Published in final edited form as:
Nutr Cancer. 2012 ; 64(5): 666–673. doi:10.1080/01635581.2012.676143.

LOW GLYCEMIC LOAD EXPERIMENTAL DIET MORE SATIATING THAN HIGH GLYCEMIC LOAD DIET

Kevin T. Chang[1], **Johanna W. Lampe**[2,3], **Yvonne Schwarz**[2], **Kara L. Breymeyer**[2], **Karen A. Noar**[2], **Xiaoling Song**[2], and **Marian L. Neuhouser**[2,3]

[1]School of Medicine, University of Washington, Seattle, WA

[2]Cancer Prevention Program, Fred Hutchinson Cancer Research Center, Seattle, WA

[3]Interdisciplinary Graduate Program in Nutritional Sciences and Department of Epidemiology, University of Washington, Seattle, WA

Abstract

Effective strategies for reducing food intake are needed to reduce risk of obesity-related cancers. We investigated the effect of low and high-glycemic load (GL) diets on satiety and whether satiety varied by BMI, gender, and serum leptin. 80 normal weight (BMI=18.5-24.9 kg/m^2) and overweight/obese (BMI=28.0-40.0 kg/m^2) adults participated in a randomized, cross-over controlled feeding study testing low-GL vs. high-GL diets. The 28-day diets were isocaloric with identical macronutrient distributions, differing only in GL and fiber. Participants completed visual analog satiety surveys and fasting serum leptin after each 28-day period. T-tests compared mean within- and between-person satiety scores and leptin values. Participants reported 7% greater satiation on the low-GL vs. the high-GL diet (p=0.03) and fewer food cravings on the low-GL vs. the high-GL diet (p<0.001). Compared to males, females reported less hunger (p=0.05) and more satiety on the low-GL vs. the high-GL diet (p<0.01). Participants with low body fat (<25.0% for men; <32.0% for women) and BMI < 25.0 kg/m^2 reported study food was tastier on the low-GL vs. the high-GL diet (p=0.04 and p=0.05, respectively). In summary, reducing GL, and/or increasing fiber, may be an effective way to lower calories consumed, improve energy balance and ultimately reduce cancer risk.

Keywords

glycemic index; glycemic load; obesity; cross-over studies

INTRODUCTION

Growing evidence suggests states of energy imbalance, such as obesity, the resulting hyperinsulinemia and insulin resistance are serious risk factors for several chronic diseases, including cardiovascular disease, diabetes and cancer [1-8]. Increased body weight has also been shown to be associated with higher rates of death from cancer and other chronic diseases [5]. For example, 14% of deaths from cancer in men and 20% of deaths from cancer in women can be attributed to excess body weight [5]. Closely linked with obesity and excess body weight is insulin resistance, which animal and human studies have demonstrated to be correlated with colorectal cancer [6]. Diabetes mellitus, a disease characterized by an abnormal insulin response, has also been associated with increased risk

Corresponding Author: Marian L Neuhouser, PhD, RD, Cancer Prevention Program, Fred Hutchinson Cancer Research Center, 1100 Fairview Avenue North, M4-B402, Seattle, WA 98109, Tel: 206-667-4797, Fax: 206-667-7850, mneuhous@fhcrc.org.

of cancer [7]. The carcinogenic effects of hyperinsulinemia/insulin resistance are possibly due to the mitogenic, proliferative, and anti-apoptotic signals that insulin-induced production of insulin-like growth factor-I stimulates in epithelial cells [2, 3]. Furthermore, metabolic syndrome, a state characterized by a collection of conditions with insulin resistance as the underlying pathophysiology, has been shown to be linked with high rates of colorectal and prostate cancer, as well as the recurrence of breast cancer [8].

With nearly two thirds of adult Americans either overweight [body mass index (BMI) = 25.0-29.9 kg/m^2] or obese (BMI ≥ 30.0 kg/m^2), the link between energy balance and cancer is clearly a pressing one to investigate further, since the potential number of people affected is high [9]. It is thus crucial to understand how energy imbalances are created and how they can be ameliorated if we are to gain a better understanding of this facet of cancer prevention. One of the main determinants of the body's energy state is the point at which one reaches satiation during a meal and the duration of the satiety. Increasing satiety levels could help with both reducing the amount of total food eaten as well as normalizing the body's insulin/glucose response. One determinant of satiety is a food's Glycemic Index (GI) [10]. GI is a measure of the ability of a food to raise blood glucose levels in relation to a dose of white bread or glucose. High GI foods rapidly increase blood glucose and insulin responses following ingestion while low GI foods attenuate the postprandial glucose and insulin responses. Glycemic load (GL) is the overall glycemic effect of a diet or diet pattern and is adjusted for the amount of available carbohydrate [11]. Numerous studies comparing glycemic responses and changes in hunger, satiety, and energy intake suggest that low-GI foods increase satiety and decrease hunger [12, 13, 14]. Some studies even found lower voluntary energy intake in response to eating low-GI foods [15].

