Published in final edited form as:
Eur J Clin Nutr. 2009 December ; 63(12): 1411–1418. doi:10.1038/ejcn.2009.102.

Energy density of foods, but not beverages, is positively associated with body mass index in adult women

Heather L. Hartline-Grafton[1], **Donald Rose**[1], **Carolyn C. Johnson**[1], **Janet C. Rice**[2], and **Larry S. Webber**[2]

[1]Department of Community Health Sciences, Tulane University School of Public Health and Tropical Medicine, New Orleans, LA

[2]Department of Biostatistics, Tulane University School of Public Health and Tropical Medicine, New Orleans, LA

Abstract

Background/Objectives—Energy density (kJ/g) may have a strong influence on energy balance. Although beverages are a considerable source of energy in the US diet, rarely have studies among free-living populations investigated the energy density of foods (EDF) and the energy density of beverages (EDB) simultaneously. We examined the independent simultaneous associations of EDF and EDB on energy intake and Body Mass Index (BMI) in adult women.

Subjects/Methods—This cross-sectional design focused on 348 elementary school employees randomly selected at baseline of a worksite wellness trial in southeastern Louisiana. Two 24-hour recalls were collected, and measured heights and weights were converted into BMI (kg/m^2).

Results—Those in the highest EDF tertile consumed more energy and had higher BMIs than those in the lowest tertile ($P<0.05$). Employees in the highest EDB tertile consumed more energy than those in the lowest, yet there was no difference in BMIs between the two groups. Multivariate regression, with controls for demographic and health variables, confirmed the positive association between EDF and BMI; a 1 kJ/g increase in EDF was associated with a 0.39 kg/m^2 increase in BMI ($P=0.038$). Models that did not control for EDB gave estimates of EDF that were 8% to 10% lower.

Conclusions—These findings suggest that EDF and EDB play important, yet distinct, roles in energy intake and BMI. Future studies should evaluate both types of energy density as independent predictors since our results suggest that EDB can confound the association of EDF with BMI.

Address correspondence to Donald Rose, Department of Community Health Sciences, Tulane University School of Public Health and Tropical Medicine, 1440 Canal Street, Suite 2301, New Orleans, LA 70112. Fax: 504-988-3540. Telephone: 504-988-5742. diego@tulane.edu..

HLH and DR contributed to the conception and design of the study. HLH was one of the three dietary interviewers and had primary responsibility for data analysis and manuscript preparation. DR, CCJ, and LSW provided contributions to manuscript preparation and overall study design. DR and JCR oversaw the data analysis.

CONFLICT OF INTEREST The authors declare no conflict of interest.

Keywords

energy density; energy intake

INTRODUCTION

Two-thirds of adults in the United States are overweight or obese, making this the most important nutrition problem in the country (Ogden et al, 2006). Despite a considerable amount of attention paid to this issue, professionals disagree about the type of diet that should be promoted for weight loss and maintenance. Low-fat and low-carbohydrate diets, in particular, each have been the focus of research efforts (Astrup et al, 2000; Nobel & Kushner, 2006; Willett, 2004). Growing evidence suggests, however, that energy density has a stronger influence on energy intake than any single macronutrient (Drewnowski et al, 2004).

Energy density, defined as the energy in a given weight of food and expressed as kilojoules per gram (kJ/g), ranges from 0 kJ/g to 37.7 kJ/g (0 to 9 kcal/g) (Drewnowski, 1998; Rolls et al, 2005a). Individuals tend to consume a consistent weight of food, thus selecting low-energy-dense over high-energy-dense foods could help people “feel full on fewer calories” (Rolls & Barnett, 2000). In fact, laboratory studies suggest that low-energy-dense foods reduce and high-energy-dense foods increase energy intake in the short-term (Drewnowski et al, 2004; Kral & Rolls, 2004; Rolls et al, 2006). Research suggests that this relationship is independent of the diet's macronutrient composition (Bell et al, 1998; Bell & Rolls, 2001; Poppitt & Prentice, 1996; Rolls et al, 1999). Laboratory study results have been confirmed by cross-sectional and longitudinal studies (Drewnowski et al, 2004; Kant & Graubard, 2005; Ledikwe et al, 2006b; Ledikwe et al, 2007; Stookey, 2001). Cross-sectional studies have provided mixed results, however, for energy density and weight, possibly because of differences in calculations of the energy density variable or because of confounding of age and energy expenditure (Drewnowski et al, 2004; Cox & Mela, 2000; Kant & Graubard, 2005; Ledikwe et al, 2006a; Marti-Henneberg et al, 1999; Stookey, 2001). Several longitudinal studies have found that low-energy-dense diets do promote weight loss (Ello-Martin, 2007; Ledikwe et al, 2007; Rolls et al, 2005b).

