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High fat and sugar consumption during ad libitum intake predicts weight gain

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Abstract

Objective—To determine how macronutrients accompanying high-EnDen foods affect energy intake and weight gain.

Methods—214 subjects(130 males, BMI:32 ± 7 kg/m^2) ate *ad libitum* for 3-days. Food intake was expressed as mean daily intake(kcal) and percentage of weight-maintaining energy needs(%WMEN). EnDen was expressed as the ratio of intake(kcal) to food weight(g). Food choices were expressed as absolute and percent intake(kcal), categorized as high(HF; ≥45% kcal) or low in fat(LF; <20% kcal) and further categorized as high in complex-carbohydrates(HCC; ≥30% kcal), simple-sugars(HSS; ≥30% kcal), or protein(HP; ≥13% kcal). 99 subjects had follow-up weights(65m, range:6months-11yrs).

Results—EnDen was associated with BMI(r= .28, p<.0001), %body fat(r=.18, p=.007), and percent intake from HF/HP(r=.34, p <.0001), HF/HSS(r=.31, p< .0001), LF/HP (r=−.37, p<.0001) and LF/HSS(r=−.68, p< .0001). %WMEN was associated with EnDen(r=.16, p=.01), HF/HSS (r=.33, p<.0001) and LF/HP intake(r=−.25, p=.0002). In a multivariate model, only HF/HSS intake remained a significant predictor of %WMEN(β=1.4% per 1% change, p<.0001). Percent intake from HF/HSS(r=.23, p=.02), not EnDen(p=.54), was associated with weight gain, even after adjusting for follow-up time(yrs) and covariates.

Conclusions—Relatively greater consumption of HF/HSS foods independently predicted overeating and weight gain. Nutrient compositions of high-EnDen foods may be important for weight management.

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Author contributions
E.S. analyzed and interpreted data and wrote the manuscript. S.V., P.P., and J.K. assisted with the interpretation of the data, and revised the manuscript. M.I. and C.V. supported with the interpretation of the data and reviewed the manuscript. S.V. and J.K. designed, implemented and conducted the study. All authors read and approved the final manuscript. All authors critically revised the draft and approved the final manuscript. E.S. had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis

Keywords

Obesity; sugar; high-fat diet; energy density

Introduction

The wide availability of palatable and low cost energy-dense foods may be a catalyst for increased energy intake and the increasing prevalence of obesity [1]. Recent studies have shown that manipulating energy density (EnDen), a measure of calories per gram of food [2], is associated with increased energy intake [3] and subsequent weight gain [4]. Thus, EnDen has been implicated as an important factor in weight management [5, 6].

EnDen values of macronutrients range from 0 kcal/g (water) to 9 kcal/g (fat). Water content within foods accounts for some of the variability in EnDen values, although it provides no energy. Due to its high energy content, fat influences EnDen more than carbohydrates and protein [7, 8]. Thus, it has been proposed that targeting fat content would lead to lower energy intake [9]. One study used three different methods to lower EnDen 1) decreased fat content 2) increased fruit/vegetable intake, or 3) increased water content). All led to reductions in intake but intake was reduced the most by decreasing fat content (mean 396 kcal/day reduction) compared to increased fruit/vegetable or water intake[10]. However, other studies have reported that diets high in EnDen were associated with increased energy intake regardless of the dietary' macronutrient composition [4]. That is, high-energy dense foods whether due to high carbohydrate or high fat content had the same effect on energy intake. Furthermore, when macronutrient composition of diets is kept constant [11], higher energy dense diets led to overconsumption of food. Thus, whether manipulation of EnDen through macronutrient composition is sufficient to alter energy intake and subsequent weight is unclear.

While there is evidence linking EnDen with longer term energy intake and subsequent weight gain, the majority of studies have examined short-term changes in energy intake (at the current or subsequent meal) with prior or concurrent manipulation of EnDen [12, 13]. Furthermore, in the longer-term studies, reporting of ingestion of high fat foods, which tend to be high in EnDen, is often underreported [14]. The aim of the current study was to use an objectively acquired measure of EnDen via an ad libitum automated vending machine paradigm to investigate associations between EnDen and nutrient composition, with measures of adiposity. Furthermore, we hypothesized that higher EnDen would be associated with increased weight gain and this association would be driven by high energy dense food groups.

