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Liquid versus solid carbohydrate: effects on food intake and body weight

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BACKGROUND: Beverages are contributing an increased proportion of energy to the diet. Because they elicit a weak compensatory dietary response, they may increase risk of positive energy balance.
OBJECTIVES: This study aimed to document the differential effects of matched liquid and solid carbohydrate loads on diet and body weight.
DESIGN: In a cross-over design, seven males and eight females consumed dietary carbohydrate loads of 1880 kJ/day as a liquid (soda) or solid (jelly beans) during two 4 week periods separated by a 4 week washout. Subjects were permitted to consume the loads however they chose. In addition to baseline measurements, diet records were obtained on random days throughout the study, body composition was measured weekly, physical activity was assessed before and after treatments and hunger was assessed during washout and midway through each treatment.
RESULTS: Free-feeding energy intake during the solid period was significantly lower than intake prior to this period. Dietary energy compensation was precise (118%). No decrease in free-feeding energy intake occurred during the liquid period. Total daily energy intake increased by an amount equal to the load resulting in dietary compensation of −17%. Consequently, body weight and BMI increased significantly only during the liquid period. Physical activity and hunger were unchanged.
CONCLUSIONS: This study indicates that liquid carbohydrate promotes positive energy balance, whereas a comparable solid carbohydrate elicits precise dietary compensation. Increased consumption of energy-yielding fluids may promote positive energy balance.
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Keywords: liquid; solid; rheology; food intake; body weight; dietary compensation; obesity

Introduction

Recent increases in the prevalence of overweight and obesity[1] are likely to have behavioral etiologies that permit expression of inherent physiological processes for energy storage. Attention has focused on both decreased physical activity (ie energy expenditure) and increased energy intake. Survey data of changes in lifestyle and physical activity implicate the former.[2–5] However, trends reported by the CDC's Behavioral Risk Factor Surveillance System[6] indicate that, while activity levels are low in the population, they have been stable over the past decade. Thus, the high level of inactivity may be playing a permissive role in weight gain, but does not explain recent trends. Total daily energy intake has increased from the late 1970s by approximately 800 kJ/day,[7] due principally to increments in protein and carbohydrate consumption. While the US diet is high in fat and energy density, a condition that facilitates positive energy balance,[8] levels have been stable over the past two decades.[7] Thus, this practice also fails to account for recent body weight trends. Protein and carbohydrate are reported to elicit strong oxidative and behavioral responses that should dampen their potential to contribute to positive energy balance,[9–12] but there is increasing reason to believe this can be modified by the form of food consumed.[13] A trend in the US diet, which has only recently been recognized, is a marked increase in energy consumption through beverages.

Since 1978, the onset of the rapid rise in overweight in the US, ingestion of soda has increased by about 40%.[14] In 1997, Americans consumed an estimated 204 liters per capita and only 24% were sweetened with high-intensity sweeteners. Data from the NHANES II survey[15] revealed soft drinks were the seventh largest contributor of energy to the diet, accounting for 4.72% of the total. Based on the 1996 CSFII survey (assuming an average energy content of 711 kJ/336 g serving),[16] the proportion has risen to 6.73%. Juice consumption has increased by about 22% over the same time period. In 1997, estimated per capita consumption was 33 liters.[14] Sports drinks were a trivial market in the late 1970s, but growth has averaged 10.5% throughout the 1990s and this category now represents the sixth largest among beverages.[17] Estimated 1997 per capita consumption was 6.1 liters. Coffee and tea consumption provided 1.35% of daily energy intake according to NHANES II data, but have been among the fastest

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growing supermarket categories. Ready-to-drink teas, in particular, have grown rapidly and, in 1997, per capita consumption was over 9.3 liters.[17] NHANES II data indicated ethanol was the third highest single source of energy in the US diet, accounting for 5.6% of the total. Beer accounts for the overwhelming majority of ethanol ingestion and annual intake has been stable over the past two decades at about 85 liters per capita. Fluid dairy product consumption is lower than two decades ago, but has stabilized over the past 5 y.[18]

One reason the generally positive trend in beverage consumption poses an important public health concern is that energy-containing beverages elicit little dietary compensation. It has been shown that, following covert manipulation of the energy composition of foods, there is more precise compensation for the energy challenge following solid food consumption compared with semi-solid or, especially, liquid foods.[13] Thus, adding energy from fluids to the diet may increase total energy intake. This has been documented for coffee, alcoholic beverages, soda, fruit juice and fluid milk.[13,19] Because the largest increment in energy intake over the past two decades has been due to carbohydrate and this macronutrient is the predominant source of energy in beverages experiencing the most marked rate of growth over the past two decades, this study sought to directly test the effects of liquid *vs* solid carbohydrate loads on diet and body weight.

