Effects of fruit and vegetable, consumed in solid vs. beverage forms on acute and chronic appetitive responses in lean and obese adults

Jenny A. Houchins, PhD, Sze-Yen Tan, PhD, Wayne W. Campbell, PhD, and Richard D. Mattes, PhD
Department of Nutrition Science, Purdue University, Stone Hall, 700 W State Street, West Lafayette, IN 47907, U.S.A

Abstract

Background—The effects of fruits and vegetables in solid vs. beverage forms on human appetite and food intake acutely and over eight weeks, are unclear.

Methods—This 21-week, randomised, crossover study assessed appetitive ratings following the inclusion of fruits and vegetables, in solid and beverage form, into the habitual diet of healthy lean (n=15) and overweight/obese (n=19) adults with low customary consumption. The primary acute outcomes were satiation (amount of challenge meal consumed), satiety (latency of subsequent eating event), and dietary compensation after a 400 kcal fruit preload. Ratings of appetite were also obtained before and after 8 weeks of required increased fruit and vegetable consumption (20% estimated energy requirement).

Results—Acutely, overweight/obese participants reported smaller reductions of hunger after consuming the fruit preload in beverage compared to solid form (preload × form × BMI effects, P=0.030). Participants also consumed significantly less of a challenge meal (in both gram and energy) after the ingestion of the solid fruit preload (P<0.005). However, the subsequent meal latency was not significantly different between the solid and the beverage fruit preloads. Total daily energy intake was significantly higher when the obese participants consumed the beverage fruit preload compared to the solid (P<0.001). Daily energy intake was markedly, but not significantly, higher among the lean with the beverage versus solid food-form. Hunger and fullness ratings remained stable when participants consumed fruits and vegetables in solid or beverage form for eight weeks each.

Conclusion—Acute post-ingestive appetitive responses were weaker following consumption of fruits in beverage versus solid food-forms. Consumption of beverage or solid fruit and vegetable food loads for 8 weeks did not chronically alter appetitive responses.
INTRODUCTION

Decreasing the energy density of the diet through increased consumption of fruits and vegetables has been suggested as a method to decrease or maintain body weight (ref. 1, 2, 3, 4). The purported mechanism is based on energy displacement where foods of higher volume and lower energy density lead to decreased hunger, increased fullness, and decreased total energy intake (ref. 5, 6, 7, 8). Short-term preload and some long-term weight-loss trials provide experimental evidence to support this hypothesis (ref. 3, 7, 9, 10), but long-term, more ecologically valid data derived from trials with non-covert energy density manipulations (ref. 8, 11), using common foods such as fruits and vegetables in populations encompassing both sexes, a range of BMI categories, and minimal counseling intervention (representing the general population), are needed to verify this effect. Although the Dietary Guidelines for Americans (ref. 12) suggests there is strong evidence to support a relationship between low energy density and weight loss/weight loss maintenance among adults, a deeper examination of the literature suggests alternate interpretations are viable and recommendations should proceed with caution.

Well established data incongruous with the energy displacement hypothesis pose a challenge to its veracity. First, reduced food intake noted with gastric distention (ref. 13, 14, 15) may be short lived (ref. 16). Over a period longer than several hours, other factors (e.g. the absolute energy content of the meal) also contribute to satiety, particularly when low energy dense foods are included as part of the typical diet (ref. 11, 17, 18, 19, 20). Second, foods at the extremes of the energy density continuum do not support energy density as the primary control of energy intake. Due to their high water content, sweetened beverages have very low energy densities (e.g., cola = 0.4 kcal/g (ref. 21)), so they should aid weight management. However, the evidence is strong, albeit not uniform (ref. 22), that sweetened beverages elicit weak dietary compensation (ref. 23, 24, 25, 26, 27) and may promote weight gain (ref. 23, 28). In contrast, nuts have high energy density (e.g. dry peanuts = 5.8 kcal/g (ref. 21)) and should theoretically promote weight gain. To the contrary, acute feeding studies consistently demonstrate nuts are satiating (ref. 29, 30, 31) and do not contribute to weight gain (ref. 32, 33, 34, 35, 36). Third, disagreement in the literature of how to report energy density may lead to energy density associations that are of questionable practical significance. For instance, many studies reporting an association between energy density of the diet and total energy intake exclude beverages from the analysis and the relationship is not present or markedly diminished when they are included (ref. 37, 38, 39, 40, 41). It has been suggested that beverages should be removed from analyses because they add variance to data and reduce statistical power (ref. 3, 37, 42, 43, 44). A physiological rationale for this argument is lacking and is required given that energy-containing beverages now contribute ~18% of dietary energy (ref. 45). Fourth, if energy density is a primary factor affecting energy intake, there should be evidence that dietary energy density has changed over the past three decades coincident with the increased obesity incidence. Again, these data are not
clear. Between the years 1971-2000, there was a decrease in the proportion of fat in the American diet, an increase in carbohydrate, and maintenance of protein and fiber (ref. 46, 47, 48). Since 2000, trends of fat and carbohydrate consumption have reversed (ref. 49) while fiber intake has remained unchanged (ref. 50). Data on total water consumption are sparse, but there is no evidence that water consumption has decreased over time (ref. 51, 52, 53). Combined, the three main contributing factors to energy density (water, fat and fiber) are unchanged or shifting in the direction opposite to the expected increasing energy density in the American diet. Overall, these observations raise questions about the long-term effects of energy displacement through consuming low energy dense foods on appetite and energy intake. Since there was a strong emphasis on energy density for weight management in the most recent *Dietary Guidelines for Americans* (ref. 2), it is critical to continue to review the applicability of this diet strategy for Americans.