GI is also a measure of the body's glucose-insulin response and GL is the overall glycemic effect of a diet pattern. The higher the food's GI, the greater the rise in blood glucose and insulin following ingestion, i.e. foods with a high GI, such as bread made with white flour, are broken down quickly releasing high levels of glucose and eliciting a greater insulin response. Foods with low GI, such as whole grains, are broken down more slowly releasing lower levels of glucose and eliciting a lower insulin response [16]. Dietary patterns with sustained high GL, and thus a high glucose and insulin response, may be one of the sources of the metabolic abnormalities that have become increasingly prevalent [17].

The aim of this study is to investigate whether GL influences satiety, and whether personal characteristics, such as gender, ethnicity, BMI, and body fat percentage have additional influences on these relationships. We hypothesize that a low-GL meal pattern will result in greater satiation compared to a high-GL meal pattern in the context of an experimental feeding study.

METHODS

Study design

This study was a randomized, crossover feeding study, designed to study the effects of low GL vs. high GL in a highly controlled, mixed diet. The intervention periods were four weeks each, separated by a four week washout period during which participants consumed their own foods. As a cross-over study, participants completed both study arms and diet sequence assignment was determined randomly. This trial is registered at Clinicaltrials.gov identifier: NCT00622661.

Subjects

We recruited 82 men and premenopausal women, 18-45 years of age, with the use of flyers, newspaper announcements, and other informational materials in clinics, colleges and

universities, churches, and other organizations throughout Seattle, WA. We used block randomization to recruit an equal number of men and women as well as an equal number of subjects who were normal weight (BMI = 18.5-24.9 kg/m^2) and overweight or obese (BMI=28.0-40.0 kg/m^2) BMI. Since the intent was to obtain sufficient contrast of the experimental diet response of normal weight with the overweight/obese group, we excluded those at the lower end of the overweight distribution (BMI=25.0-27.9 kg/m^2). We also excluded those with BMI <18.5 and >40.0 kg/m^2 because persons outside this range frequently have metabolic conditions that would have precluded study participation. We employed additional efforts to recruit minority participants, especially Hispanics and African-Americans, two minority groups with high levels of obesity by the use of advertisements on radio stations and publications targeted to the respective communities, and working with organizations that serve these communities. All participants self-identified their race/ethnicity. Exclusion criteria included: (1) current physician-diagnosed disease that required certain medications or dietary restrictions or modifications, including but not limited to, diabetes mellitus, kidney disease, and cardiovascular disease; (2) impaired glucose tolerance (defined as fasting blood glucose > 100 mg/dL measured at a screening visit; (3) BMI between 25.0-27.9 kg/m^2 and BMI of less than 18.5 kg/m^2 or over 40.0 kg/m^2; (4) current or planned pregnancy or lactation; (5) use of any hormonal treatments, cessation of menses; (6) cancer diagnosis or treatment within the previous five years; (7) restrained eating habits using the three-factor eating scale administered at a screening clinic visit; (8) current use of tobacco or alcohol (greater than or equal to 2 drinks per day); (9) or the inability or unwillingness to consume the foods on the feeding study protocol (18). The study protocol was reviewed and approved by the Fred Hutchinson Cancer Research Center Institutional Review Board and all participants signed written informed consent.

Dietary intervention

All foods and beverages for the two study periods were prepared in the Human Nutrition Laboratory at the Fred Hutchinson Cancer Research Center. We used a 7-day menu cycle so each day's menu was consumed four times on each 28-day feeding period (Table 1). Participants ate dinner at our study center every weekday evening and were given breakfast, lunch and snack for the following day (or for two days if on a Friday). Food intake was tracked with a Monitored Daily Intake Record (MDIR), which is a check-off list where participants indicate which study foods they consumed in their entirety. Any extra food or beverage consumed was recorded, and any uneaten food was returned to the center, where it was measured and documented. The diets were isocaloric and the total kcals provided were individually calculated based on usual intake from a baseline 3-day food record plus baseline weight, height and usual physical activity so as to maintain weight stability for each participant. High-GL and low-GL diets were designed to provide overall GLs of 250 and 125, respectively. Both diets provided 55% of total energy from carbohydrate, 30% from fat and 15% from protein. While study foods were not explicitly chosen based on fiber, but rather on glycemic index, the low and high GL diets differed by fiber, possibly because many low GI foods are also high in fiber. Thus, fiber was higher on the low GL diet (55 g/day) than the high GL diet (28 g/day). The GI values for the individual food items were derived from Foster-Powell and Brand-Miller and the total carbohydrate was considered in the calculation of GL [19]. All dry, frozen, and fresh food was purchased from the same vendor/producer to minimize variability. HACCP standards of food handling and quality control were followed.