Methods

General protocol

A cross-over study design was used. To minimize potential bias during dietary reporting, subjects were told that the purpose of the study was to document the effects of sweet loads on stress perception. Baseline data were collected over a 1 week period prior to commencing the dietary manipulation. One form of dietary load was provided during the next 4 weeks. This was followed by a 4 week washout period and another 4 week treatment period when the alternative load was provided. Diets were alternately selected for sequentially recruited subjects. Anthropometric data were collected once a week during each treatment period. Dietary data were collected on random days throughout each treatment period. Hunger was assessed midway through each treatment and during washout. Physical activity was assessed by each participant at the beginning and end of each treatment period using the Seven-Day Physical Activity Recall questionnaire.[20] Each participant provided informed consent and the protocol was approved by the Purdue University Committee on the Use of Human Research Subjects.

Subjects

Seven males and eight females with a mean (s.d.) age of 22.8 ± 2.73 y and baseline BMI of 21.9 ± 2.2 were recruited by public advertisement. Eligibility criteria included: (1) classification as an unrestrained eater by scoring ≤ 9 on the Revised Restraint Scale[21] (eight females and three males), or ≤ 13 on the restraint scale of the Three-Factor Eating Questionnaire[22] (four males); (2) no self-imposed dietary restrictions; (3) consumption of ≤ 8 servings of candy and ≤ 8 cans of soda in an average week; (4) no major illnesses within the past 3 months; (5) not taking medications, except birth control pills; (6) not planning to start a new exercise regimen in the next 3 months; (7) reporting $\geq 51\%$ control over the selection and preparation of the food they consumed; and (8) willingness to consume the required amount of jelly beans or soda each day for 4 weeks. Data on the timing of menstrual cycle was not available.

Baseline

Following recruitment and determination of flavor preferences for the dietary loads, subjects indicated the times of day they could to be reached for a diet recall. They were required to indicate at least 1 h each day so that they could be contacted on a random basis. They were then provided information about portion sizes utilizing NASCO food models (Fort Atkinson, WI) and completed a baseline stress questionnaire. Dietary intervention was initiated 1 week later to permit collection of three random-day baseline diet recalls.

Weekly visits

Subjects reported to the testing laboratory each week on the same day and at the same time during the two treatment periods. They were instructed not to eat or drink after midnight before their visit. They completed the stress questionnaire to maintain the 'study ruse'. Body weight and composition measurements were taken with subjects in hospital gowns using a TANITA Bodyfat Analyzer, model TBF-105 (Tanita Corp. of America Inc., Skokie, IL). At the end of the session, subjects were provided with their weekly supply of the appropriate solid or liquid load. They were instructed to consume the stipulated portion each day, but had the freedom to consume it whenever and however they desired. Subjects were provided with four stress questionnaires to complete at home each week of the 4 week washout period.

Experimental foods

The solid load comprised an 1883 kJ (450 kcal) serving of jelly beans (Blueberry, Bubble Gum, Champagne Punch, Cherry, Grape, Green Apple, Island Punch, Lemon, Orange Sherbet, Raspberry, Strawberry Daiquiri and Tangerine, Jelly Belly — National Bulk Food Distributors, Inc., Taylor, Michigan). The liquid load was an 1883 kJ (450 kcal) serving of caffeine-free soda (A&W Root Beer, Dallas, TX; Coca-Cola, Atlanta, GA, Faygo Creme, Grape, Orange and Red Pop, Detroit, MI; Pepsi, Somers, NY; and Sprite, Atlanta, GA). The energy density of the jelly beans was 16.7 kJ/g (4 kcal/g) and the energy densities of the sodas ranged from 165 kJ/ml (0.39 kcal/kJ/ml) to 2.30 kJ/ml (0.55 kcal/ml). Because of differences in the energy content of the sodas and flavor preferences, slight variations were made in quantities provided so energy content was fixed. Nearly all of the energy from the sodas and jelly beans was in the form of carbohydrate. Eight of the subjects, four males and four females, were provided with the solid load for 28 consecutive days, followed by a washout period of 28 days, and the liquid load for the final 28 days. The remaining seven subjects, three males and four females, were tested in reverse order.