Foods in beverage form are consumed faster (ref. 54) hence producing shorter oral exposure time (ref. 55), and they are emptied faster from the stomach than the solid forms (ref. 56). For these reasons, short-term trials demonstrated that energy compensation for beverage forms of fruits and vegetables (ref. 57, 58, 59) is weak in comparison to solid forms of these foods. However, long-term appetite data are needed to confirm this observation and establish its nutritional implications. Using data from a previously published study (ref. 60), the primary aim of this paper was to assess acute and chronic changes in appetite with prescribed inclusion of fruits and vegetables in solid versus beverage form in the diet. A second aim of this paper was to contrast appetitive effects between lean and overweight/obese groups, as there is evidence of weaker dietary compensation and propensity towards weight gain in individuals with higher BMI (ref. 60, 61, 62, 63).

**METHODS**

**Experimental protocol**

This protocol was a 21-week, randomised, crossover intervention with a one-week pre-intervention period (first baseline, week 1), an 8-week intervention (weeks 2-9), followed by a 3-week washout (weeks 10-12), a second one-week pre-intervention (second baseline, week 13), and second 8-week intervention (weeks 14-21). Each participant consumed their usual, unrestricted diet during the two pre-intervention weeks and the 3-week washout. They were provided portioned quantities of fruits and vegetables to consume daily along with their otherwise usual, unrestricted diet during the 8-week intervention periods. Approximately half of the participants were randomly assigned to consume isoenergetic portions of fruits and vegetables in solid (raw) form during the first intervention and in beverage form during the second intervention, while the remaining subjects completed the beverage intervention first and the solid intervention second. Selected outcomes (energy intake and body weight changes) of this study were previously published (ref. 60). In the current paper, we examine the acute and 8-week appetite-regulation aspects of the original study. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human participants were approved by the Purdue University Institutional Review Board. Written informed consent was obtained from all participants. This trial was registered at clinicaltrials.gov as NCT00260130.
Participants

Participants (n=34, 18 females/16 males) were 18-38 years of age (mean 23±0.8 years), normal (n=15, mean BMI=20.9±0.3 kg/m$^2$) or overweight/obese (n=19, mean BMI=29.9±0.4 kg/m$^2$), weight stable during the previous 3 months, able to maintain a consistent activity pattern throughout the study, low fruit/vegetable consumption (able to comfortably double their baseline intake), not taking medications known to significantly influence appetite, non-restrained eater (<14 on restraint scale of the Three Factor Eating Questionnaire (ref. 64)), and willing to consume the required study foods. The original study required at least 27 participants to detect a difference of 1.5 kg in weight change between study groups at 80% power. Thirty-one participants completed the full protocol, while two participants completed only the beverage treatment and one completed only the solid treatment. All 34 of these participants were included in analyses by using group means in place of their missing values.

Measures

1) Acute appetite and dietary compensation—During the first and second pre-intervention baseline periods, each participant completed two days, one was without a preload and the other included a fruit preload. Both entailed monitoring of short-term appetite and ingestive behavior. The day without preload acted as baseline and preceded day with preload so that participants remained naïve to the treatment. On each testing day, participants arrived at the facility at around noon, 3 hours after their usual breakfast meal. Appetite ratings before fruit preload were recorded, and this was immediately followed by consumption of an ad libitum test meal. The preloads were in solid or liquid form, and the form given during the pre-intervention corresponded to the form the participants would consume during the 8-week intervention period, determined randomly.

The solid and beverage fruit preloads contained 400 kcal (Table 1). The solid preload included a medium Gala apple, red seedless grapes, dried apples, raisins, and 470 grams of water to match the volume of the beverage preload. Forty percent of the energy was from the Gala apple and red grapes and 60% of the energy was from the dried fruit (similar to the long-term intervention). The beverage preload contained apple juice and grape juice (200 kcal of each) and 150 grams of water. Soluble fibre was added to the grape juice in an amount equal to that of the solid preload.

The challenge meal was macaroni and cheese (M&C) (Easy Mac®, Kraft Foods, Inc., Glenview, IL) (150 kcal/100g, 15% energy as fat, 12% energy as protein, and 73% energy as carbohydrate). On the fruit preload testing days, the participants were asked to consume the entire preload, immediately followed by as much M&C as they desired to reach a comfortable level of fullness (3 on a 9-point scale of arbitrary units: 1= extremely full, 9= not full at all). On the testing days without a fruit preload, the participant was asked to consume only the M&C until the same fullness level was reached. Participants were asked to pace themselves to reach a fullness sensation of “3” within 20 minutes, and all participants remained seated at the dining table for the entire 20 minutes. After completing the meal, appetite ratings were completed. Subsequently, participants recorded their appetitive
responses hourly and the quantity and timing of all foods and beverages consumed for the remainder of the day away from the laboratory.

Acute appetite responses were measured as 1) hunger, 2) fullness, 3) satiation, quantified by the amount of M&C challenge meal consumed to the nearest tenth of a gram, 4) satiety, as indicated by the latency of the subsequent meal (>100 kcal) in minutes after the M&C test meal, and 5) dietary compensation (equation shown in Data Analysis). Both hunger and fullness ratings were recorded on visual analog scales (VAS) electronically on a Palm Pilot® device (Palm, Inc., Sunnyvale, CA).

2) Chronic Appetite and energy intake—During the 8-week solid and liquid fruit and vegetable exposures, appetite ratings (ref. 65) were completed on a Palm Pilot® (Palm, Inc., Sunnyvale, CA). Hunger and fullness ratings were recorded every waking hour for 24 hours during two days that included a weekday and a weekend day at the baseline, the middle, and the final week of each food-form intervention period. Pre-programmed timers reminded participants to make the hourly recordings. Most data were recorded between 10 AM to 10 PM and were included in the data analyses. Energy intake was assessed by self-administered 24-h diet records on three consecutive days which included two weekdays and a weekend day at baseline and week eight of each intervention period. The diet records were subsequently checked for accuracy by trained personnel. Compliance to dietary interventions (solid and beverage fruits and vegetables) was assessed through the measurements of plasma ascorbic acid and carotenoid (ref. 60).