Anthropometry

We assessed participants' weight, height, hip and waist circumferences and body composition at the beginning of the study. We measured participant weight to the nearest 0.5 kg at baseline and thrice weekly with a calibrated digital platform scale and we measured

their height at baseline to the nearest 0.5 cm with a wall-mounted stadiometer. We used a fiberglass tape (Becklee, Inc, Stratford, CT) to measure body circumferences to the nearest 0.5 cm. We assessed participants' lean mass, fat mass, and bone mass using dual energy X-ray absorptiometry (DXA, GE Lunar DPX-Pro) at the beginning of the study.

Measurement of Satiety

Participants completed a Food Rating Questionnaire at the beginning and end of each four-week feeding period. This questionnaire has been validated and asks participants to rate their feelings of hunger, fullness, food tastiness, nausea, thirst, and food cravings on a 9 point scale, with (1) representing "not hungry," "not full," etc, and (9) representing "extremely hungry," "extremely full" [20]. We included one question on food cravings; each participant recorded the food(s) they were craving and to rate the strength of their craving (1 = no craving and 9 = extreme craving). The survey was a visual analog scale.

Leptin Analysis

After an overnight fast, morning blood samples were collected from all participants on the first day of each feeding period and the morning after the end of each feeding period. For these analyses we used the measures from the last day of each feeding period to coincide with the satiety questionnaire. We assayed serum leptin concentrations by Human Leptin ELISA (Millipore, Inc., Billerica, MA). Blind duplicates were included in each batch to determine inter- and intra- batch variability; the intra-assay coefficient of variation (CV) was 4.8% and the inter-assay CV was 6.6%. The median blind duplicate CV was 1.3%. Laboratory personnel completing the assays were blinded to the intervention status of the participants. Three values (1.9%) were replaced with the mean leptin concentration from the respective diet period (one from the high GL diet period, and two from the low GL diet period) due to outliers deemed to be unrealistic.

All procedures followed were in accordance with the ethical standards of the Fred Hutchinson Cancer Research Center and the University of Washington. All participants signed written informed consent.

Statistical Analysis

We used descriptive statistics to characterize the study sample; continuous data are presented as mean ± standard deviation and categorical data are presented as frequencies and percents. Missing values (2.8% of total responses) on satiety questionnaires were replaced with the mean value of all the responses for that question in that specific diet. Analyses were performed with and without the imputed values and results did not differ so the imputed values were retained for the analyses presented. There were no missing values for other variables used in this analysis. The primary analysis compared mean scores for each question on the satiety survey for the low- vs. high-GL diets using the paired t-test. Stratified analyses were conducted by gender, baseline BMI, baseline percent body fat and race/ethnicity using the paired t-test or the independent samples t-test, as appropriate. SPSS for Windows (version 16.0, 2009, SPSS, Inc, Chicago, IL) was used for statistical analysis. All tests were two-sided and statistical significance was set at $p< 0.05$.

RESULTS

Characteristics of the study sample

Forty normal weight (mean BMI=22.2 kg/m^2) and 42 overweight/obese (mean BMI=32.5 kg/m^2) healthy volunteers participated **(**Table 2**)**. As expected, the overweight/obese participants had a higher percentage of body fat, as well as larger waist and hip

circumferences. The normal weight participants were younger than the overweight/obese participants (mean age = 26.5 years and 32.5 years, respectively). Equal numbers of males and females were recruited for each BMI sub-group. Two participants only completed one feeding arm, and were excluded.

Comparison of overall mean satiety measures

Participants reported significantly greater fullness during the low-GL feeding period than during the high-GL feeding period (P=0.03; Table 3). This difference in satiety scores represents an approximate 7% greater satiety on the low GL diet. The percentage of participants reporting food cravings was also significantly lower with the low-GL diet than the high-GL diet (P<0.001). When asked to state what food they were craving, participants on the high-GL diet appeared to crave snacks/sweets/desserts (n=24 vs. n=19), fruits/vegetables (n=7 vs. n=3), and main entrée dishes (n=46 vs. n=42) more often than participants on the low-GL diet (data not shown). However, participants on the low-GL diet craved foods such as salt, spicy foods and grilled items (n=10 vs. n=7) more often than their high-GL diet counterparts (data not shown).

Comparison of mean satiety measures and leptin by gender

Women reported significantly greater overall fullness and less overall hunger on the low-GL diet than on the high-GL diet (P=0.05 and <0.01, respectively; Table 4). However, men demonstrated no significant differences in overall hunger or fullness between the two diets. Serum leptin concentrations for both men and women did not differ between the two diets (P=0.99 and 0.67, respectively). There were no other significant relationships between satiety-related measures on the two diets, and no other differences in how the two genders responded to the diets.