Dietary assessments
Twenty-four hour diet recalls were obtained from subjects over the telephone. They were called on random days and asked to report all foods and beverages consumed during the previous day. Recalls were conducted three times during baseline and six times during treatments and washout. Recalls were only conducted if subjects indicated the prior day was not markedly atypical. Subjects also self-reported the manner in which the loads were consumed, either as a meal, with a meal or as a snack.

Hunger ratings
Hunger questionnaires were completed by subjects after an overnight fast at the end of the third weekly meeting of each load period and twice during the washout period. Self-reported hunger and fullness ratings were obtained on a 13-point scale where 1 = not at all and 13 = extremely. Subjects then consumed one of four preloads: (1) 941.4 kJ (225 kcal) of jelly beans; (2) 941.4 kJ (225 kcal) of soda; (3) 129.48 g Vlasic Dill Spears (Camden, NJ); or (4) deionized water (matched in volume to the soda) in 20 min. The pickles and water were used as weight and volume controls for the jelly beans and soda, respectively. Immediately after preload consumption, hunger and fullness were re-rated. Subjects were then allowed to leave the testing laboratory but continued ratings at 15, 30, 60, 90, 120, 150; and 180 min. Subjects were instructed not to eat or drink anything until after completion of the 180 min period.

Compliance
To enhance compliance with load consumption, subjects were asked to provide an unstimulated, 3 min saliva sample each week. They were told that the saliva would be analyzed for compounds in the jelly beans and soda that would indicate their compliance, although this was not the case.

Data analysis
Statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS), version 7.5.2 (Norusis, 1993). The level of significance used for all analyses was $P < 0.05$. The stress questionnaires and saliva samples were not analyzed. All diet records were analyzed by a single individual using the Nutritionist IV nutrient database, version 4.1 (First DataBank, San Bruno, CA). Repeated measures ANOVA was performed on data (e.g. energy and macronutrient intake, body weight, body composition) obtained at the start and completion of each treatment period (i.e. four time points). When appropriate, *post-hoc* comparisons were made by paired *t*-tests. Body weight was available for all 15 participants, however, only 14 were analyzed for body composition indices due to a malfunction of the body composition analyzer. Hunger data were analyzed four ways. Difference values were calculated by subtracting baseline ratings from 180 min ratings, rebound was calculated by subtracting time zero ratings (immediately after preload consumption) from 180 min ratings, initial change was calculated by subtracting baseline values from time zero values, and the recovery slope was calculated from 0 to 180 min. Percentage dietary energy compensation was calculated as [((baseline intake + 1883 kJ) − (free-feeding intake plus 1883 kJ))/1883 kJ] × 100.

Results

Diet records
Mean (s.d.) free-feeding energy intake was comparable prior to use of the solid and liquid loads (Figure 1). Significant differences emerged during treatments ($F = 10.214$, $P < 0.001$). Free-feeding energy intake during the solid load use was significantly lower than intake prior to this manipulation ($P < 0.001$). When the loads were added to the free-feeding intake, total daily energy consumption was similar prior to and during solid load use. Compensation for the solid load was 118%. The 95% confidence interval was 0.88–1.48, indicating the responses were not significantly different from 1.00 or perfect compensation. All 15 of the participants had lower free-feeding energy intakes during solid load use ($P < 0.001$ based on binomial probability). In contrast, free-feeding energy intake prior to and during use of the liquid load was unchanged. Due to the lack of dietary energy adjustment, addition of the fixed liquid load to free-feeding intake resulted in a significantly elevated total daily energy intake relative to baseline ($P < 0.001$). The compensation score of the liquid load was −17% (ie not only did the subjects fail to compensate for the energy in the liquid load, they actually ate slightly more of their customary diet). The 95% confidence interval was −0.60–0.26, indicating significant