Although growing evidence exists that energy density is associated with energy intake and body weight, only a limited number of ecological studies have investigated energy density in the US, and just a few of these have investigated associations with Body Mass Index (BMI) (Kant & Graubard, 2005; Ledikwe et al, 2006a). Given the current high prevalence of obesity in most developed countries, more research is needed to evaluate energy density and its correlates. Moreover, researchers often investigate the energy density of foods (EDF), but exclude from their analysis the energy density of beverages (EDB) (Cox & Mela, 2000; Goris & Westerterp, 2000; Kant & Graubard, 2005; Ledikwe et al, 2005; Westerterp-Plantenga, 2004). Beverages supply a considerable amount of energy to the diet, so their exclusion from analysis represents a serious gap in the energy density literature (Duffey & Popkin, 2007). To address this gap, the current study investigated both EDF and EDB simultaneously, in particular, their associations with energy intake and BMI in a sample of adult women.

SUBJECTS AND METHODS

Study Sample

The sample for this study comes from a school-based worksite wellness trial, funded by the National Institutes of Health, and set in a suburban county of southeastern Louisiana (Webber et al, 2007). Data are cross-sectional and were collected at baseline of the intervention. From each of the 22 participating schools, 20 individuals were randomly selected for dietary interviews. The sample for this paper ($n = 348$) included all non-pregnant, non-lactating women with non-missing data on key analytic variables, who were not classified as underreporters. Individuals with reported energy intake below a 2.0 standard deviation (SD) cut-off of predicted energy were considered underreporters based on Huang and colleagues' method for identifying implausible reports of energy intake (Huang et al, 2005). Using this criterion, 11% of otherwise eligible women were classified as underreporters and were excluded from the analysis. Not all individuals had blood draws; data on glucose, insulin, and Table 6 results were based on a sub-sample ($N=307$).

Data Collection Methods and Procedures

All baseline measurements were conducted during the fall of 2006. The Tulane University Institutional Review Board approved protocols and participants provided voluntary written consent. During a physical examination, trained examiners measured height in duplicate to the nearest 0.1 cm using a portable stadiometer and weight in duplicate to the nearest 0.1 kg with a calibrated scale. Fasting blood samples were obtained from participants and analyzed using standard procedures for glucose (enzymatic procedure with Hitachi 902 Autoanalyzer) and insulin (radioimmunoassay with kit from Pharmacia Diagnostics). Insulin resistance was assessed using a homeostasis model assessment (HOMA-IR) equation given by:

$$\text{HOMA- IR}=(\text{FPI} \ \text{ X } \ \text{FPG})/22.5,$$

, where FPI is fasting plasma insulin (mU/l) and FPG is fasting plasma glucose (mmol/l) (Wallace et al, 2004).

Date-of-birth, race-ethnicity, gender, and tobacco use data were collected via self-report through short written surveys. Job category was collected from employee rosters provided by the school. Physical activity was measured by an ActiGraph uniaxial accelerometer (ActiGraph LLC, Pensacola, FL, USA), which participants were instructed to wear for seven complete days except while sleeping and during water activities. The ActiGraph data were converted into mean minutes of moderate-to-vigorous physical activity (MVPA) per day (Catellier et al, 2005).

Three trained registered dietitians administered in-person 24-hour dietary recalls on two non-consecutive days using the Nutrition Data System for Research (NDSR) (version 2006; University of Minnesota, Nutrition Coordinating Center, Minneapolis, MN, USA).

Participants were scheduled for one recall per week, with at least one day of data collection at each school on a Monday for recall of a weekend day.

NDSR, a computer-assisted software program with a food and nutrient database containing over 18,000 items, features the multiple-pass approach, thus providing multiple opportunities for respondents to recall consumed foods and beverages in order to reduce underreporting (Guenther et al, 1996). The study protocol provided standardized probes, prompts, and measurement aids to further reduce recall bias.

Definition of Key Variables

The variables of primary interest were energy density (independent variable) and BMI and energy intake (dependent variables). Energy (kJ), the percentage of energy from macronutrient sources, and total dietary fiber intake (g) were calculated from foods and beverages in the dietary recall. Measured height and weight were converted into BMI (kg/m^2), and the latter was used to classify participants as normal weight (BMI < 25.0 kg/m^2), overweight (BMI 25.0–29.9 kg/m^2), or obese (BMI ≥ 30.0 kg/m^2) (NHLBI, 1998).

Energy density of foods (EDF) and beverages (EDB) were calculated from the dietary recall data by: 1) coding items as a “food” or “beverage” according to the NCC Database Food Group IDs (e.g., beef, milk); and 2) calculating EDF and EDB per day for each participant by dividing the energy from food and beverages (kJ) by the weight of food and beverages (g), respectively. Table 1 provides information on the specific inclusion and exclusion criteria for these calculations and their rationale.