Methods

Two-hundred-fourteen individuals age 18-65 (BMI range: 18-52) without diabetes were recruited from the greater Phoenix area to participate in a larger study assessing eating behaviors and food preferences as risk factors for obesity (Clinical Trial Identifier: NCT00342732). Racial groups included the following: 127 Native Americans of Southwestern heritage, 41 Whites, 12 Hispanics, 10 Blacks, and 14 participants of mixed ethnicity. Prior to participation, all subjects were informed of the nature, purpose and risks of the study and written informed consent was obtained. The protocol was approved by the Institutional Review Board of the NIDDK. All subjects were found to be healthy based on medical history, physical examinations, and laboratory tests. Any evidence of acute or chronic disease was basis for exclusion from participation in the study.

Upon admission to the Obesity and Diabetes Clinical Research Unit (Phoenix, AZ), subjects were fed a weight maintaining diet with a macronutrient distribution of 50% carbohydrate, 30% fat and 20% protein for 3-5 days prior to ad libitum food consumption. Weight maintenance calories were calculated for each subject based on weight, gender and BMI, as previously described [15]. Body composition was determined by dual energy x-ray absorptiometry (DXA, LUNAR Prodigy, GE). Subjects underwent an oral glucose tolerance test (OGTT) to confirm non-diabetic status on day 3 of admission.

Follow-up visits

Data from return visits or from re-enrollment into other studies on our research unit with assessment of body composition measures was used to assess changes in adiposity over time. Subjects' last available return or re-enrollment visit was used as follow-up.

Vending Machine Paradigm

Ad libitum food intake was measured using automated vending machines, as previously described [16–18]. Previous studies on our unit have shown high reproducibility in intra-person energy intake pattern during repeated visits [16]. This method provides a highly accurate assessment of energy intake for persons confined in a research unit. After admission to the metabolic ward, subjects completed an eighty-item Food Preferences Questionnaire (FPQ) containing typical breakfast, lunch, dinner, and snack items as described by Geiselman et al [19]. Subjects were asked to rate their preference for a wide variety of foods on a 9-point Likert scale. Forty different foods given an intermediate rating were used to stock the vending machines for ad libitum food intake. These 40 foods were available each of the three days along with condiments (Supplementary Fig. S1). Subjects were given free access to the machines for 23.5 hours with thirty minutes per day needed to re-stock the machine. The machines are computer operated and require a unique code given to each subject for access. The machines record the time of day each food was accessed. This data is then imported into Food Processor SQL Edition (version 10.0.0, ESHA Research) or the CBORD Professional Diet Analyzer Program (version 4.1.11, CBORD Inc, Ithaca, NY), which provide calories and macronutrient content of the foods (Supplementary Figure S1). EnDen (kcal/g) was calculated as the average calories consumed over the 3-days of ad libitum feeding divided by the weight (g) of food eaten per day. Weights of foods were taken from Food Processer and CBORD output. In order to correct for actual food intake, the metabolic kitchen staff weighed food leftovers which were returned by the individuals. Beverage consumption was included in the EnDen calculations.

Macronutrient Categories

Each food on the vending questionnaire was categorized into one of six groups (Supplementary Figure S2), based on the macronutrient content as a percentage of the total energy. Foods were categories as high in fat (≥45% kcal) or low in fat (<20% kcal) and then further categorized as being high in complex carbohydrates (≥30% kcal), high in simple sugars (≥30% kcal), or high in protein (≥13% kcal). These categorizations produced six different groups of food: high-fat/high-complex carbohydrate (HF/HCC), high-fat/high-protein (HF/HP), high-fat/high-simple sugar (HF/HSS), low-fat/high-complex carbohydrate (LF/HCC), low-fat/high-protein (LF/HP), and low-fat/high-simple sugar (LF/HSS) [19]. The raw energy intake (kcal) from each food group was further converted to percentage of total energy intake.