Comparison of satiety measures by obesity

For analyses related to percent body fat and BMI, the information presented in the tables is restricted to questions directly related to appetite, tastiness, and leptin concentrations. Participants of normal percentage body fat and normal BMI reported the food on the low-GL diet as being significantly tastier than the food on the high-GL diet (P=0.04, 0.05 respectively; Table 5).

Comparison of satiety measures by race/ethnicity

We next conducted exploratory analyses intended to assess whether satiety varied across the race/ethnic groups. Compared to minority participants (Hispanic, African-American and Asian), non-Hispanic white participants reported being significantly less hungry while on the low-GL diet (P=0.04) but not on the high-GL diet (data not shown). Comparing effects of GL on each individual minority group, no significant results were seen, possibly due to a small sample size for each group. However, the non-Hispanic white participants reported significantly more overall hunger on the high-GL diet, significantly more overall fullness on the low GL diet, and reported the food on the low-GL diet to be tastier than the high-GL food (P=0.01, 0.004, 0.023, respectively; data not shown). Neither non-Hispanic white participants nor minority participants demonstrated significant differences in serum leptin between the two diets (P=0.74, 0.82; data not shown).

DISCUSSION

In this randomized, controlled feeding study, we found that a low-GL diet resulted in significantly more overall fullness than a high-GL diet. The 7% greater satiety on the low GL diet is likely to be clinically meaningful for persons wishing to decrease overall food

intake. In sub-group analyses, this association was even stronger for women and non-Hispanic white participants, compared to men and minority participants, respectively. These data suggest that while findings are somewhat modest, lowering the GL of a diet may be a useful strategy to help patients reach satiation, particularly for women.

The rapidly increasing rates of metabolic disorders and of overweight and obesity in the United States is particularly troubling in light of the growing evidence suggesting states of energy imbalance may be strong risk factors for developing and dying from metabolic-related diseases such as cardiovascular disease, diabetes, and some cancers [1-8]. One possible source of the rise in prevalence of metabolic disorders is decreased satiety derived from the typical American diet. The significantly increased satiety amongst all participants after four weeks on a low-GL diet when compared to a high-GL diet presents GL as a possible way to help patients with reaching satiety. Weight loss was not a goal of this study since the primary intent was to test the effect of the diet composition; weight change would have made it very difficult to disentangle effects from weight change with those from diet. As such, the experimental diets were designed to meet each participant's individual daily energy needs. Further investigation is needed to determine whether the increased satiety of a low-GL diet might be an effective weight loss strategy.

The cause of this increased satiety on the low-GL is still unknown, though some studies suggest the dietary fiber of food is responsible for increased satiety [21]. We recognize that the glycemic index of a food encompasses many aspects of a food, including moisture content, starch gelatinization, fiber and cooking time [11,12,16,19]. In fact, some low GI foods, such as milk and tomato juice are low in fiber and some high GI foods, such as bran flakes breakfast cereal are high in fiber [19]. Since the two diets arms in this study did differ in fiber, it is possible that this aspect of the diets may explain the differences in satiety. Leptin, a satiety hormone released in proportion to adiposity and thought to have an anorexigenic effect, was hypothesized to be higher in participants while on the low-GL diet [22]. However, there was no significant difference in serum leptin concentrations between the two diets, despite there being a statistically significant difference in satiety. In subgroup analysis, women experienced greater satiety and less hunger on the low-GL diet, whereas there was no effect in men, and both subgroups experienced no difference in leptin concentrations. There are well-known gender differences in leptin concentrations, with women, who generally have more adipose tissue than men, having higher serum leptin concentrations [23]. This is consistent with the findings in this report. There was also no significant difference in leptin concentrations between diets for any of the body fat percentage of BMI subgroups, and also no change in satiety or hunger. The relationship between leptin, GL, and satiety warrants further investigation since other factors, such as leptin resistance and sensitivity, and the effect of estradiol on satiety, are not fully understood and may be influencing our results [22, 23, 24].

To our knowledge, this is the first study of its kind testing overall satiety over a controlled four week period with an experimental diet, as opposed to a post-prandial survey immediately assessing satiety over only a few hours after a test meal. Most previous studies only tested satiety in a strictly post-prandial context, and suffer from either small sample sizes or reliance on data from self-reported dietary assessment. Given these limitations, there has understandably been little consensus as to what the exact relationship is between GL and satiety. Nevertheless, previous studies have demonstrated in a post-prandial context that food intake and hunger were lower after a low-GL breakfast versus a high-GL breakfast, and that a high-GL meal resulted in increased food intake at subsequent meals [25]. Other studies have demonstrated that the change in pre- and post-meal satiety was greater after a low-GL meal than a high GL meal [26]. Furthermore, in a 2009 review, the authors concluded from their review of four studies, that a low-GL diet was more satiating than a

high-GL diet in the short term (1-3 days), but the review also stated there was not enough evidence to determine if there was a long-term relationship between GL and satiety, citing a lack of relevant studies [27]. These studies, along with our work, suggest a low-GL diet can be an effective way to increase satiety and potentially decrease the amount of food ingested over time.