Statistical Analysis

Dietary analyses were based on mean intake per individual. For the 7.5% of participants ($n = 26$) who completed only one recall, data from this single recall were used in place of mean intake. T-tests and ANOVA were used to examine differences in EDF and EDB. Mean EDB was not distributed normally, therefore, statistical tests for EDB in Table 2 were based on log-transformed mean intakes (the natural log of 0.01 was added to mean EDB values to account for those with a mean EDB of 0 kJ/g). The same procedure (i.e. log-transformed means for inferential tests) was followed for HOMA-IR. Linear regression was used to test the independent associations of EDF and EDB on energy intake and BMI, while controlling for gender, race-ethnicity, age, job category (i.e., instructional or non-instructional staff), minutes of MVPA per day, smoking status (i.e., smoker or non-smoker), and insulin resistance (i.e., top tertile of HOMA-IR or not). All control variables were dichotomous indicator variables with the exception of age and physical activity which were continuous. The models used mean EDF and an indicator variable for a high EDB (in the highest tertile), since the distribution of EDB was highly skewed. Use of alternate specifications of EDB (i.e. logarithmic form or energy from beverages) yielded similar results. For comparison to other research, additional models were developed to test EDF-only and total energy density (i.e., kJ from all foods and beverages ÷ g weight of all foods and beverages). Statistical analyses were performed using SPSS software (version 14.0.1; SPSS Inc, Chicago, IL, USA).

RESULTS

Sample Characteristics

Most participants were between 30–59 years of age (mean age 47.4 years ± 10.6), White, and instructional personnel (Table 2). The mean BMI was 29.1 kg/m^2 (± 6.7) (not shown). Approximately 69% of the sample was overweight or obese, 91.1% ($n = 317$) was nonsmoking, and all were classified as sedentary (i.e., engaged in less than 30 minutes of daily MVPA) (not shown).

Characteristics of Diets Low, Medium, and High in Energy Density

Mean EDF and EDB are presented in Table 2. Total energy density was 2.68 kJ/g (± 0.88) (not shown). There were notable differences in EDF based on age and race-ethnicity. For example, the mean EDF was significantly ($P < 0.05$) higher for African-Americans compared to Whites. Tertile cutoffs were used to classify diets as low (tertile 1), medium (tertile 2), or high (tertile 3) for EDF (Table 3). Individuals in the low EDF tertile consumed significantly less energy, less energy from fat, more energy from protein and carbohydrate, and more fiber compared to those in the medium and highest tertiles. In fact, those consuming a diet low in EDF consumed 1507 fewer kJ than those with a diet high in EDF. In addition, compared to those in the highest tertile, those in the lowest tertile had a lower BMI and diets lower in EDB. There were no differences across EDF tertiles in fasting glucose, fasting insulin, or insulin resistance.

Table 4 presents dietary and BMI data by EDB tertiles. Compared to those in the highest tertile, individuals in the low EDB tertile consumed significantly less energy, more energy from fat and protein, less energy from carbohydrate and alcohol, more dietary fiber, and had diets lower in EDF. More specifically, those consuming a diet low in EDB consumed 1468 fewer kJ than those with a diet high in EDB. Although this difference in energy intake between the low and high EDB tertiles was about the same as the difference in intake between the low and high EDF tertiles, no BMI differences were observed among EDB tertiles. There were no differences across EDB tertiles in fasting glucose, fasting insulin, or insulin resistance.

Models of the Relationship between Energy Density and Energy Intake

Table 5 presents multiple linear regression models testing associations between energy intake and energy density. Energy Model 1 tested the independent associations of energy intake with mean EDF and the high EDB tertile when controlling for demographic and health characteristics. The additional models represent those commonly used in the literature (i.e., mean EDF-only, total energy density). For all of the energy models, energy density was a positive and significant predictor of energy intake. In Energy Models 1 and 2, a 1 kJ/g increase in mean EDF was associated with a 273 kJ or 306 kJ increase in energy intake, respectively. Being in the highest EDB tertile (i.e., consuming a diet high in EDB) was associated with a 1071 kJ greater energy intake. Note that the Adjusted R^2 value was lower in Energy Model 2, the only one of the three models that excluded beverages. Insulin resistance was not a significant predictor of energy in any of these models, nor did its inclusion significantly affect results reported here (not shown).

Models of the Relationship between Energy Density and BMI

Table 6 is similar to Table 5 except that the multiple linear regression models test associations between BMI and energy density and include a measure of insulin resistance. In BMI Model 1, a 1 kJ/g increase in mean EDF was associated with a significant 0.39 kg/m^2 increase ($P < 0.038$) in BMI. BMI Model 1 is the only model that tests the association of EDF with BMI while controlling for EDB. The coefficient on energy density in BMI Models 2 and 3 – which test other expressions of this variable commonly used in the literature – is lower than in BMI Model 1 by 10% and 8%, respectively. Insulin resistance, as measured by a high HOMA-IR, was positively ($P < 0.001$) related to BMI in all three models. Comparisons to models that excluded this variable showed similar results on the energy density variables, but revealed that models with insulin resistance explained over twice the variability in BMI as models without this variable.