During the two 8-week intervention periods, each participant was provided pre-portioned quantities of fruits and vegetables equal to 20% of their estimated energy need (calculated using the sex-specific Harris Benedict equation of resting energy expenditure multiplied by an activity factor of 1.55) rounded to the nearest 50 kcal (between 400-550 kcal/day) on a daily basis. They were provided on a weekly basis. Participants were asked to consume their daily pre-portioned fruits and vegetables only and avoid these foods from other sources.

For the solid food intervention, 10% of energy from the prescribed fruits and vegetables was provided as raw broccoli, carrots, and cauliflower, which was equivalent to approximately 1.3-2.8 servings of vegetables per day based on the USDA National Nutrient Database for Standard Reference (ref. 66). The remainder of energy was provided as fruits (40% as fresh fruit and 60% as dried fruit) which included fresh apples, grapefruit, grapes, oranges, and a variety of dried fruit (Sun-Maid®, Kingsburg, CA): apples, apricots, cranberries, mixed dried fruit, peaches, and raisins. Dried fruits, which have a higher energy density than fresh fruits, were used to help achieve the energy prescription while keeping the volume to consume reasonable. Together, the fruits and vegetables provided to the participants during the solid intervention equalled ~6-8 servings per day. Participants were allowed to select fruits and vegetables according to preference with the exception of apples and carrots (these were consumed daily by all participants, unless substituting broccoli or cauliflower for carrots).

For the beverage intervention, fruit and vegetable juices were isoenergetic to the solid food-forms. All juices were commercially available products and included: V8 Splash® (The
Campbell Soup Company, Camden, NJ), Juicy Juice® (Nestlé, Glendale, CA), Minute Maid® apple (The Coca-Cola Company, Atlanta, GA), Minute Maid® orange (The Coca-Cola Company, Atlanta, GA), grapefruit (The Kroger Co., Cincinnati, OH), Dole® grape (PepsiCo, Inc., Purchase, NY), Ocean Spray® cranberry (Ocean Spray Cranberries, Inc., Lakeville-Middleboro, MA), and Dole® pineapple (PepsiCo, Inc., Purchase, NY). Soluble fiber (Nutriose® FB 06 (Wheat Dextrin), Roquette America, Inc., Keokuk, IA), in an amount matching the corresponding fresh and dried fruits and vegetables, was added to the juice. Participants were required to consume apple juice and V8 Splash® at least four days per week, but were allowed to vary other juices according to preferences.

**Data Analysis**

During the acute appetite test days, dietary compensation for the lunch visits was calculated as: $100\% - \left\{ \frac{\text{test meal total energy intake (kcal) on day with preload} - \text{test meal total energy intake (kcal) on day without preload}}{\text{Preload energy: 400 kcal}} \right\} \times 100\%$. Dietary intake data were collected by 24-hour diet records and energy intake was analyzed using the University of Minnesota Nutrition Data System for Research 2005 and 2006.

Hunger and fullness ratings were collected with visual analogue scales and converted to percent of VAS line on a Palm Pilot by asking participants to answer “How strong is your 9 feeling of hunger?” and “How strong is your feeling of fullness?”. For longer-term appetite assessment, these questions were answered every hour, on the hour, for a weekday and weekend day at the baseline (week 1), middle (week 6), and end (week 9) of each intervention period. In addition, the area under the curve (AUC, determined using the trapezoidal rule) of hunger and fullness ratings reported by participants during the 8-week food-form intervention periods was also calculated for each of the two recording days, and the average AUC (weekday and weekend day) for hunger and fullness was taken for a better representation of daily appetite at the three stages (at baseline, middle, and final) of the intervention periods.

Statistical analyses were conducted with the Statistical Package for the Social Sciences (SPSS), version 16.0. The criterion for statistical significance was set at $p \leq 0.05$, two-tailed. Repeated-measures analysis of variance, with post-hoc comparisons (Bonferroni correction) when appropriate, was conducted to assess appetite and energy consumption. T-tests were used to compare satiety between treatments. Data are reported as means ± standard errors.

**RESULTS**

1) Acute Appetite Responses

**Hunger and fullness ratings**—Hunger ratings were significantly different following challenge meals with vs. without preload, for solid vs. beverage preloads as well as between lean and overweight/obese participants (repeated measures ANOVA; preload × form × BMI interaction effects, $p=0.030$). As shown in Figure 1, overweight/obese participants reported significantly greater hunger on the beverage fruit preload visit compared to the solid preload visit. No significant difference was noted in lean participants. A trend for a similar interaction was noted for fullness ratings ($p=0.055$) (results not shown).
Satiation and dietary compensation (Table 2)—There were significant preload effects, as well as food-form × preload × BMI interaction (F(1,64)=5.638, p=0.021) interactions for the amount of M&C challenge meal consumed. Without a fruit preload, the participants consumed 535±40 g and 542±32 g of the challenge meal on the testing days corresponding with the solid and beverage intervention periods, respectively. Consumption of the 400 kcal fruit preload in either form significantly decreased the amount of M&C consumed when compared to days when participants consumed only M&C without any preload, but intake suppression was greater when the preload was a solid (350±41 g or 57%5 less than without preload), versus beverage (216±20 g or 41% less than without preload) (p=0.005). Consumption of the challenge meal was observed to be higher after the beverage compared to the solid preload, especially in overweight/obese participants (188±44 g) but less so in lean participants (80±50 g) (p=0.114, NS). In the full sample, dietary compensation for the solid preload was 136±13%, but only 73±7% with the beverage preload.