Statistical Analysis

Statistical analysis was done using SAS (Version 9.3) and SAS Enterprise Guide (Version 5.1). Alpha was set at 0.05 for all analyses. Normally distributed data is presented as means ± standard deviation, while non-parametric data is presented as median (Interquartile rage [IQR]). Gender and racial differences for anthropometric data was assessed using Student's *t* tests and differences between categorical variables were analyzed using chi-squared tests. There were no differences between Whites, Hispanics, Blacks, and Other (n = 87) thus we combined these individuals to compare Native Americans (n = 127) to all other racial groups. EnDen is reported as the average calories eaten over 3 vending days divided by the average food weight eaten over the same 3 days. Differences in absolute average daily energy intake from each of the 6 groups and percent daily energy intake from each food group were assed using analysis of variance (ANOVA). Analysis of covariance (ANCOVA) was used to assess absolute average daily energy intake form each of the 6 groups adjusted for total average daily energy intake. Post-hoc pair-wise comparisons with Bonferroni adjustments were used for significant outcomes. Differences in baseline values between subjects with and without follow-up data were analyzed using Student's *t* test. Pearson correlation coefficients were used to assess relationships between normally distributed variables, and Spearman correlation coefficients were used for skewed data. Change in weight was assessed by calculating the difference between baseline and follow-up weight. Thus, a positive change in weight is representative of weight gain. Multivariate linear models were used to control for age, sex, and race in the cross-sectional analysis and for age, sex, race, and follow-up time in the longitudinal analysis.

Results

Subject characteristics are shown in Table 1. Men had lower percent body fat, fat mass ($p < .0001$), BMI, and higher fat free mass. Men had higher energy intakes and overate a larger percent of their weight maintaining calories. Native Americans had higher percent body fat ($p = .001$), fat mass ($p = .01$), tended to be younger ($p = .05$), and had higher energy intakes ($p = .02$). The average percent weight maintenance (%WMEN) calories was 148%, suggesting the majority of individuals overate on the vending machine paradigm which is consistent with the literature [16, 19]. %WMEN was calculated by dividing the total average calories by weight maintenance energy needs (WMEN) and expressed as a percent.

In the cross-sectional analyses EnDen was positively associated with weight (r = .23, $p = .0008$), BMI (r = .28, $p > .0001$), percent body fat (r = .18, $p = .007$), FM (r = .23, $p = .0007$), FMI (r = .24, p = .0005), FFM (r = .15, p = .03) and FFMI (r = .26, p = .0002). These relationships remained unchanged after adjustment for age, sex and race. EnDen was positively correlated with percent daily energy intake from HF/HP (r = .34, p < .0001; Fig. 1A) and HF/HSS (r = .31, p < .0001; Fig. 1B) and negatively correlated with the percent daily energy intake from LF/HP (r = −.37, p <.0001; Fig. 1C) and LF/HSS (r = −.68, p < .0001; Fig. 1D). There were no associations with HF/HCC (r = .10, p = .14) and LF/HCC (r = −.02, p = .75). These relationships were still significant after adjustments for age, sex, and race. Similar associations were found for absolute daily energy intake from the 6 food groups as well as with absolute food intake from each group adjustment for total daily energy intake. EnDen (r = .16, p = .01) and percent intake from HF/HSS (r = .33, p < .0001) were also positively associated with %WMEN while percent intake from LF/HP was negatively associated with %WMEN (r = −.25, p = .0002). Percent intake from HF/HP (r = .03, p = .64) and LF/HSS (r = −.10, p = .15) were not associated with %WMEN. In a multivariable linear model containing age, sex, race, EnDen, percent intake from HF/HSS and percent intake from LF/HP, only percent intake from HF/HSS (β = 1.4% per 1% change in HF/HSS, 95% CI [0.76–2.1], p < .0001) remained a significant predictor of %WMEN.

ANOVA revealed significant differences in absolute daily energy (kcal/d) consumed from the 6 food groups (p < .0001; Fig. 2). Post-hoc pair-wise comparisons with Bonferroni adjustments reported the highest daily energy intake was from the HF/HP food group (M = 1141, 95% CI [1097, 1185]). Individuals ate relatively similar amounts of energy from the HF/HSS (M = 770, 95% CI [726, 815]) and LF/HSS (M = 715, 95% CI [671, 760]) as well as similar amounts from the HF/HCC (M = 538, 95% CI [485, 591]) and LF/HP food groups (M = 439, 95% CI [394, 482]). The lowest daily energy intake was from the LF/HCC food group (M = 318, 95% CI [274, 362]). Results were identical for the ANCOVA model using absolute energy intake from each food group adjusted for total average daily energy intake.

There were significant differences in percent daily energy consumed from the 6 food groups (p <.0001). Post-hoc pair-wise comparisons with Bonferroni adjustments reported the highest percent of daily energy intake was from the HF/HP food group (M = 27.5%, 95% CI [26.5, 28.6]). Individuals ate relatively similar amounts of energy from the HF/HSS (M = 17.4%, 95% CI [16.3, 18.5]) and LF/HSS (M = 17.8%, 95% CI [16.8, 18.9]) food groups as well as similar amounts from the HF/HCC (M = 12.7%, 95% CI [11.7, 13.8]) and LF/HP food groups (M = 11.3%, 95% CI [10.3, 12.4]). The lowest percent daily energy intake was from the LF/HCC food group (M = 8.4%, 95% CI [7.4, 9.5]).