DISCUSSION

This paper presents one of the few cross-sectional, ecological studies investigating the energy density of US diets and, to our knowledge, is the first to examine the independent simultaneous associations of EDF and EDB on energy intake and BMI. We found that EDF and EDB were positive predictors of energy intake. EDF was positively associated with BMI in regression models, but a diet high in EDB was related to a lower BMI. These findings suggest that energy densities of foods and beverages play distinct roles in energy intake and BMI among elementary school personnel.

Comparing dietary intake and BMI by tertiles of EDF and EDB offers insight into variables associated with energy density. High EDF diets (i.e., the highest EDF tertile) were associated with higher energy and fat intake, lower fiber intake, and higher BMI, which is consistent with previous research (Kant & Graubard, 2005; Ledikwe et al, 2006a). Low EDB diets (i.e., the lowest EDB tertile) were associated with lower energy intake as well as lower carbohydrate and alcohol intake, most likely because those consuming such diets were not drinking sweetened and/or alcoholic beverages that are more energy dense beverage choices.

Consistent with other cross-sectional research as well as the EDF tertile analysis, energy density was positively associated with energy intake and BMI in a variety of regression models that controlled for demographic and health behavior variables (Howarth et al, 2006; Ledikwe et al, 2007; Murakami et al, 2007; Stookey, 2001). For example, BMI Model 2 is similar to a model tested previously among a sample that used self-reported height and weight and food frequency questionnaire data (Howarth et al, 2006). In that study, a 1 kJ/g increase in EDF was associated with a significant increase of approximately 1 kg/m^2 in BMI across a variety of ethnic-sex groups (Howarth et al, 2006). These and other findings suggest that selecting low-energy-dense foods over high-energy-dense foods could reduce total energy intake and body weight while providing satisfying portions (Ello-Martin et al, 2007; Ledikwe et al, 2007; Rolls et al, 2005a). Portion size itself can also be an important independent factor contributing to energy intake. Research in the U.S. has documented an increase over time in marketplace food portions that roughly parallels the rise in obesity rates (Young and Nestle, 2002).

Beverages represent 21% of total daily energy intake in the American diet, yet few energy density studies in the US or abroad include a separate EDB calculation (Duffey & Popkin, 2007). Many authors exclude beverages altogether (Ledikwe et al, 2005; Ledikwe et al, 2006a). One of the only studies to investigate EDB independently concluded that EDB was not an important determinant of average daily energy intake (Westerterp-Plantenga, 2004). In the current multivariate models, however, consuming a diet high in EDB (which translates to a mean EDB > 0.67 kJ/g) was associated with a 1071 kJ greater energy intake ($P < 0.001$). However, being in the highest EDB tertile was associated with a 1.32 kg/m^2 lower BMI ($P = 0.080$), a relationship likely explained by reverse causality. As people gain weight, they often switch to low-energy-dense beverages (e.g., water, diet drinks) to lose weight or prevent further weight gain, thus a diet low in EDB might be a marker of overweight. BMI, of course, is not a direct measure of adiposity, so we are limited in the conclusions we can make regarding body composition and EDB. More studies, particularly longitudinal studies with additional measures, are needed to better understand the relationship between beverage energy density and weight status. From a public health perspective, it would also be of interest for future research to explore the association between EDF and the consumption of fruits and vegetables, or between EDB and soda drinks.

There is no consensus on how to calculate energy density, and it is apparent here that the methodology is very important. In the multivariate models, we followed the recommendation of Ledikwe and colleagues to include a variety of calculation methods as well as an EDF-only calculation (Ledikwe et al, 2005). We investigated EDF and EDB when analyzed simultaneously, an EDF-only calculation, and total energy density of the diet. For some items, grouping into a food or beverage category can be a challenge (e.g. liquid meal replacement), since this involves judgments by the investigator about the role of certain items in the diet as well as limited information from 24-recall data on the physical nature of foods as consumed. We have followed conventional techniques in our grouping, and have run models with various specifications to address this concern.

The importance of investigating EDF and EDB simultaneously is particularly evident in the BMI models. When EDB was omitted from a model predicting the relationship between EDF and BMI, the coefficient estimate on EDF fell from 0.39 kg/m^2 to 0.35 kg/m^2, or 10%. When beverages were combined with foods to calculate total energy density, the coefficient was 8% lower and not statistically significant. These results suggest that failure to control for the independent effects of EDB would result in an underestimation of the association between EDF and BMI. Along with EDF, future investigators should consider exploring EDB independently given the potential importance of this dietary variable on energy intake and BMI. Notwithstanding the importance of dietary factors, this research also demonstrates that biochemical factors, such as insulin resistance, have much greater explanatory power in predictions of body mass index.

The current research has a number of strengths, including the investigation of independent expressions of EDF and EDB, collection of objective physical activity, height, weight, and biochemical data, and use of a 24-hour dietary recall methodology. The latter was designed to minimize underreporting and we also removed underreporters using objective procedures.