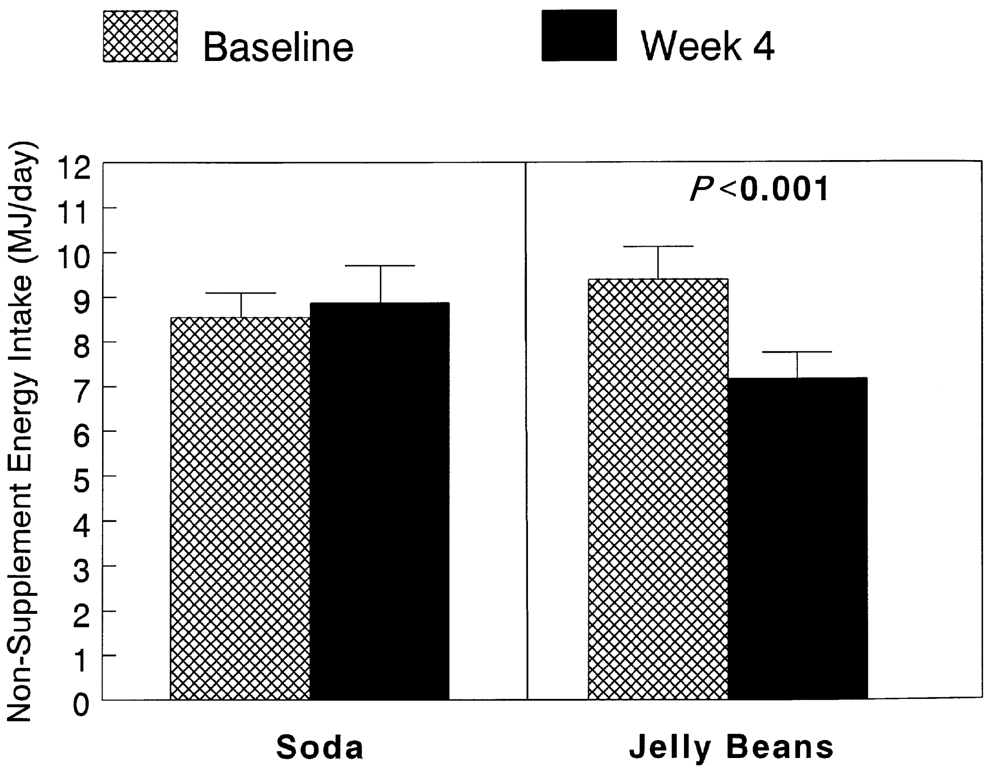

Figure 1 Mean reported energy intake (s.e) prior to and at the end of both intervention periods.

under-compensation. Only seven of the 15 participants had lower free-feeding energy intake during liquid load use (not significantly different from chance based on binomial probability). Four of these individuals had reductions equal to less than 20% of the load. Daily energy intake with the liquid load was significantly greater than intake with the solid load ($P < 0.001$). No significant sex differences were observed.

Free-feeding carbohydrate, fat and protein, as well as sugar and non-sugar carbohydrate intakes during each test period are listed in Table 1. For all five variables, intakes prior to solid and liquid load use were comparable. Total free-feeding carbohydrate intake was significantly lower during both test conditions than during both pre-conditions (solid $P < 0.001$ and liquid $P = 0.002$). Sugar intake during both test conditions was significantly lower than during both preconditions (both $P < 0.001$). Non-sugar carbohydrate intake (total carbohydrate intake minus sugar intake) was significantly lower during solid load use than the prior period ($P = 0.001$). There was no significant change of non-sugar carbohydrate intake between pre- and post-liquid load use. Fat and protein intakes during solid load use were significantly lower than during the prior period ($P < 0.001$). During liquid load use, fat and protein intakes were significantly higher than during the prior period (fat $P < 0.001$ and protein $P = 0.009$).

Based on self-reports, the jelly beans were consumed as a snack 82% of the time, *vs* only 45% for soda. Soda was consumed with a meal 49% of the time, whereas jelly beans were incorporated into the meal only 9% of the time. The experimental loads replaced meals 6% of the time for soda and the incidence was 9% for jelly beans.

Hunger

No significant differences were found for the calculated values of difference, rebound, initial change, or recovery slope.

Anthropometry

Body weights and BMI values at the beginning of the solid and liquid load periods were comparable (Table 2). There was no significant change of body weight during solid load use. In contrast, body weight at the end of the liquid load period was significantly higher than at the beginning ($P < 0.05$), although there was no difference between the change in body weight in the two conditions. BMI also increased significantly over the liquid load period ($P < 0.05$), but the change was not different from that with the solid load. Percentage body fat and kilograms of body fat were comparable at the beginning and end of each condition. However, there was a trend for both of these values to increase during use of the liquid load (percent body fat $P = 0.085$ and kilograms of body fat $P = 0.077$). There were no significant differences in lean body mass. No significant sex differences were observed.