Satiety or latency of subsequent meal—The time to the next eating occasion was not significantly different between days with and without preloads (p=0.484), between BMI groups (p=0.722), food-form of preload (p=.765), or an interaction effect among these factors (preload × BMI × food-form: F(1,64)=0.004, p=0.948). With preload in beverage form, meal latency was 270±28 min in lean and 306±37 min in overweight/obese adults (t-test, p=0.750). In contrast, the solid fruit preload led to a longer between-meal interval in lean (291±25 min), but shorter interval in overweight/obese (255±34 min) participants (lean vs. overweight/obese: t-test, p=0.472). All data combined, meal latency was 271±22 minutes for the solid and 290±24 minutes for the beverage preload (latency × BMI × food-form: F(1,64)=0.004, p=0.948).

Daily energy intakes and dietary compensation (Table 2)—There was a significant preload effect (F(1,64)=75.429, p<0.001), as well as food-form × preload (F(1,64)=55.001, p<0.001) interaction for energy intake from the challenge meal, but this interaction was not affected by the BMI status of participants (F(1,64)=0.008, p=0.929). Total daily energy consumed was higher, but not significantly, during the beverage preload visit (2729±280 kcal/day) compared to the solid preload visit (2328±123 kcal/day) (one-way ANOVA, p=0.194). Overweight/obese participants consumed 547±462 kcal/day more when given the beverage than the solid preload, while lean individuals consumed only 218±280 kcal/day more, but this difference was not statistically significant (p=0.572, NS). The total daily energy consumed was not significantly different between days with vs. no preloads, or the food-forms of preloads, although the total daily energy intake tended to be higher on days with the beverage preload. Total daily energy intake compensation was 36±59% on the beverage preload day and 133±33% on the solid preload day. There were no BMI group differences in total energy intake.

2) Longer-term Appetitive Responses (Figures 2)

There was no significant time × food-form or time × food-form × BMI interaction effects for the hunger and fullness ratings as mean percent of VAS line or AUC. However, strong and significant correlations were observed between the AUC for hunger and fullness ratings at
baseline, middle, and the final week of solid and beverage exposure (fullness: baseline vs. middle, \( r=0.811, p<0.001 \); baseline vs. final, \( r=0.750, p<0.001 \); hunger: baseline vs. middle, \( r=0.598, p<0.001 \); baseline vs. final, \( r=0.522, p<0.001 \)).

**DISCUSSION**

Short-term and some longer-term studies indicate that low energy dense foods, such as fruits and vegetables, lead to increased fullness and satiety (ref. 3, 7, 9, 10, 67). These observations have been extrapolated to long-term diet recommendations for weight loss or weight maintenance (ref. 68) with minimal data showing long-term effects on appetite and intake in representative American populations. Indeed, there is evidence that adding fruits and vegetables to the diet leads to weight loss (ref. 69, 70, 71), weight gain (ref. 72), and weight maintenance (ref. 73, 74, 75, 76).

Our data revealed lower satiation (greater M&C consumed) when fruit beverages were consumed at a lunch visit compared to when solid fruits were consumed under comparable conditions, especially for the overweight/obese participants. Satiety, as indicated by time until the next eating occasion, was not different between treatments (with or without a fruit preload). This is consistent with some other short-term data (ref. 24, 25, 77). Only beverages were associated with greater energy intake at the subsequent M&C challenge meal. The overweight/obese participants experienced smaller reductions of hunger on the beverage preload day and had higher intake of a challenge meal and markedly (about 550 kcal) higher total daily energy intake (albeit not statistically significant). The lack of statistical significance for the latter observation may reflect true lack of food form effects.

Alternatively, it may be attributable to limited statistical power as daily energy intake is highly variable and the power calculation for this study was based on body weight changes. Nonetheless, this increase is potentially clinically important as it suggests imprecise dietary compensation and this may translate into weight gain over time. Indeed, significant weight gain was observed in both the lean (+1.61±0.44 kg, \( p=0.003 \)) and especially in overweight/obese (+2.22±0.47 kg, \( p=0.001 \)) participants during the 8-week beverage fruit and vegetables consumption, as reported previously (ref. 60). Weight gain was due to the failure to compensate for the additional fruits and vegetables provided to the participants.

Chronic appetitive responses remained unchanged after eight weeks of fruit and vegetable consumption in both solid and beverage forms. Thus, reports that fruits and vegetables increase fullness and decrease hunger sensations (ref. 68, 78) may be mediated by acute post-ingestion appetitive regulation, rather than longer-term adjustments. Furthermore, this study demonstrated that the satiating effects of fruits and vegetables diminished when they were in an isocaloric beverage form. Although fiber was added to beverages, it might be argued that the fiber choice did not represent fiber commonly found in fruit (i.e. pectin). However, evidence suggests that fiber added to beverages does not have an effect on satiety (ref. 79). In this study, being exposed to beverage forms of fruits and vegetables significantly increased the energy intake and body weight of lean and overweight/obese individuals after the 8-week exposure periods (ref. 60). Solid exposure increased the intake and body weight of overweight/obese, but not in lean adults. This suggests that fruits and
vegetables, despite being low in energy density, did not prevent weight gain in adults who were already overweight or obese. Our findings call for careful implementation of recommendations through counseling and/or follow-up intervention to increase fruit and vegetable consumption to ensure these foods do not promote positive energy balance and weight gain.

