger incremental area under the curve for subjective feelings of hunger after intake of sucrose-sweetened and artificially sweetened fruit drink compared with orange juice and semi-skimmed milk, suggesting that the presence of other macronutrients (protein and fat) also influence hunger levels.

These findings are consistent with a previous experiment in which Davy *et al.* [54] also reported precise compensation for a caloric preload by men but not women who consumed a large energy preload (360–470 kcal) 30 min before lunch. Both studies indicate a potential sex difference in energy compensation after a caloric beverage preload. This sex difference warrants further research.

Short-term experiments suggest that satiety and satiation may be lower for liquid carbohydrates compared with solid ones but long-term randomized controlled trials of sugar-sweetened beverages on satiety and eventual body weight are limited. Nevertheless, accumulating evidence from short-term blinded randomized controlled trials, medium-term nonblinded randomized trials, and long-term prospective cohort studies indicates that reduced consumption of sugar-sweetened beverages is beneficial for weight management [55].

Although artificial sweeteners are now widely used to replace fructose and high-fructose corn syrup, their long-term effects on appetite, energy intake, and body weight are uncertain. Several studies and reviews recommend that the use of artificial sweeteners should be limited because of their effects on sweet taste preference and increased appetite [56,57]. Currently, there is little evidence that substituting artificial sweeteners for high caloric ones aids in weight management in the long term [58]. Therefore, high-quality, long-term clinical trials are needed to investigate the effects of artificially sweetened beverages compared to sugar-sweetened and nonsweetened, calorie-free fluids, such as water. In the interim, water is a healthy calorie-free substitute that reduces energy intake and may improve weight control and management [59].

Methodological issues

Food intake, including satiety modulation, is a complex process that involves pregastric factors (e.g., food appearance and odor, learned preferences and aversions, psychiatric issues, environmental factors) and food characteristics (e.g., energy content, macronutrient composition, taste, physical structure) [60•]. Studies in this area are continually evolving but remain controversial; thus, understanding methodological and research limitations is critical.

First, self-reported scales (visual analog) are commonly used to evaluate the effects of food on satiety and hunger. Objective measures, such as postprandial biomarkers (e.g., glucose, insulin, leptin, ghrelin, cholecystokinin, GLP-1, PYY) and energy intake in subsequent meals, are important surrogates for satiety and should be incorporated into future study protocols.

Second, for preload test meal studies, the volume of the preload and time lapse between the preload and the test meal are important factors. Generally, solids are more satiating than liquids when the time lapse is long (>2 h), whereas liquids can be more satiating with a high preload volume (>600 ml) and a short time lapse (<1 h) [32].

Third, the isolated tests in the laboratory may not be directly reproduced in real life because the effect of any food or food component on satiety could be influenced by other dietary factors. Thus, results from short-term well controlled interventions may not be representative of a real-life setting, and long-term clinical trials on different physical forms of carbohydrates on energy intake and weight management are still lacking.

Finally, there is some evidence that responses of satiety may vary with participants' characteristics (e.g., sex, race, baseline body weight). These differences require further investigation.

Conclusion

Successful weight loss and maintenance require sustainable satiety and reduced energy intake. A better understanding of the mechanisms of how the gastrointestinal tract responds to specific forms of dietary components will help researchers develop effective strategies to prevent and manage obesity. In parallel with the growing obesity epidemic, global intake of liquid carbohydrates by adults and adolescents has dramatically increased. There is increasing evidence that liquid carbohydrates are less satiating and energy compensation at subsequent meals is incomplete and imprecise, which leads to increased energy intake. Growing evidence has linked intake of higher caloric beverages with weight gain [39,40]. Current recommendations call for restricted intake of beverages high in added sugars to reduce the risk of excessive weight gain and cardiometabolic disorders. Sugar-sweetened beverages should be replaced by healthy alternatives, such as water.

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References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

• of special interest
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Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 416).

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