The cutoff for exclusion of underreported energy intake was less stringent than in other studies; however, using a more stringent criterion of 1.5 SD in additional analyses did not alter the main outcomes.

Despite these strengths, the study has several limitations. The data were cross-sectional, thus we were unable to establish causality between energy density, energy intake, and BMI. In addition, no dietary intake data were collected for Friday or Saturday because interviews were scheduled during the school week. People tend to consume more energy, fat, and alcohol on the weekend (Friday-Sunday) than weekdays (Monday-Thursday) (Haines et al, 2003). Because fat and alcohol are the two most energy dense macronutrients, it is possible that the omission of Friday and Saturday intake could impact the results by underestimating EDF, EDB, and energy intake. However, we did obtain data on Sundays for close to half (44%) of our sample. Although sub-sample analysis on these individuals did reveal a slightly higher mean EDF (7.99 kJl/g versus 7.83 kJ/g), it did not change the relationships in our predictive models. Another potential limitation is the focus on a narrow sample – school employees from one state in the US. This group is relatively homogeneous compared to national samples, which could limit the generalizability of findings to other areas, as well as explain why the R^2 statistics in our regression models were somewhat low.

In conclusion, these findings suggest that diets lower in EDF are associated with lower BMI, lower energy and fat intake, and higher fiber intake. Elementary school personnel, like the general US population, have high rates of overweight and obesity. This trend might be reversed through health promotion efforts that encourage low-energy-dense foods such as fruits and vegetables. Longitudinal research would be especially useful in a further examination of the role of energy density in energy balance. The role of EDB on energy intake and BMI requires special attention in future studies as we observed it played a significant role in our prediction of the relationship between EDF and BMI.

ACKNOWLEDGEMENTS

This study was supported by a grant from the National Heart, Lung, and Blood Institute, National Institutes of Health (HL079509). We thank the ACTION school employees for their participation in the study, and gratefully acknowledge the contributions of the ACTION staff members to the data collection effort.

REFERENCES

Astrup A, Grunwald GK, Melanson EL, Saris WH, Hill JO. The role of low-fat diets in body weight control: a meta-analysis of ad libitum dietary intervention studies. Int. J. Obes. Relat. Metab. Disord. 2000; 24:1545–1552. [PubMed: 11126204]

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]

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]

Catellier DJ, Hannan PJ, Murray DM, Addy CL, Conway TL, Yang S, et al. Imputation of missing data when measuring physical activity by accelerometry. Med. Sci. Sports. Exerc. 2005; 37(Suppl, 11):S555–S562. [PubMed: 16294118]

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]

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

Drewnowski A, Almiron-Roig E, Marmonier C, Lluch A. Dietary energy density and body weight: is there a relationship? Nutr. Rev. 2004; 62:403–413. [PubMed: 15622713]

Duffey KJ, Popkin BM. Shifts in patterns and consumption of beverages between 1965 and 2002. Obesity (Silver Spring). 2007; 15:2739–2747. [PubMed: 18070765]

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]

Goris AH, Westerterp KR. Improved reporting of habitual food intake after confrontation with earlier results on food reporting. Br. J. Nutr. 2000; 83:363–369. [PubMed: 10858694]

Guenther PM, DeMaio TJ, Ingwersen LA, Berlin M. The multiple-pass approach for the 24-h recall in the Continuing Survey of Food Intakes by Individuals. FASEB. J. 1996; 10:A198. (abstract).

Haines PS, Hama MY, Guilkey DK, Popkin BM. Weekend eating in the United States is linked with greater energy, fat, and alcohol intake. Obes. Res. 2003; 11:945–949. [PubMed: 12917498]

Howarth NC, Murphy SP, Wilkens LR, Hankin JH, Kolonel LN. Dietary energy density is associated with overweight status among 5 ethnic groups in the multiethnic cohort study. J. Nutr. 2006; 136:2243–2248. [PubMed: 16857848]

Huang TT, Roberts SB, Howarth NC, McCrory MA. Effect of screening out implausible energy intake reports on relationships between diet and BMI. Obes. Res. 2005; 13:1205–1217. [PubMed: 16076990]

Kant AK, Graubard BI. Energy density of diets reported by American adults: association with food group intake, nutrient intake, and body weight. Int. J. Obes. (Lond). 2005; 29:950–956. [PubMed: 15917854]

Kral TV, Rolls BJ. Energy density and portion size: their independent and combined effects on energy intake. Physiol. Behav. 2004; 82:131–138. [PubMed: 15234601]

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]

Ledikwe JH, Blanck HM, Khan LK, 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. 2006a; 83:1362–1368. [PubMed: 16762948]

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. 2006b; 106:1172–1180. [PubMed: 16863711]