Hunger and fullness ratings remained stable throughout the 8-week intervention periods in this study. This is consistent with observations from another study of similar study length that manipulated dietary fat intake (a high energy dense dietary manipulation)(ref. 80). However, it should be noted that there is large inter-individual variability in appetite ratings with some individuals reporting low daily mean hunger (e.g., 15-20% on a 100mm scale) and others with strong daily means (e.g., 55-60% of scale)(ref. 81). It is also notable that despite the consistency of appetitive responses over time, energy intake and body weight increased significantly in lean and especially overweight/obese adults after an 8-week exposure to beverage forms of fruits and vegetables (ref. 60). Together, these observations suggest that greater energy intake during this beverage intervention period was sought to maintain pre-exposure appetitive responses. This observation is consistent with the previous findings that liquids are less satiating and elicit weaker dietary compensation than solid food-forms (ref. 82).

It is acknowledged that the current intervention did not faithfully follow the Dietary Guidelines for Americans in variety of fruits and vegetables and recommended number of servings of fruits versus vegetables. The overall purpose of the study was to compare beverage versus solid food-forms (ref. 60). Another limitation of the present study was that participants were provided with both fruits and vegetables daily during the 8-week intervention periods to test for chronic dietary effects on appetitive responses whereas only fruits were used in the acute preload study sessions. Further, pre-study testing lead to inclusion of dried fruit, to achieve portions of fruits deemed achievable long-term in low-fruit and vegetable consumers. Additional testing of long-term appetitive effects upon addition of fruits and vegetables, completely consistent with Dietary Guidelines for Americans, is an area of future research. Interventions should include both men and women, all BMI categories, and populations who are not involved in weight-loss trials with significant dietary counseling.

**CONCLUSION**

In summary, our data confirm weaker acute satiation and satiety effects of beverage compared to solid food-forms of fruits as measured by appetitive responses and energy intake, especially among the overweight/obese. Over eight weeks, there was no altered chronic appetitive response upon addition of fruits and vegetables (beverage or solid) to the diet. These data suggest that implementing energy displacement strategies for weight management requires careful consideration of total energy intake.

**ACKNOWLEDGEMENTS**

This study was funded by the National Institutes of Health (Grant #R01 – DK63185).
**Funding source:** National Institutes of Health (Grant #R01 – DK63185

**REFERENCES**

1. Rolls BJ, Ello-Martin JA, Tohill BC. What can intervention studies tell us about the relationship between fruit and vegetable consumption and weight management? Nutr Rev. 2004; 62:1–17. [PubMed: 14995052]

2. United States Department of Agriculture. Report of the Dietary Guidelines Advisory Committee on the Dietary Guidelines for Americans. 2010

3. Ello-Martin JA, Roe LS, Ledikwe JH, Beach AM, Rolls BJ. Dietary energy density in the treatment of obesity: a year-long trial comparing 2 weight-loss diets. Am J Clin Nutr. 2007; 85:1465–1477. [PubMed: 17556681]

4. Pérez-Escamilla R, Obbagy JE, Altman JM, Essery EV, McGrane MM, Wong YP, et al. Dietary energy density and body weight in adults and children: a systematic review. J Acad Nutr Diet. 2012; 112:671–684. [PubMed: 22480489]

5. Drewnowski A. The role of energy density. Lipids. 2003; 38:109–115. [PubMed: 12733741]

6. Rolls BJ, Bell EA. Intake of fat and carbohydrate: role of energy density. Eur J Clin Nutr. 1999; 53:S166–173. [PubMed: 10365994]

7. Bell EA, Rolls BJ. Energy density of foods affects energy intake across multiple levels of fat content in lean and obese women. Am J Clin Nutr. 2001; 73:1010–1018. [PubMed: 11382653]

8. Yao M, Roberts SB. Dietary energy density and weight regulation. Nutr Rev. 2001; 59:247–258. [PubMed: 11518179]

9. Rolls BJ, Roe LS, Meengs JS. Salad and satiety: energy density and portion size of a first-course salad affect energy intake at lunch. J Am Diet Assoc. 2004; 104:1570–1576. [PubMed: 15389416]

10. Bell EA, Castellanos VH, Pelkman CL, Thorwart ML, Rolls BJ. Energy density of foods affects energy intake in normal-weight women. Am J Clin Nutr. 1998; 67:412–420. [PubMed: 9497184]

11. Stubbs J, Ferres S, Horgan G. Energy density of foods: effects on energy intake. Crit Rev Food Sci Nutr. 2000; 40:481–515. [PubMed: 11186237]

12. US Department of Agriculture, US Department of Health and Human Services. Dietary Guidelines for Americans. 7th edn. US Government Printing Office; Washington DC: 2010.

13. Geliebter A. Gastric distension and gastric capacity in relation to food intake in humans. Physiol Behav. 1988; 44:665–668. [PubMed: 3237852]

14. Rolls BJ, Castellanos VH, Halford JC, Kilara A, Panyam D, Pelkman CL, et al. Volume of food consumed affects satiety in men. Am J Clin Nutr. 1998; 67:1170–1177. [PubMed: 9625090]

15. Van Walleghen EL, Orr JS, Gentile CL, Davy BM. Pre-meal water consumption reduces meal energy intake in older but not younger subjects. Obesity. 2007; 15:93–99. [PubMed: 17228036]

16. Pasquali R, Besteghi L, Casimirri F, Melchionda N, Di Febo G, Zoccoli G, et al. Mechanisms of action of the intragastric balloon in obesity: effects on hunger and satiety. Appetite. 1990; 15:3–11. [PubMed: 2241140]

17. Birch LL, Johnson SL, Jones MB, Peters JC. Effects of a nonenergy fat substitute on children’s energy and macronutrient intake. Am J Clin Nutr. 1993; 58:326–333. [PubMed: 8237841]

18. de Castro JM. Dietary energy density is associated with increased intake in free-living humans. J Nutr. 2004; 134:335–341. [PubMed: 14747669]