Table 1 Mean (s.d.) macronutrient and sugar intake by test condition

Test condition	*Carbohydrate (g)*	*Sugar (g)*	*Non-sugar carbohydrate (g)*	*Fat (g)*	*Protein (g)*
	$F=9.862$, $P<0.001$	$F=15.906$, $P<0.001$	$F=5.417$, $P=0.003$	$F=13.444$, $P<0.001$	$F=6.134$, $P<0.001$
Pre-solid	297±99	129±50	168±60	76±27	86±30
Post-solid	24±60[a]	95±31[a]	130±36[a]	56±22[a]	72±25[a]
Pre-liquid	291±53	161±30	165±28	77±35	130±46
Post-liquid	242±44[b]	78±22[b]	163±35	85±27[b]	91±30[b]

[a]Solid supplementation significantly different from pre-solid supplementation, $P\leq 0.002$.
[b]Liquid significantly different from pre-liquid, $P\leq 0.009$.

Table 2 Mean (s.d.) body weight and composition values[a]

	Body weight kg (lb)	*Body mass index*	*Percentage body fat*	*Fat mass kg (lb)*	*Lean body mass, kg (lb)*
Pre-solid	68.0±5.0 (149.5±33.1)	22.1±2.3	21.9±5.7	14.6±3.4 (32.1±7.4)	53.4±14.1 (117.4±31.0)
Post-solid	68.3±14.9 (150.3±32.8)	22.2±2.2	22.1±5.8	14.8±3.5 (32.6±7.6)	53.5±14.1 (117.6±31.0)
Pre-liquid	67.7±14.7 (149.0±32.3)	21.8±2.2	21.8±6.1	14.6±3.7 (32.1±8.2)	53.1±14.0 (116.9±30.7)
Post-liquid	68.2±14.5 (150.1±31.9)[b]	21.9±2.1[b]	23.3±6.4	15.0±4.0 (32.9±8.7)	53.3±13.9 (117.2±30.6)

[a]All analyses were performed with an n of 15 except for BMI during liquid supplementation ($n=14$).
[b]End of liquid supplementation significantly different from pre-treatment values, $P\leq 0.05$.

Physical activity

The mean change of physical activity energy expenditure during the jelly bean condition was +0.11 kcal/kg/day and during the soda condition was +0.51 kcal/kg/day. A paired *t*-test indicated that these changes were not significantly different.

Discussion

The present within-subject contrast of dietary responses to isoenergetic solid and liquid loads of carbohydrate revealed this rheological attribute exerts a marked influence on energy regulation. During the solid load condition, subjects compensated for the provided energy by reducing free-feeding intake such that the overall compensation score was 118%. However, when a liquid load, closely matched for energy and macronutrient content, was included in the diet, no compensation was observed. In fact there was a slight increase in free-feeding intake such that the failure to compensate resulted in a score of −17% (ie the energy from the load was added to the customary diet which also increased slightly (17%)). These results agree with a meta analysis of 42 studies[13] that found the mean compensatory dietary response error to solid food challenges was approximately 36% whereas the error for fluid vehicles was 109%. Because energy expenditure, as assessed by an activity questionnaire, did not change over the course of the loading periods, this dietary pattern resulted in increased body weight and BMI during liquid use. No significant changes were observed during solid load ingestion.

Consumption of the solid load did not result in a macronutrient-specific response. During use of the solid load, the reduction in energy derived from the customary diet was achieved by significantly lower intakes of protein, fat and carbohydrate. Total energy, but not macronutrient compensation has also been reported by others conducting longer-term studies of free-living individuals using modified foods (eg Gatenby *et al*.[23] With the liquid load, there was no change of non-sugar carbohydrate and a rise in protein and fat consumption. Only sugar use declined, probably due to sensory factors. This pattern of changes with the fluid load suggests the increment in energy intake was not simply attributable to the addition of the beverage energy. Rather, the beverage prompted a shift of food selection since there was no protein or fat in the provided beverages. This observation is consistent with earlier findings where ingestion of beer or cola resulted in increased protein and fat consumption and little change in non-sugar carbohydrate intake.[13] Increases of protein and fat have also been reported on days when fruit juice is consumed.[19]