Ninety-nine subjects had follow-up data available. In a comparative analysis between subjects with follow-up data and subjects without follow-up data, there were no significant differences on continuous or categorical variables (Table 2). EnDen itself (r = .06, p = .54), %WMEN (r = .07, p = .48), as well as the absolute daily energy intake from all 6 food groups (*p-values* > .05) were not associated with change in weight. However, absolute daily energy intake from the HF/HSS food group adjusted for total daily energy intake approached significance with weight gain (r = .19, p = .06). Similarly, energy intake from those who ate a greater percentage of their calories from the HF/HSS food group gained more weight (years) (r = .23, p = .02; Fig. 3). In a multivariate linear model with weight change as the dependent variable, adjusted for age, sex, race, and follow-up time, percentage of calories from the HF/HSS food group predicted weight gain (β = 0.18 kg per 1% change in HF/HSS, 95% CI [0.03, 0.33], $p = .03$, $\eta^2 = .06$). Results using the absolute calories from the HF/HSS food group adjusted for total daily calories instead of expressed as a percentage resulted in similar results (β = 0.4 kg per 100 kcal change in HF/HSS, 95% CI [0.001, 0.008], $p = .03$ $\eta^2 = .06$). Results did not change with adjustment for baseline weight (date not shown).

Discussion

In the current study, we show that intake from HF/HSS foods, rather than EnDen, independently predicts overeating and weight gain. Individuals who consumed foods with greater overall EnDen had higher adiposity, consumed a greater proportion of energy(kcal) from HF/HP and HF/HSS food groups and consumed a lower proportion of energy from LF/HP and LF/HSS food groups. Although EnDen and intake from HF/HSS food groups were both associated with overeating, in a model containing all significant predictors of overeating adjusted for age, sex, and race only intake from HF/HSS food groups remained significant. Furthermore, in a longitudinal analysis, relatively greater consumption from HF/HSS foods but not EnDen predicted weight gain. These findings indicate that the nutrient composition of energy dense foods rather than EnDen itself may be more important for weight management.

Our results broaden existing knowledge of EnDen to free-living conditions in a research unit, using ad libitum conditions utilizing an objective measure of energy intake [19]. This ad libitum vending machine system has been shown to be valid and highly reliable within individuals during repeated trials [16, 19, 20]. In contrast, other research has examined intake using less reliable measures such as, self-reported dietary intake or 24-hour food recalls which leads to underreporting of energy intake and biased food reports[21–23]. Furthermore, our utilization of 6 different nutrient mixtures allowed us to identify a potential mechanism by which energy dense foods may drive caloric intake. The positive association between intake from HF/HP and HF/HSS and the inverse association from LF/HP and LF/HSS food groups with EnDen supports fat content as an important factor determining EnDen [4]. However, only intake from HF/HSS food groups predicted overeating (%WMEN) and weight gain. Thus, although we found associations between EnDen and adiposity measures, it was the specific nutrient mix of high-energy dense food (i.e. HF/HSS) which determined both overeating and weight gain and thus indicating a mechanism by which energy dense foods may drive caloric intake.

The current study builds upon existing literature which suggests the quality of the nutrient mix of fat and sugar intake adversely affects energy intake through reward mechanisms [10, 24]. Neuroimaging studies have found that both high-fat and high-sugar food activate reward areas within the brain [25]. Rodent models have found that rats fed high fat and high sugar diets are motivated to obtain sugar rewards even when satiated [26]. Furthermore, studies examining energy intake report that sugar is associated with overeating due to its desirable sweet taste [27, 28], as well as its association with impaired cognitive function [29]. Specifically, high fat and sugar intake is related to poorer hippocampal function which leads to less accurate memories of prior food intake as well as reduced hunger and satiety signals.

Thus, our finding that HF/HSS food associated with greater energy intake and predicted weight gain is consistent with previous studies.

Some limitations of the current study should be acknowledged. First, the vending machine paradigm is an artificial environment with no limitations or barriers to food consumption which leads to facilitation of overeating. However, the vending machine paradigm yields greater reliability of food intake compared to traditional self-report assessments [16, 30]. Secondly, our longitudinal analysis did not include everyone who was studied. However, there were no significant differences between those who had follow-up and those who did not. Thirdly, the average BMI at baseline and follow-up was in the obese range (≥ 30 kg/m^2) which may have led to biases in the associations between adiposity measures and EnDen.