19. Mazlan N, Horgan G. Stubbs RJ. Energy density and weight of food effect short-term caloric compensation in men. Physiol Behav. 2006; 87:679–686. [PubMed: 16545404]

20. Westerterp-Plantenga MS. Effects of energy density of daily food intake on long-term energy intake. Physiol Behav. 2004; 81:765–771. [PubMed: 15234182]

21. Drewnowski A. Energy density, palatability, and satiety: implications for weight control. Nutr Rev. 1998; 56:347–353. [PubMed: 9884582]

22. Forshee RA, Anderson PA, Storey ML. Sugar-sweetened beverages and body mass index in children and adolescents: a meta-analysis. Am J Clin Nutr. 2008; 87:1662–1671. [PubMed: 18541554]
23. DiMeglio DP, Mattes RD. Liquid versus solid carbohydrate: effects on food intake and body weight. Int J Obes. 2000; 24:794–800.

24. Mattes RD. Dietary compensation by humans for supplemental energy provided as ethanol or carbohydrate in fluids. Physiol Behav. 1996; 59:179–187. [PubMed: 8848479]

25. De Castro JM. The effects of the spontaneous ingestion of particular foods or beverages on the meal pattern and overall nutrient intake of humans. Physiol Behav. 1993; 53:1133–1144. [PubMed: 8346296]

26. Shields DH, Corrales KM, Metallinos-Katsaras E. Gourmet coffee beverage consumption among college women. J Am Diet Assoc. 2004; 104:650–653. [PubMed: 15054352]

27. Harnack L, Stang J, Story M. Soft drink consumption among US children and adolescents: nutritional consequences. J Am Diet Assoc. 1999; 99:436–441. [PubMed: 10207395]

28. Malik VS, Schulze MB, Hu FB. Intake of sugar-sweetened beverages and weight gain: a systematic review. Am J Clin Nutr. 2006; 84:274–288. [PubMed: 16895873]

29. Kirkmeyer SV, Mattes RD. Effects of food attributes on hunger and food intake. Int J Obes Relat Metab Disord. 2000; 24:1167–1175. [PubMed: 11033986]

30. Alper CM, Mattes RD. Peanut consumption improves indices of cardiovascular disease risk in healthy adults. J Am Coll Nutr. 2003; 22:133–141. [PubMed: 12672709]

31. Mattes RD, Kris-Etherton PM, Foster GD. Impact of peanuts and tree nuts on body weight and healthy weight loss in adults. J Nutr. 2008; 138:1741S–1745S. [PubMed: 18716179]

32. Almario RU, Vonghavaravat V, Wong R, Kasim-Karakas SE. Effects of walnut consumption on plasma fatty acids and lipoproteins in combined hyperlipidemia. Am J Clin Nutr. 2001; 74:72–79. [PubMed: 11451720]

33. Fraser GE, Bennett HW, Jaceldo KR, Sabate J. Effect on body weight of a free 76 Kilojoule (320 calorie) daily supplement of almonds for six months. J Am Coll Nutr. 2002; 21:275–283. [PubMed: 12074256]

34. Alper CM, Mattes RD. Effects of chronic peanut consumption on energy balance and hedonics. Int J Obes Relat Metab Disord. 2002; 26:1129–1137. [PubMed: 12119580]

35. Hu FB, Stampfer MJ, Manson JE, Rimm EB, Colditz GA, Rosner BA, et al. Frequent nut consumption and risk of coronary heart disease in women: prospective cohort study. Br Med J. 1998; 317:1341–1345. [PubMed: 9812929]

36. Hollis J, Mattes R. Effect of chronic consumption of almonds on body weight in healthy humans. Br J Nutr. 2007; 98:651–656. [PubMed: 17445351]

37. Ledikwe JH, Blanck HM, Khan LK, Serdula MK, Seymour JD, Tohill BC, et al. Dietary energy density determined by eight calculation methods in a nationally representative United States population. J Nutr. 2005; 135:273–278. [PubMed: 15671225]

38. Kant AK, Graubard BI. Secular trends in patterns of self-reported food consumption of adult Americans: NHANES 1971-1975 to NHANES 1999-2002. Am J Clin Nutr. 2006; 84:1215–1223. [PubMed: 17093177]

39. Stubbs RJ, Johnstone AM, Harbron CG, Reid C. Covert manipulation of energy density of high carbohydrate diets in ‘pseudo free-living’ humans. Int J Obes Relat Metab Disord. 1998; 22:885–892. [PubMed: 9756247]

40. Westerterp-Plantenga MS. Analysis of energy density of food in relation to energy intake regulation in human subjects. Br J Nutr. 2001; 85:351–361. [PubMed: 11299081]

41. Vernarelli JA, Mitchell DC, Hartman TJ, Rolls BJ. Dietary energy density is associated with body weight status and vegetable intake in U.S. children. J Nutr. 2011; 141:2204–2210. [PubMed: 22049295]

42. Cox DN, Mela DJ. Determination of energy density of freely selected diets: methodological issues and implications. Int J Obes Relat Metab Disord. 2000; 24:49–54. [PubMed: 10702750]

43. Ledikwe JH, Blanck HM, Kettel Khan L, Serdula MK, Seymour JD, Tohill BC, et al. Dietary energy density is associated with energy intake and weight status in US adults. Am J Clin Nutr. 2006; 83:1362–1368. [PubMed: 16762948]