Ledikwe JH, Rolls BJ, Smiciklas-Wright H, Mitchell DC, Ard JD, Champagne C, et al. Reductions in dietary energy density are associated with weight loss in overweight and obese participants in the PREMIER trial. Am. J. Clin. Nutr. 2007; 85:1212–1221. [PubMed: 17490955]

Marti-Henneberg C, Capdevila F, Arija V, Perez S, Cuco G, Vizmanos B, et al. Energy density of the diet, food volume and energy intake by age and sex in a healthy population. Eur. J. Clin. Nutr. 1999; 53:421–428. [PubMed: 10403576]

Murakami K, Sasaki S, Takahashi Y, Uenishi K. Dietary energy density is associated with body mass index and waist circumference, but not with other metabolic risk factors, in free-living young Japanese women. Nutrition. 2007; 23:798–806. [PubMed: 17936194]

Mustad VA, Jonnalagadda SS, Smutko SA, Pelkman CL, Rolls BJ, Behr SR, et al. Comparative lipid and lipoprotein responses to solid-food diets and defined liquid-formula diets. Am. J. Clin. Nutr. 1999; 70:839–846. [PubMed: 10539744]

National Heart, Lung, and Blood Institute. Clinical guidelines on the identification, evaluation, and treatment of overweight and obesity in adults: the evidence report. NIH Publication. 1998; 98-4083

Noble CA, Kushner RF. An update on low-carbohydrate, high-protein diets. Curr. Opin. Gastroenterol. 2006; 22:153–159. [PubMed: 16462172]

Ogden CL, Carroll MD, Curtin LR, McDowell MA, Tabak CJ, Flegal KM. Prevalence of overweight and obesity in the United States, 1999–2004. Jama. 2006; 295:1549–1555. [PubMed: 16595758]

Poppitt SD, Prentice AM. Energy density and its role in the control of food intake: evidence from metabolic and community studies. Appetite. 1996; 26:153–174. [PubMed: 8737167]

Rolls, BJ.; Barnett, RA. The volumetrics weight-control plan: Feel full on fewer calories. HarperCollins Publishers; New York, NY: 2000.

Rolls BJ, Bell EA, Castellanos VH, Chow M, Pelkman CL, Thorwart ML. Energy density but not fat content of foods affected energy intake in lean and obese women. Am. J. Clin. Nutr. 1999; 69:863–871. [PubMed: 10232624]

Rolls BJ, Bell EA, Thorwart ML. Water incorporated into a food but not served with a food decreases energy intake in lean women. Am. J. Clin. Nutr. 1999; 70:448–455. [PubMed: 10500012]

Rolls BJ, Drewnowski A, Ledikwe JH. Changing the energy density of the diet as a strategy for weight management. J. Am. Diet. Assoc. 2005a; 105:S98–S103. [PubMed: 15867904]

Rolls BJ, Roe LS, Beach AM, Kris-Etherton PM. Provision of foods differing in energy density affects long-term weight loss. Obes. Res. 2005b; 13:1052–1060. [PubMed: 15976148]

Rolls BJ, Roe LS, Meengs JS. Reductions in portion size and energy density of foods are additive and lead to sustained decreases in energy intake. Am. J. Clin. Nutr. 2006; 83:11–17. [PubMed: 16400043]

Stookey JD. Energy density, energy intake and weight status in a large free-living sample of Chinese adults: exploring the underlying roles of fat, protein, carbohydrate, fiber and water intakes. Eur. J. Clin. Nutr. 2001; 55:349–359. [PubMed: 11378808]

Wallace TM, Levy JC, Matthews DR. Use and abuse of HOMA modeling. Diabetes Care. 2004; 27:1487–1495. [PubMed: 15161807]

Webber LS, Johnson CC, Rose D, Rice JC. Development of ACTION! Wellness Program for Elementary School Personnel. Obesity (Silver Spring). 2007; 15(Suppl, 1):48S–56S. [PubMed: 18073341]

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

Willett WC. Dietary fat plays a major role in obesity: no. Obes. Rev. 2002; 3:59–68. [PubMed: 12120421]

Young LR, Nestle M. The contribution of expanding portion sizes to the US obesity epidemic. Am J Public Health. 2002; 92:246–249. [PubMed: 11818300]

TABLE 1

Energy density calculations and items classified as foods or beverages

Calculation	**Items Classified as Foods or Beverages**
EDF = kJ from food ÷ g of food	Solid, semi-solid, and liquid items consumed as foods or added to foods[2] (e.g., soups, yogurt, smoothies, milkshakes[3], sauces, gravy, milk on cereal); liquid meal replacements[4]
EDB = kJ from beverages ÷ g of beverages	Milk, juice, alcoholic beverages, coffee, tea, soda, and water not added to foods; foods added to beverages[2] (e.g., sugar in coffee)

[1] For purposes of these calculations, items were classified as either a food or a beverage, but not both.