Conclusion

In summary, we demonstrated that EnDen is associated with higher levels of adiposity, greater relative consumption of HF/HP and HF/HSS foods, and lower consumption of LF/HP and LF/HSS foods. EnDen and consumption of relatively larger percentage HF/HSS foods were associated with overeating. However, in adjusted models only percent intake from HF/HSS foods predicted overeating. In longitudinal analysis, greater consumption of HF/HSS foods specifically, rather than overall EnDen, %WMEN, or other high energy dense food groups (i.e. HF/HP), predicted weight gain. Thus, within foods with greater EnDen, overall nutrient composition appears to be important in determining overeating and weight gain.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Sources of support

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Study Important Questions

What is already known about this subject?

- Energy density (EnDen) of food has been associated with increased energy intake and subsequent weight gain.
- EnDen is primarily determined by fat content due to its high energy content (9 kcal/g).

What does this study add?

- EnDen was associated with higher levels of adiposity and greater consumption of high fat/high protein and high fat/high simple sugar foods as assessed using a highly reliable and valid ad libitum vending machine paradigm.
- A larger proportion of energy consumed from high fat/high simple sugar foods rather than EnDen predicted overeating.
- Greater relative consumption of high fat/high simple sugar foods independently predicted weight gain.

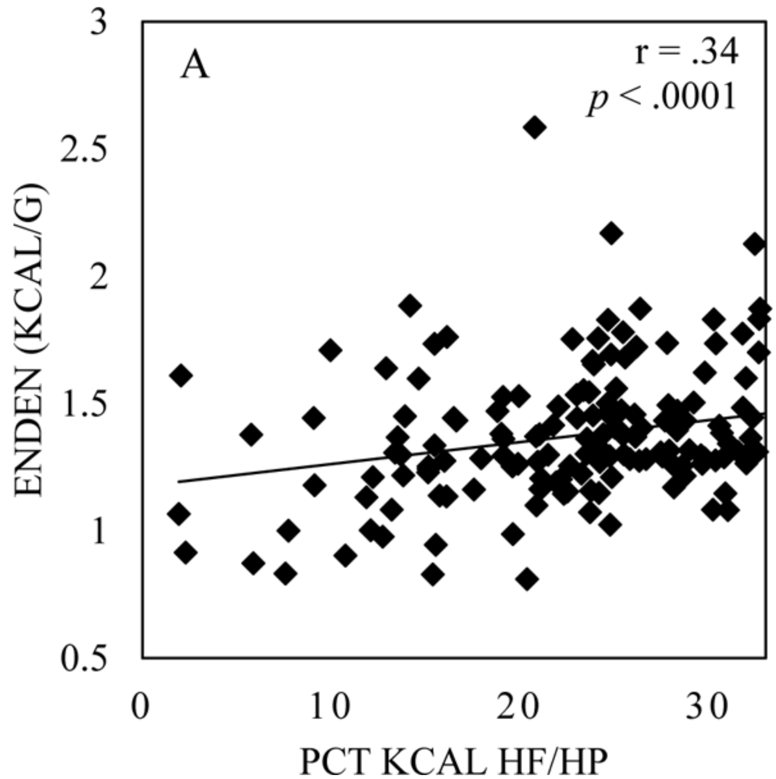

Fig. 1A.
Baseline correlations between energy density (kcal/g) and percent daily energy intake from the (A) HF/HP food group.