There are several mechanisms that may account for this phenomenon. The act of masticating the solid may provide an internal satiety signal not triggered by simply swallowing the liquid. Haber *et al*[24] reported higher satiety ratings from individuals consuming apple slices that had to be chewed when compared to ratings after eating apple puree or drinking juice that required less mastication. Both early pancreatic exocrine and endocrine responses to oral stimulation with viscous or solid stimuli are greater than those to fluids.[25–27] Accumulating evidence indicates these early responses (eg insulin release) modulate postprandial metabolism (eg glucose tolerance[28–30]) with potential resultant effects on hunger and feeding. A cephalic phase release of the purported satiety promoting peptide, cholecystokinin (CCK), has also been demonstrated with a solid meal,[31] but never contrasted to responses following oral exposure to a fluid.

The large differences in the volume, energy density and osmotic properties of most liquids and solids could also be involved. Meals of larger volume, lower energy density and lower osmotic potential are emptied from the stomach at a more rapid rate.[32–34] To the extent that gastric sensing elements for these properties generate signals influencing feeding, fluids may evoked weaker signals. The more rapid transit of fluids also results in a different time course of exposure of nutrients to purported nutrient sensors in the gut or proximal duodenum with possible implications for meal initiation.[35,36] However, the limited data from experimental manipulations of these variables in humans have not been associated with consistent shifts in reports of hunger and satiety.[34] Self-reported hunger and fullness ratings during the two treatment arms were also comparable in the present study.

Cognitive influences could also contribute to the present findings. If solid foods are considered higher in energy content, this could lead to reduced intake. There are reports that the perceived energy content of a food is a better predictor of hunger and intake than true energy content.[37] When questioned during screening, most subjects indicated compliance would be more difficult with the jelly beans because of their expected higher satiety value. After the study was completed, 12 of the 15 subjects maintained this was still the case. There was a noteworthy higher frequency of use of the solid load as a snack. Use patterns were not experimentally controlled because one aim of the work was to identifiy how such loads would be incorporated into the diet in free-living individuals. However, a recent review of the effects of eating patterns on energy balance indicates this is not likely to account for the more precise compensatory dietary response to the solid load.[38]

While the above hypothesized mechanisms focus on factors that may influence energy balance through modulation of hunger and feeding, discrepant metabolic and cardiovascular responses to liquid *vs* solid meals may contribute through an influence on energy expenditure. Metabolic rate and heart rate are higher acutely after ingestion of a solid meal as compared to an isoenergetic, high carbohydrate liquid meal.[39] If true on a chronic basis, this could be a factor in the smaller increment of body weight during the solid load period.

One methodological aspect of this study that could bear on the outcome is the fact that the forms of carbohydrate were not perfectly matched. The beverages contained high fructose corn syrup as the predominant sweetener,whereas the jelly beans were high in sucrose. Based on the glucostatic theory of hunger.[40,41] the higher fructose-containing load (soda) should be more satiating. However, no differences in subjective appetitive responses were observed and the dietary responses were contrary to this expectation. Other recent work that documented differences in blood glucose levels after loads containing fructose *vs* glucose has also failed to reveal differential satiety or energy intake effects over a two hour period after these treatments.[42]

A second methodological issue concerns the use of 24 h food recalls to document dietary intake. While this is clearly an imperfect measure, it does not appear to pose a threat to the interpretation of the present data. First, because this was a within-subject design, individual reporting biases and inaccuracies would likely have held equally during both treatment arms. Secondly, subjects were unaware of the true purpose of the study so could not anticipate the expected outcome. Finally, the lack of sensitivity of recalls would be expected to mask treatment effects rather than produce them.

Combined with other published data, this study indicates that compensatory dietary responses to energy-yielding beverages are less precise than those to isoenergetic solid loads. Whether this is contributing to positive energy balance and the recent increase of body weight in the population warrants careful consideration. Ingestion of a wide array of energy-yielding beverages has increased markedly over the past two decades.[14–16] Alternatively, this lack of regulation may be used to advantage. If energy-yielding fluids evoke relatively weak satiety signals, they represent a vehicle for promoting energy intake by those in need.

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