[2] Results of a controlled feeding study suggest that water consumed as a beverage with food has less of an impact on total energy intake than water consumed as part of the food (Rolls et al, 1999); therefore, any liquid added to a food (e.g., milk on cereal) was considered a part of the food. Similarly, a food added to a beverage (e.g., sugar to coffee) was counted as part of the beverage.

[3] Milkshakes were grouped with ice cream, ice milk, sherbet, and nondairy frozen desserts in the NDSR Database Food Group IDs and, therefore, were considered a “food” for this analysis. Milkshakes were not frequently consumed.

[4] Liquid meal replacements were considered a “food” because they are often consumed in place of food, have similar nutrient composition as solid foods, and may be as satiating as solid foods (Mustad etal, 1999).

TABLE 2

Demographic characteristics and the mean energy density of foods and beverages among adult female study participants

	n	%	Energy Density of Foods (kJ/g)			Energy Density of Beverages (kJ/g)		
			$\bar{x}$	± SD	p[1]	$\bar{x}$	± SD	p[1]
All	348	n/a	7.82	1.88	n/a	.54	.42	n/a
Age group								
< 30 years	23	6.6	8.16	1.81		.56	.37	
30–39 years	75	21.6	8.42	2.09		.60	.42	
40–49 years	87	25.0	7.98	1.71	0.002[2]	.51	.46	0.349
50–59 years	127	36.5	7.37	1.72		.53	.40	
≥ 60 years	36	10.3	7.57	2.04		.54	.41	
Race-ethnicity[3]								
White	277	79.6	7.73	1.86		.51	.40	
African-American	63	18.1	8.37	1.94	0.016	.68	.49	0.068
Hispanic	8	2.3	6.60	.96		.48	.18	
Job category								
Instructional	283	81.3	7.83	1.91		.55	.41	
Non-instructional	65	18.7	7.78	1.79	0.831	.54	.43	0.761
Weight status								
Normal weight	108	31.0	7.54	2.05		.55	.42	
Overweight	103	29.6	7.76	1.84	0.062	.58	.45	0.799
Obese	137	39.4	8.10	1.74		.51	.39	

[1] T-tests (two groups) or ANOVA (three or more groups) were performed. Because mean energy density of beverages (EDB) was not normally distributed, statistical tests for EDB were based on log-transformed means.

[2] LSD multiple comparison tests indicate that 30–39 year olds had diets significantly higher in energy density of foods (EDF) compared to 50–59 year olds (*P* < 0.001) and those over 60 (*P* = 0.023), and 40–49 year olds had significantly higher EDF than 50–59 year olds (*P* = 0.018).

[3] Comparisons by race-ethnicity were performed for Whites and African-Americans only.

TABLE 3

Dietary intake, insulin resistance, and body mass index (BMI) by tertiles of energy density of foods (EDF) among adult female study participants[1]

	EDF Tertile 1 (*n* = 116)	**EDF Tertile 2 (*n* = 116)**	**EDF Tertile 3 (*n* = 116)**	**P**[2]
EDF (kJ/g)	5.81 ± 0.76	7.74 ± 0.47	9.92 ± 1.16	n/a
EDB (kJ/g)	0.47 ± 0.38^{a}	0.53 ± 0.37	0.63 ± 0.48^{b}	0.013
Energy (kJ)	7064 ± 1683^{a}	7752 ± 1598^{b}	8571 ± 2508^{c}	<0.001
% energy from fat	30.4 ± 6.7^{a}	35.5 ± 6.2^{b}	37.8 ± 6.8^{C}	<0.001
% energy from carbohydrate	52.7 ± 8.7^{a}	48.4 ± 8.6^{b}	48.1 ± 9.2^{b}	<0.001
% energy from protein	17.4 ± 3.9^{a}	16.1 ± 3.4^{b}	14.0 ± 3.7^{c}	<0.001
% energy from alcohol	1.6 ± 4.4	1.4 ± 3.6	1.5 ± 4.8	0.916
Total dietary fiber (g)	17.2 ± 5.7^{a}	13.9 ± 4.3^{b}	13.2 ± 4.8^{b}	<0.001
Fasting glucose (mg/dl)[3]	91.4 ± 26.2	93.3 ± 25.0	90.3 ± 34.5	0.741
Fasting insulin (mU/l)[3]	9.8 ± 11.8	10.7 ± 7.9	12.2 ± 13.1	0.307
Insulin resistance (HOMA-IR)[3]	2.55 ± 4.13	2.66 ± 2.47	2.73 ± 3.12	0.454
BMI (kg/m^{2})	27.8 ± 5.7^{a}	29.4 ± 6.7	30.1 ± 7.4^{b}	0.031

[1] All values are $\bar{x}$ ± SD.

[2] ANOVA was used to compare individuals within the three EDF tertiles. Means with different superscripts in a row are significantly different *(P* < 0.05) based on LSD post hoc tests.