44. Ledikwe JH, Blanck HM, Khan LK, Serdula MK, Seymour JD, Tohill BC, et al. Low-energy-density diets are associated with high diet quality in adults in the United States. J Am Diet Assoc. 2006; 106:1172–1180. [PubMed: 16863711]
45. United States Department of Agriculture, Agricultural Research Service. What we eat in America. 2011
46. Wright, JD.; Kennedy-Stephenson, J.; Wang, CY.; McDowell, MA.; Johnson, CL. Trends in Intake of Energy and Macronutrients -- United States, 1971–2000. In: National Center for Health Statistics. , editor. Center for the Control of Diseases. 2004. p. 80-82.
47. Oza-Frank R, Cheng YJ, Narayan KM, Gregg EW. Trends in nutrient intake among adults with diabetes in the United States: 1988-2004. J Am Diet Assoc. 2009; 109:1173–1178. [PubMed: 19559133]
48. Gross LS, Li L, Ford ES, Liu S. Increased consumption of refined carbohydrates and the epidemic of type 2 diabetes in the United States: an ecologic assessment. Am J Clin Nutr. 2004; 79:774–779. [PubMed: 15113714]
49. U.S. Department of Agriculture. Loss-adjusted food availability. Economic Research Service. , editor. 2011.
50. King DE, Mainous AG, Lambourne CA. Trends in Dietary Fiber Intake in the United States, 1999-2008. J Acad Nutr Diet. 2012; 112:642–648. [PubMed: 22709768]
51. International Bottled Water Association. Beverage Marketing 2008 Market Report Findings. 2008
52. Heller KE, Sohn W, Burt BA, Eklund SA. Water consumption in the United States in 1994-96 and implications for water fluoridation policy. J Public Health Den. 1999; 59:3–11.
53. Duffey KJ, Popkin BM. Shifts in patterns and consumption of beverages between 1965 and 2002. Obesity. 2007; 15:2739–2747. [PubMed: 18070765]
54. Kissileff HR. Effects of physical state (liquid-solid) of foods on food intake: procedural and substantive contributions. Am J Clin Nutr. 1985; 42:956–965. [PubMed: 4061368]
55. de Graaf C. Why liquid energy results in overconsumption. Proceedings of the Nutrition Society. 2011; 70:162–170. [PubMed: 21356139]
56. Siegel JA, Urbain J-L, Adler LP, Charkes ND, Maurer AH, Krevsky B, et al. Biphasic nature of gastric emptying. Gut. 1988; 29:85–89. [PubMed: 3343018]
57. Hulshof T, De Graaf C, Weststrate JA. The effects of preloads varying in physical state and fat content on satiety and energy intake. Appetite. 1993; 21:273–278. [PubMed: 8141598]
58. Porrini M, Crovetti R, Riso P, Santangelo A, Testolin G. Effects of physical and chemical characteristics of food on specific and general satiety. Physiol Behav. 1995; 57:461–468. [PubMed: 7753882]
59. Tournier A, Louis-Sylvestre J. Effect of the physical state of a food on subsequent intake in human subjects. Appetite. 1991; 16:17–24. [PubMed: 2018401]
60. Houchins JA, Burgess JR, Campbell WW, Daniel JR, Ferruzzi MG, McCabe GP, et al. Beverages and solid fruits and vegetables: effects on energy intake and body weight. Obesity. 2012; 20:1844–1850. [PubMed: 21720441]
61. Ebbeling CB, Feldman HA, Osganian SK, Chomitz VR, Ellenhoren SJ, Ludwig DS. Effects of decreasing sugar-sweetened consumption on body weight in adolescents: a randomized, controlled pilot study. Pediatrics. 2006; 117:673–680. [PubMed: 16510466]
62. Gillis LJ, Bar-Or O. Food away from home, sugar-sweetened drink consumption and juvenile obesity. J Am Coll Nutr. 2003; 22:539–545. [PubMed: 14684760]
63. Troiano RP, Briefel RR, Carroll MD, Bialostosky K. Energy and fat intakes of children and adolescents in the united states: data from the national health and nutrition examination surveys. Am J Clin Nutr. 2000; 72:1343S–1353S. [PubMed: 11063476]
64. Stunkard AJ, Messick S. The three-factor eating questionnaire to measure dietary restraint, disinhibition and hunger. J Psychosom Res. 1985; 29:71–83. [PubMed: 3981480]
65. Hill AJ, Blundell JE. Nutrients and behaviour: research strategies for the investigation of taste characteristics, food preferences, hunger sensations and eating patterns in man. J Psychiatr Res. 1982; 17:203–212. [PubMed: 6764938]
66. Romanov SA, Guilmette RA, Khokhryakov VF, Phipps A, Aladova EE, Bertelli L, et al. Comparison of dose estimation from occupational exposure to 239Pu using different modelling approaches. Radiat Prot Dosimetry. 2007; 127:486–490. [PubMed: 18045798]
67. Flood-Obbagy JE, Rolls BJ. The effect of fruit in different forms on energy intake and satiety at a meal. Appetite. 2009; 52:416–422. [PubMed: 19110020]
68. Rolls BJ, Drewnowski A, Ledikwe JH. Changing the energy density of the diet as a strategy for weight management. J Am Diet Assoc. 2005; 105:98–103. [PubMed: 15635353]
69. Shintani TT, Hughes CK, Beckham S, O’Connor HK. Obesity and cardiovascular risk intervention through the ad libitum feeding of traditional Hawaiian diet. Am J Clin Nutr. 1991; 53:1647S–1651S. [PubMed: 2031501]
70. Epstein LH, Paluch RA, Beecher MD, Roemmich JN. Increasing healthy eating vs. reducing high energy-dense foods to treat pediatric obesity. Obesity. 2008; 16:318–326. [PubMed: 18239639]
71. Lanza E, Schatzkin A, Daston C, Corle D, Freedman L, Ballard-Barbash R, et al. Implementation of a 4-y, high-fiber, high-fruit-and-vegetable, low-fat dietary intervention: results of dietary changes in the Polyp Prevention Trial. Am J Clin Nutr. 2001; 74:387–401. [PubMed: 11522565]
72. Greene LF, Malpede CZ, Henson CS, Hubbert KA, Heimburger DC, Ard JD. Weight maintenance 2 years after participation in a weight loss program promoting low-energy density foods. Obesity. 2006; 14:1795–1801. [PubMed: 17062810]
73. Pierce JP, Natarajan L, Caan BJ, Parker BA, Greenberg ER, Flatt SW, et al. Influence of a diet very high in vegetables, fruit, and fiber and low in fat on prognosis following treatment for breast cancer: the Women’s Healthy Eating and Living (WHELP randomized trial. JAMA. 2007; 298:289–298. [PubMed: 17635889]
74. Smith-Warner SA, Elmer PJ, Tharp TM, Fosdick L, Randall B, Gross M, et al. Increasing vegetable and fruit intake: randomized intervention and monitoring in an at-risk population. Cancer Epidemiol Biomarkers Prev. 2000; 9:307–317. [PubMed: 10750670]
75. Whybrow S, Harrison CL, Mayer C, James Stubbs R. Effects of added fruits and vegetables on dietary intakes and body weight in Scottish adults. Br J Nutr. 2006; 95:496–503. [PubMed: 16512935]
76. Djuric Z, Poore KM, Depper JB, Uhley VE, Lababidi S, Covington C, et al. Methods to increase fruit and vegetable intake with and without a decrease in fat intake: compliance and effects on body weight in the nutrition and breast health study. Nutr Cancer. 2002; 43:141–151. [PubMed: 12588694]
77. DellaValle DM, Roe LS, Rolls BJ. Does the consumption of caloric and non-caloric beverages with a meal affect energy intake? Appetite. 2005; 44:187–193. [PubMed: 15808893]
78. Wolfe BM. Effects of gastro-entero-pancreatic hormones upon triglyceride synthesis and secretion by rat hepatocytes. Clin Invest Med. 1992; 15:30–41. [PubMed: 13492747]
79. Slavin JL. Position of the American Dietetic Association: health implications of dietary fiber. J Am Diet Assoc. 2008; 108:176–1731. [PubMed: 18953766]
80. Iyer SS, Boaeng LA, Sales RL, Coelho SB, Lokko P, Monteiro JB, et al. Effects of peanut oil consumption on appetite and food choice. Int J Obes. 2006; 30:704–710.
81. McKiernan F, Houchins JA, Mattes RD. Relationships between human thirst, hunger, drinking, and feeding. Physiol Behav. 2008
82. Mattes R. Fluid calories and energy balance: the good, the bad, and the uncertain. Physiol Behav. 2006; 89:66–70. [PubMed: 16516935]
FIGURE 1. Acute hunger ratings measured as the percentage of 100mm visual analog scale used
Lunch intervention × treatment × BMI group interaction (p=0.030, n=34)
Acute hunger ratings were presented as the mean percentage of VAS scale before and after
fruit preloads and hourly subsequently until 10 PM on lunch visit days.
FIGURE 2. Longer-term hunger and fullness ratings, measured as the percentage of 100mm visual analog scale used, at week 1, 6, and 9 of intervention period