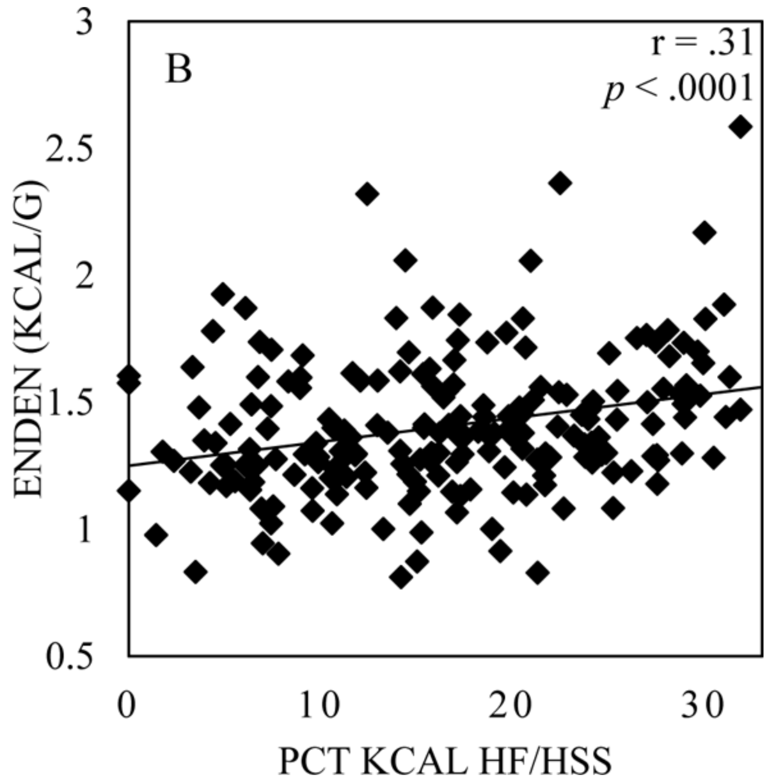

Fig. 1B.

Baseline correlations between energy density (kcal/g) and percent daily energy intake from the (B) HF/HSS food group.

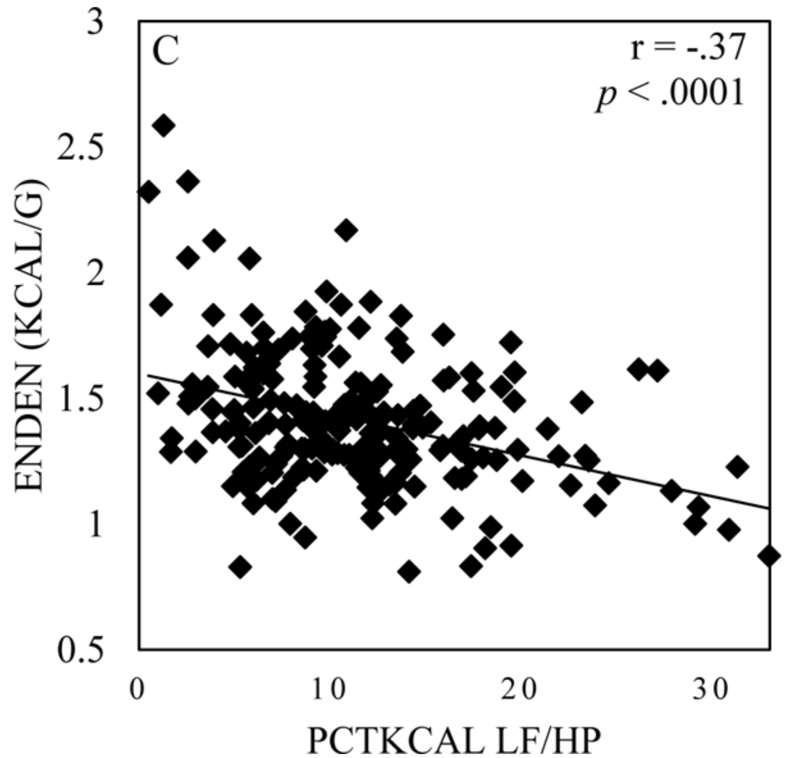

Fig. 1C.

Baseline correlations between energy density (kcal/g) and percent daily energy intake from the (C) LF/HP.