[3] Laboratory values for fasting glucose and fasting insulin and the calculated value of insulin resistance, HOMA-IR, were only available for a sub-sample (N=307).

Table 4

Dietary intake and body mass index (BMI) by tertiles of energy density of beverages (EDB) among adult female study participants[1]

	EDB Tertile 1 (*n* = 116)	**EDB Tertile 2 (*n* = 116)**	**EDB Tertile 3 (*n* = 116)**	**P**[2]
EDB (kJ/g)	0.14 ± 0.09	0.47 ± 0.10	1.02 ± 0.32	n/a
EDF (kJ/g)	7.51 ± 1.90^{a}	7.71 ± 1.82^{a}	8.25 ± 1.85^{b}	0.008
Energy (kJ)	7179 ± 1704^{a}	7561 ± 1816^{a}	8647 ± 2335^{b}	<0.001
% energy from fat	36.2 ± 7.8^{a}	34.7 ± 7.5^{a}	32.8 ± 6.1^{b}	0.001
% energy from carbohydrate	48.0 ± 9.4^{a}	48.9 ± 9.3^{a}	52.3 ± 7.9^{b}	0.001
% energy from protein	17.0 ± 3.7^{a}	16.4 ± 3.9^{a}	14.1 ± 3.6^{b}	<0.001
% energy from alcohol	0.5 ± 1.6^{a}	1.8 ± 3.8^{b}	2.3 ± 6.0^{b}	0.003
Total dietary fiber (g)	15.7 ± 5.4^{a}	15.0 ± 5.1	13.7 ± 5.1^{b}	0.013
Fasting glucose (mg/dl)[3]	95.1 ± 37.2	90.4 ± 27.9	89.5 ± 18.4	0.308
Fasting insulin (mU/l)[3]	10.8 ± 12.7	10.2 ± 8.8	11.7 ± 11.9	0.597
Insulin resistance (HOMA-IR)[3]	2.76 ± 4.27	2.47 ± 2.64	2.71 ± 2.98	0.802
BMI (kg/m^{2})	29.3 ± 6.3	29.2 ± 6.9	28.9 ± 6.9	0.913

[1] All values are $\bar{x}$ ± SD.

[2] ANOVA was used to compare individuals within the three EDB tertiles. Means with different superscripts in a row are significantly different *(P* < 0.05) based on LSD post hoc tests.

[3] Laboratory values for fasting glucose and fasting insulin and the calculated value of insulin resistance, HOMA-IR, were only available for a sub-sample (N=307).

TABLE 5

Energy intake associations with energy density of foods (EDF) and energy density of beverages (EDB) among adult female study participants

	Energy Model 1		Energy Model 2		Energy Model 3	
Independent Variables	**b**[1]	**P**	**b**	**P**	**b**	**P**
EDF (kJ/g)	+273.07	<0.001	+306.10	<0.001	-	-
High EDB tertile	+1070.86	<0.001	-	-	-	-
Total energy density (kJ/g)	-	-	-	-	+979.39	<0.001
African-American	+21.61	.938	+214.72	.447	−112.95	.680
Hispanic	−208.90	.763	−383.57	.591	−442.60	.514
Age (years)	−10.98	.277	−10.07	.334	−10.11	.304
Instructional staff	−68.68	.800	−54.46	.846	−143.68	.590
Physical activity (minutes)	−21.29	.543	−29.94	.406	−7.06	.838
Smoker	+79.72	.829	+377.17	.315	+619.45	.083
Constant	+5899.34	<0.001	+5896.78	<0.001	+5735.11	<0.001
Adjusted R^2	0.138		0.084		0.168	

[1] Values are unstandardized beta coefficients from multiple regression analysis, N=348.

TABLE 6

Body mass index (BMI) associations with energy density of foods (EDF) and energy density of beverages (EDB) among adult female study participants

	BMI Model 1		BMI Model 2		BMI Model 3	
Independent Variables	**b[1]**	**P**	**b**	**P**	**b**	**P**
EDF (kJ/g)	+0.39	.038	+0.35	.065	-	-
High EDB tertile	−1.28	.091	-	-	-	-
Total energy density (kJ/g)	-	-	-	-	+0.36	.396
African-American	+2.55	.009	+2.32	.016	+2.38	.015
Hispanic	−1.66	.443	−1.45	.501	−1.69	.434
Age (years)	+0.00	.959	+0.00	.929	−0.01	.715
Instructional staff	−1.26	.160	−1.27	.157	−1.31	.146
Physical activity (minutes)	−.34	.002	−0.33	.003	−0.33	.003
Smoker	+0.01	.991	−0.34	.770	−0.13	.913
High insulin resistance tertile	+5.41	<.001	+5.41	.001	+5.36	<.001
Constant	+25.83	<0.001	+25.89	<0.001	+28.09	<0.001
Adjusted R^2	0.242		0.237		0.230	

[1] Values are unstandardized beta coefficients from multiple regression analysis, N=307.