Studies investigating differences in perception of food based on gender suggest there are striking, but poorly understood, differences in how men and women respond and react to food. One study using functional magnetic resonance image (fMRI) readings of participants' brains while exposed to food-related visual stimuli found that women in general were more reactive to food-related cues than men, and in general women paid more attention to food stimuli than men. Another investigation into post-meal satiety found that in a eucaloric meal, women reported higher post-meal satiety ratings than men. This same study found that in *ad libitum* meals, men ate significantly more than during the eucaloric diet phase, while women ate a similar number of calories during both eucaloric and *ad libitum* phases, suggesting perhaps an internal modulation of energy intake that differs between genders [28-30].

This study had many strengths. The participants were provided with all their food for the entire duration of the feeding study, thus allowing for a more accurate and consistent way of delivering a diet of the specified GL. This study also benefitted from being able to recruit an equal number of male and female participants and sufficient numbers of normal weight and overweight/obese participants, allowing for subgroup analysis with appropriate statistical power. This study also had a relatively large sample size for a controlled feeding study. Limitations of the study include a small sample size of participants from different ethnic backgrounds, making subgroup analyses based on race/ethnicity inconclusive. Further, while we had a priori hypotheses that the intervention diet effects on satiety would vary by gender and BMI, we were limited in statistical power for formal interaction tests. Thus, readers are urged to use caution in interpreting results. Additionally, measures of satiation may differ when people are consuming their own foods prepared with cooking methods to which they are accustomed, as opposed to a controlled feeding study where all foods were prepared and provided to participants. Finally, because our study diets differed in fiber intake, the satiety differences may have been due to the fiber and not exclusively due to the GL.

In conclusion, our study has demonstrated that a diet of low GL is more satiating than a high GL diet, and thus presents a possible strategy to decrease food consumption. This trend was especially evident among women and overall participants, but not among subgroups based on BMI, percentage body fat, or ethnicity. Given the potential for a low-GL diet to restore a person's energy balance through increased satiety and decreased food consumption, we believe this can be a practical and effective clinical intervention, particularly for women.

Acknowledgments

This study was made possible by the support of NCRR Grant TL1RR025016 and NIH Grants U54CA116847 and P30 CA015704.

References

[1]. McKeown-Eyssen G. Epidemiology of colorectal cancer revisited: are serum triglycerides and/or plasma glucose associated with risk? Cancer Epidemiol Biomarkers Prev. Dec; 1994 3(8):687–95. [PubMed: 7881343]

[2]. Kaaks R, Lukanova A. Energy balance and cancer: the role of insulin and insulin-like growth factor-I. Proc Nutr Soc. Feb; 2001 60(1):91–106. [PubMed: 11310428]

[3]. Giovannucci E. Insulin, insulin-like growth factors and colon cancer: a review of evidence. J Nutr. Nov; 2001 131(11 Suppl):3109S–20S. [PubMed: 11694656]

[4]. Gunter MJ, et al. Insulin, insulin-like growth factor-I, endogenous estradiol, and risk of colorectal cancer in postmenopausal women. Cancer Res. Jan 1; 2008 68(1):329–37. [PubMed: 18172327]

[5]. Calle EE, Rodriguez C, Walker-Thurmond K, Thun MJ. Overweight, obesity, and mortality from cancer in a prospectively studied cohort of U.S. adults. N Eng J Med. Apr 24; 2003 348(17): 1625–38.

[6]. Jee SH, Ohrr H, Sull JW, Yun JE, Ji M, Samet JM. Fasting serum glucose level and cancer risk in Korean men and women. JAMA. Jan 12; 2005 293(2):194–202. [PubMed: 15644546]

[7]. Inoue M, Iwasaki M, Otani T, Sasazuki S, Noda M, Tsugane S. Diabetes mellitus and the risk of cancer: results from a large-scale population-based cohort study in Japan. Arch Intern Med. Sep 25; 2006 166(17):1871–7. [PubMed: 17000944]

[8]. Zhou JR, Blackburn GL, Walker WA. Symposium introduction: metabolic syndrome and the onset of cancer. Am J Clin Nutr. Sep; 2007 86(3):s817–9. [PubMed: 18265474]

[9]. Flegal KM, Carroll MD, Ogden CL, Curtin LR. Prevalence and trends in obesity among US adults, 1999-2008. JAMA. Jan 20; 2010 303(3):235–41. [PubMed: 20071471]