(A) Hunger and (B) Fullness ratings at baseline, week 6, and at final week 9 No treatment or group effects were found.

Hunger was measured for 34 human participants in a randomised-crossover trial (8-weeks for each study arm). The lean (n=15) and overweight/obese (n=19) groups were purposefully recruited and were compared to test our primary hypothesis. Data collected between 10 AM-10 PM were used for analysis.
TABLE 1

Approximate energy and macronutrient content of preload

| Fruit          | Mass (g) | Energy (kcal) | Carbohydrate (g) | Protein (g) | Fat (g) | Soluble Fibre * (g) |
|----------------|----------|---------------|-------------------|-------------|---------|---------------------|
| Raw apple      | 154      | 80            | 21.3              | 0.4         | 0.3     | 1.1                 |
| Raw grapes     | 119      | 80            | 20.5              | 0.8         | 0.4     | 0.5                 |
| Dried apples   | 40       | 120           | 29.0              | 1.0         | 0       | 2.1                 |
| Raisins        | 37       | 120           | 28.7              | 0.9         | 0       | 0.4                 |
| Apple Juice    | 452      | 200           | 50.9              | 0           | 0       | 0                   |
| Grape Juice    | 317      | 200           | 49.3              | 0.7         | 0       | 4.0                 |

The solid and beverage preloads were matched on fruit type, energy, carbohydrate, and soluble fibre.

* Schankel et al. (78)

1 USDA National Nutrient Database for Standard Reference (61)

2 Food label on product
### TABLE 2

**Acute consumption data during beverage and solid preloads**

| Measurement                              | Beverage preload + macaroni | Beverage study without preload | Solid preload + macaroni | Solid study without preload |
|------------------------------------------|-----------------------------|--------------------------------|--------------------------|-----------------------------|
| Macaroni consumed (g)                    | 326±29*                     | 542±32                         | 186±28                   | 535±40                      |
| Satiety (minutes)                        | 290±30                      | 298±22                         | 270±22                   | 294±23                      |
| Energy intake at lunch (kcal)            | 891±43*                     | 785±47                         | 678±40                   | 821±53                      |
| Daily total energy intake (kcal)         | 2729±280                    | 2471±151                       | 2328±123                 | 2458±133                    |

Data were collected during two lunch visits prior to each intervention period (n=34).

Participants consumed a macaroni and cheese meal alone on the first visit (baseline), and a solid or beverage fruit/vegetable preload (intervention) before a macaroni and cheese meal on the second visit.

* *p*<0.0005 vs. solid preload + macaroni