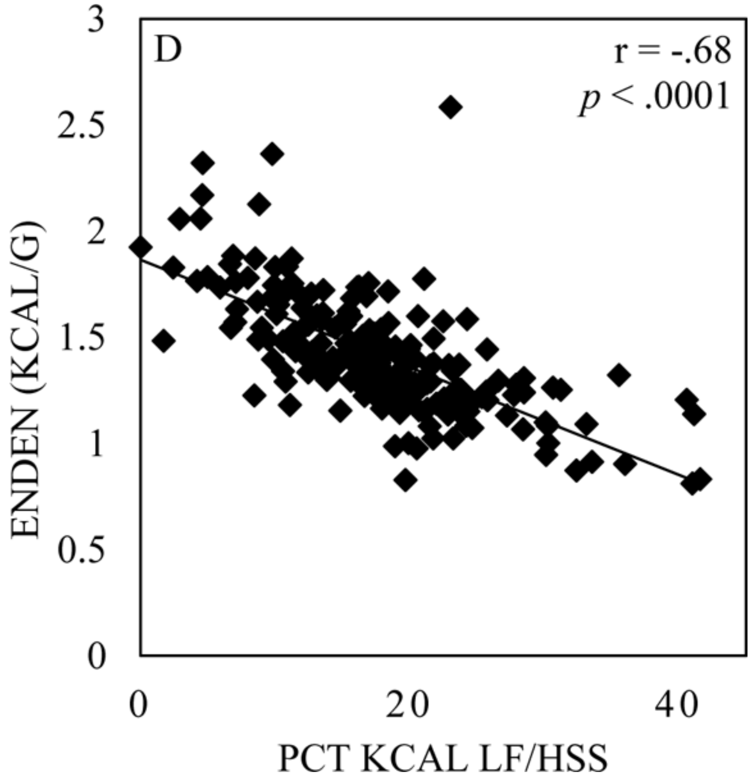

Fig. 1D.

Baseline correlations between energy density (kcal/g) and percent daily energy intake from the (D) LF/HSS food group.

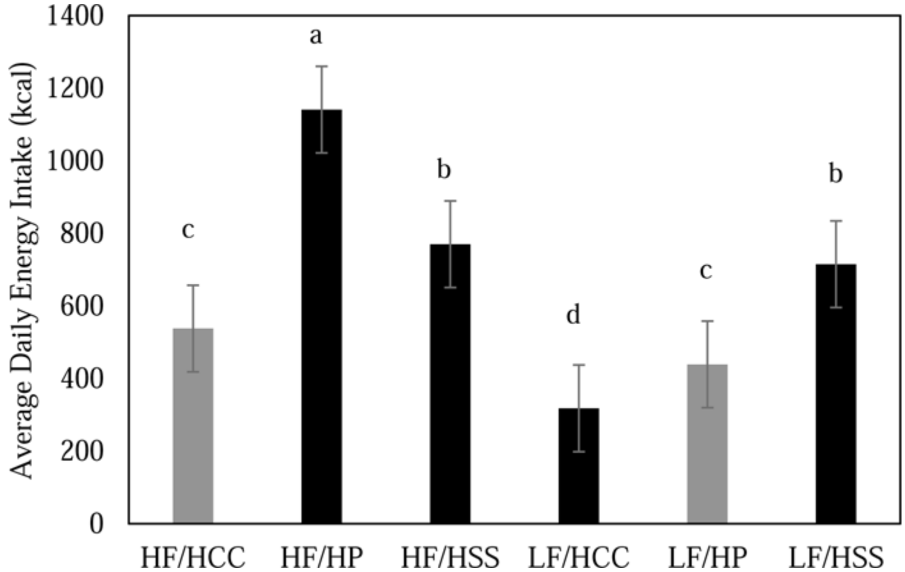

Fig. 2.

Mean energy intake (kcal) by food group. Means with different letters were significantly different ($p < .05$) as assessed with Bonferroni adjustment for multiple comparisons.

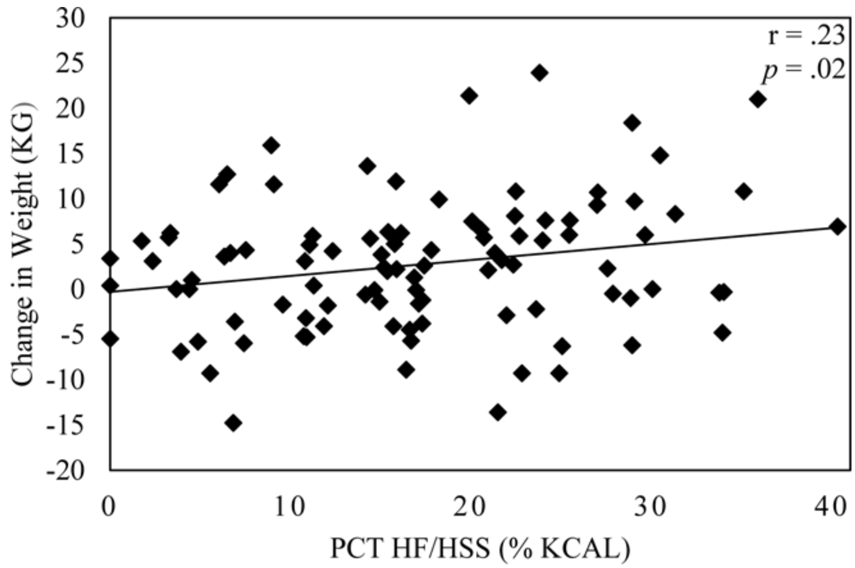

Fig. 3.