[10]. Anderson GH, Woodend D. Effect of glycemic carbohydrates on short-term satiety and food intake. Nutr Rev. May; 2003 61(5 Pt 2):S17–26. [PubMed: 12828188]

[11]. Jenkins DJA, et al. Glycemic index: overview of implications in health and disease. AM J Clin Nutr. 2002; 76:266S–73S. [PubMed: 12081850]

[12]. Ludwig D. The glycemic index: physiologic mechanisms relating to obesity, diabetes and cardiovascular disease. JAMA. 2002; 287:2414–23. [PubMed: 11988062]

[13]. Holt S, Brand J, Soveny C, Hansky J. Relationship of satiety to postprandial glycaemic, insulin and cholecystokinin responses. Appetite. 1992; 18:129–41. [PubMed: 1610161]

[14]. Holt SH, Brand Miller JC, Petocz P. Interrelationships among postprandial satiety, glucose and insulin responses and changes in subsequent food intake. Eur J Clin Nutry. 1996; 50:788–13.

[15]. Warren JM, Henry CJK, Simonites V. Low glycemic index breakfasts reduced food intake in preadolescent children. Pediatrics. 2003; 112:414–9.

[16]. Neuhouser ML, et al. Development of a glycemic index database for food frequency questionnaires used in epidemiologic studies. J Nutr. Jun; 2006 136(6):1604–9. [PubMed: 16702328]

[17]. Narayan KMV, Boyle JP, Geiss LS, Saaddine JB, Thompson TJ. Impact of Recent Increase in Incidence on Future Diabetes Burden. Diabetes Care. Sep; 2006 29(9):2114–6. [PubMed: 16936162]

[18]. Stunkard AJ, Messick S. The three-factor eating questionnaire to measure dietary restraint, disinhibition and hunger. Journal of Psychosomatic Research. 1985; 29:71–83. [PubMed: 3981480]

[19]. Foster-Powell K, Holt SHA, Brand-Miller JC. International table of glycemic index and glycemic load values: 2002. Am J Clin Nutr. Jul; 2002 76(1):5–56. [PubMed: 12081815]

[20]. Bolton RP, Heaton KW, Burroughs LF. The role of dietary fiber in satiety, glucose, and insulin: Studies with fruit and fruit juice. Am J Clin Nutr. Feb; 1981 34(2):211–7. [PubMed: 6259919]

[21]. Nilsson AC, Ostman EM, Holst JJ, Bjorck IM. Including indigestible carbohydrates in the evening meal of healthy subjects improves glucose tolerance, lowers inflammatory markers, and increases satiety after a subsequent standardized breakfast. J Nutr. Apr; 2008 138(4):732–9. [PubMed: 18356328]

[22]. Knight ZA, Hannan KS, Greenberg ML, Friedman JM. Hyperleptinemia is required for developing of leptin resistance. PLoS One. Jun 29.2010 5(6):e11376. [PubMed: 20613882]

[23]. Hickey MS, et al. Gender difference in serum leptin levels in humans. Biochem Mol Med. Oct; 1996 59(1):1–6. [PubMed: 8902186]

[24]. Butera PC. Estradiol and the control of food intake. Physiol Behav. Feb 9; 2010 99(2):175–80. [PubMed: 19555704]

[25]. Buyken AE, Trauner K, Gunther ALB, Kroke A, Remer T. Breakfast glycemic index affects subsequent energy intake in free-living healthy children. Am J Clin Nutr. Oct; 2007 86(4):980–7. [PubMed: 17921374]

[26]. Pal S, Lim S, Egger G. The Effect of Low Glycaemic Index Breakfast on Blood Glucose, Insulin, Lipid Profiles, Blood Pressure, Body Weight, Body Composition and Satiety in Obese and Overweight Individuals: A Pilot Study. J Am Coll Nutr. Jun; 2008 27(3):387–93. [PubMed: 18838526]

[27]. Niwano Y, et al. Is glycemic index of food a feasible predictor of appetite, hunger, and satiety? J Nutr Sci Vitaminol (Tokyo). Jun; 2009 55(3):201–7. [PubMed: 19602827]

[28]. Carroll JF, Kaiser KA, Franks SF, Deere C, Caffrey JL. Influence of BMI and gender on postprandial hormone responses. Obesity. Dec; 2007 15(21):2974–83. [PubMed: 18198306]

[29]. Cornier MA, Salzberg AK, Endly DC, Bessesen DH, Tregellas JR. Sex-based differences in the behavioral and neuronal responses to food. Physiol Behav. Mar 30; 2010 99(4):538–43. [PubMed: 20096712]

[30]. Uher R, Treasure J, Heining M, Brammer MJ, Campbell IC. Cerebral processing of food-related stimuli: Effects of fasting and gender. Behav Brain Res. Apr 25; 2006 169(1):111–9. [PubMed: 16445991]

Table 1

Example menus from low and high controlled feeding study diets

Meals	High Glycemic Load	Low Glycemic Load
Breakfast	Grape Nuts® cereal with sugar and milk, dried dates and cranberries	All-Bran® cereal with agave nectar and milk, strawberries and blueberries, nut mix, tomato juice
Lunch	Roast beef sandwich on white bread with condiments, raw cauliflower florets, potato salad, canned apricots in heavy syrup, fruit roll-up and jelly beans	Roast beef sandwich on pumpernickel bread with condiments, raw carrots, hummus, canned pears in own juice, M&M® peanut chocolate candies
Dinner	Chicken fajitas in baked taco shells, white rice, rice pudding and cranberry juice	Chicken fajitas in soft tortillas, chocolate mousse,
Breakfast	Buckwheat pancakes with butter & syrup, milk or yogurt, Gatorade®	Hard-boiled egg, apple bran muffin, tomato juice, fresh grapefruit, milk
Lunch	Ham on white bagel with condiments, potato salad, raw broccoli with ranch dressing, canned apricots, graham crackers, jelly beans	Turkey sandwich on sprouted whole wheat bread with condiments, curried lentil salad, raw carrots, fresh apple, berry-flavored energy bar
Dinner	Meat chili with cheddar cheese, white rice, green salad with Italian dressing, angel food cake	Whole wheat spaghetti and meatballs in tomato basil sauce, green salad, chocolate cupcake

[1]7 day menu rotation was used in study. Meals shown are examples

[2]Diets were isocaloric; each participant's individual energy needs were estimated by the Mifflin equation and usual intake from 3 d diet record. On average, daily GL = 262 and 126 for high and low GL, respectively. On average, 99% of average daily planned kcals were consumed on the high GL diet and 98% of average daily planned kcals were consumed on the low GL diet;>98% of the specified GL was consumed on both diets.

Table 2

Baseline characteristics of study participants[1]

Characteristics	No. (%) of Participants		*P-value*
	Normal wt[2]	**Overweight/obese**	
Sex			
Male	20	21	N/A
Female	20	21	
Ethnicity/race			
Non-Hispanic White	14 (35%)	22 (53.7%)	N/A
Hispanic	11 (27.5%)	9 (22%)	
Black/African American	8 (20%)	9 (22%)	
Asian/Pacific			
Islander/American Indian	7 (17.5%)	2 (4.9%)	

	Mean (SD)		*P-value*
	Normal wt	**Overweight/obese**	
Age (years)	26.5 (6.4)	32.5 (8.6)	0.01
Mean BMI (kg/m^2)	22.2 (1.6)	32.5 (3.7)	<0.001
Anthropometry			
Height (cm)	170.5 (9.9)	172.3 (11.0)	0.23
Waist circumference (cm)	74.9 (6.7)	99.6 (20.3)	<0.001
Hip circumference (cm)	92.0 (5.7)	114.2 (14.5)	<0.001
Weight (kg)	64.8 (7.8)	97.0 (18.2)	<0.001
Body-fat percentage	25.4 (9.1)	40.5 (9.2)	<0.001
Mass of body components			
Bone mass (kg)	2.8 (1.5)	3.2 (3.7)	0.22
Fat mass (kg)	15.9 (5.1)	37.7 (10.8)	<0.001
Lean Mass (kg)	44.9(9.6)	52.3 (12.3)	0.07

[1]Block randomization was used to ensure equal numbers of males and females, and overweight and obese participants so neither percentages nor tests for differences (p-values) are provided. P-values for other variables are derived from t-tests for comparisons of means.

[2]Normal weight = BMI = 18.5-24.9 kg/m^2 at baseline. Overweight/obese = BMI = 28.0-40.0 kg/m^2 at baseline. See text for details.

Table 3
Mean satiety scores for participants after low- vs. high-GL experimental diets

	Mean[1] (SD)		
Please rate:	**High GL diet (n=80)**	**Low GL Diet (n=80)**	***P Value***
How hungry you have been, on average, during this feeding period	3.94 (2.20)	3.56 (1.99)	0.18
How full you have been, on average, during this feeding period	6.40 (1.83)	6.86 (1.43)	0.03
How tasty your food has been, on average, during this feeding period	5.88 (1.83)	6.10 (1.70)	0.30
How hungry you are right now	3.01 (2.18)	3.08 (2.39)	0.83
How thirsty you are right now	4.20 (2.39)	3.83 (2.34)	0.13
How nauseated you are right now	1.74 (1.62)	1.65 (1.35)	0.64
How full you are right now	6.41 (2.23)	6.18 (2.23)	0.34
Your desire to eat right now	3.24 (2.64)	3.33 (2.47)	0.78
Percentage of participants reporting food cravings	67.5%	64.0%	<0.001
Leptin (ng/mL)	18.2 (18.7)	16.9 (17.0)	0.25

P-values computed from t-tests for comparisons of means.