Association between change in weight (kg) and percent daily energy intake from the HF/HSS food group. Unadjusted Pearson correlation coefficient is shown. Adjusted (age, sex, race, FU time) Pearson correlation coefficient (r = .23, p = .02).

Table 1

Participant Demographics

Variable	All	Male	Female
N	214	130	84
Race	127 NA; 87 O	71 NA; 59 O	56 NA; 28 O
Age	35 ± 9	35 ± 9	34 ± 9
Weight (kg)	90 ± 21	92 ± 20	87 ± 22
BMI (kg/m^2) *	32 ± 7	30 ± 6	34 ± 8
Percent Body Fat (%) *	31 ± 9	26 ± 7	38 ± 6
FM (kg) *	29 ± 12	25 ± 11	34 ± 12
FMI (kg/m^2) *	10 ± 5	8 ± 3	13 ± 5
FFM (kg) *	61 ± 13	67 ± 11	53 ± 10
FFMI (kg/m^2) *	21 ± 4	22 ± 3	20 ± 4
Fasting glucose concentration (mg/dL)	91 ± 8	91 ± 8	92 ± 8
2-hour glucose concentration (mg/dL)	125 ± 29	121 ± 27	129 ± 29
Energy Density (kcal/g)	1.4 ± 0.3	1.4 ± 0.2	1.4 ± 0.3
Energy Intake (kcal) *	4108 ± 1369	4540 ± 1265	3440 ± 1258
Food Weight (g)	2967 ± 984	3281 ± 901	2480 ± 909
PWMEN (%)	148 ± 46	158 ± 41	132 ± 48
% HF/HCC	12 ± 8	13 ± 8	13 ± 7
%HF/HP	28 ± 11	28 ± 10	27 ± 11
%HF/HSS	17 ± 9	18 ± 9	17 ± 10
%LF/HCC	8 ± 6	8 ± 5	9 ± 7
%LF/HP	11 ± 6	11 ± 6	11 ± 7
%LF/HSS	18 ± 7	18 ± 7	18 ± 8

NA=Native American; O=Other

FM=Fat Mass; FMI=Fat Mass Index; FFM=Fat-Free Mass; FFMI=Fat-Free Mass Index; HF=High Fat; HCC=High Complex Carbohydrate; HP=High Protein; HSS=High Simple Sugar; LF=Low Fat

Mean ± Standard Deviation

*Sex differences, $p < .05$

Table 2

Follow-Up Demographics

Variable	Baseline	Follow-Up
N	214	99
Sex	130m; 84f	65m; 34f
Race	127 NA, 87 O	62 NA, 37 O
Age	35 ± 9	35 ± 9
Weight (kg)	90 ± 21	89 ± 21
Weight Change (kg)	.	2.7 ± 7.3
Follow-up time (days)	.	858 (384, 1613)
BMI (kg/m2)	32 ± 7	31 ± 7
Percent Body Fat (%)	31 ± 9	29 ± 9
FM (kg)	29 ± 12	27 ± 13
FMI (kg/m^2)	11 ± 4	10 ± 5
FFM (kg)	61 ± 13	62 ± 12
FFMI (kg/m^2)	21 ± 4	21 ± 4
Fasting glucose concentration (mg/dL)	91 ± 8	92 ± 8
2-hour glucose concentration (mg/dL)	125 ± 29	123 ± 28
Energy Density (kcal/g)	1.4 ± 0.3	1.4 ± 0.3
Energy Intake (kcal)	4108 ± 1369	4243 ± 1355
Energy Volume (g)	2967 ± 984	3044 ± 925
PWMEN (%)	148 ± 46	154 ± 46
% HF/HCC	12 ± 8	13 ± 8
%HF/HP	28 ± 11	27 ± 9
%HF/HSS	17 ± 9	17 ± 9
%LF/HCC	8 ± 6	8 ± 6
%LF/HP	11 ± 6	11 ± 6
%LF/HSS	18 ± 7	18 ± 7

NA=Native American; O=Other

FM=Fat Mass; FMI=Fat Mass Index; FFM=Fat-Free Mass; FFMI=Fat-Free Mass Index; HF=High Fat; HCC=High Complex Carbohydrate; HP=High Protein; HSS=High Simple Sugar; LF=Low Fat

Mean ± Standard Deviation

*Sex differences, $p < .05$