[1]Scores range from 1-9, with “1” being “not at all hungry,” “not at all full,” etc and “9” being “extremely hungry,” “extremely full,” etc.

Table 4

Mean satiety scores[1] before and after four-week low and high GL diets by gender[2]

	Men (n=40)			Women (n=40)		
Please rate:	**High-GL Diet Mean (SD)**	**Low-GL Diet Mean (SD)**	***P-Value***	**High-GL Diet Mean (SD)**	**Low-GL Diet Mean (SD)**	***P-Value***
How hungry you have been, on average, during this feeding period	4.25 (2.05)	4.20 (2.09)	0.92	3.62 (2.34)	2.88 (1.67)	0.05
How full you have been, on average, during this feeding period	6.20 (1.87)	6.43 (1.53)	0.55	6.60 (1.78)	7.32 (1.19)	<0.01
How tasty your food has been, on average, during this feeding period	5.53 (1.69)	5.55 (1.85)	0.95	6.22 (1.92)	6.62 (1.37)	0.19
How hungry you are right now	3.60 (2.13)	3.95 (2.69)	0.54	2.42 (2.10)	2.30 (1.81)	0.73
How thirsty you are right now	4.33 (2.11)	4.22 (2.29)	0.83	4.08 (2.67)	3.45 (2.36)	0.10
How nauseated you are right now	1.90 (1.77)	1.98 (1.72)	0.85	1.58 (1.47)	1.32 (0.73)	0.33
How full you are right now	5.80 (2.29)	5.20 (2.46)	0.31	7.02 (2.02)	7.08 (1.58)	0.89
Your desire to eat right now	3.78 (2.47)	4.15 (2.55)	0.56	2.70 (2.73)	2.60 (2.23)	0.83
Leptin (ng/ml)	8.7 (7.20)	8.7 (7.80)	0.99	27.4 (21.80)	25.8 (19.6)	0.67

[1] Scores range from 1-9, with “1” being “not at all hungry,” “not at all full,” etc, and “9” being “extremely hungry,” “extremely full,” etc. Comparison of mean scores computed by t-tests within each gender.

Nutr Cancer. Author manuscript; available in PMC 2013 September 04.

Table 5

Mean scores[1] for participant satiety with subgroup analyses by baseline percent body fat[2] and BMI

	Normal percent body fat (n=29)			Excess percent body fat (n=52)		
Please rate:	**High-GL Diet Mean (SD)**	**Low-GL Diet Mean (SD)**	***P-Value***	**High-GL Diet Mean (SD)**	**Low-GL Diet Mean (SD)**	***P-Value***
How hungry you have been, on average, during this feeding period	4.38 (2.32)	4.34 (2.11)	0.94	3.63 (2.13)	3.10 (1.77)	0.13
How full you have been, on average, during this feeding period	6.24 (1.70)	6.76 (1.24)	0.19	6.52 (1.89)	6.94 (1.53)	0.13
How tasty your food has been, on average, during this feeding period	5.66 (1.86)	6.38 (1.64)	0.04	6.04 (1.83)	5.92 (1.73)	0.67
Leptin (ng/ml)	6.20 (5.70)	7.10 (7.10)	0.59	24.8 (20.1)	22.4 (18.4)	0.52

	Normal BMI (n=40)			Overweight/Obese BMI (n=41)		
Please rate:	**High GL Diet Mean (SD)**	**Low GL Diet Mean (SD)**	***P- Value***	**High GL Diet Mean (SD)**	**Low GL Diet Mean (SD)**	***P- Value***
How hungry you have been, on average, during this feeding period	3.95 (2.32)	3.80 (2.14)	0.73	**3.85 (2.14)**	3.29 (1.81)	0.25
How full you have been, on average, during this feeding period	6.45 (1.65)	6.85 (1.23)	0.20	6.39 (2.00)	6.90 (1.61)	0.20
How tasty your food has been, on average, during this feeding period	5.70 (1.84)	6.30 (1.68)	0.05	6.10 (1.83)	5.88 (1.71)	0.60
Leptin (ng/ml)	9.3 (8.1)	8.7 (7.2)	0.71	26.8 (22.0)	25.0 (19.8)	0.70

[1] Scores range from 1-9, with "1" being "not at all hungry," "not at all full," etc, and "9" being "extremely hungry," "extremely full," etc. P-values are from t-tests to compare means

[2] Normal body fat percentage was defined as < 25% for men, and <32% for women based on DXA. See text for details.