

Reproducibility of ad libitum energy intake with the use of a computerized vending machine system^{1–3}

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ABSTRACT

Background: Accurate assessment of energy intake is difficult but critical for the evaluation of eating behavior and intervention effects. Consequently, methods to assess ad libitum energy intake under controlled conditions have been developed.

Objective: Our objective was to evaluate the reproducibility of ad libitum energy intake with the use of a computerized vending machine system.

Design: Twelve individuals (mean \pm SD: 36 \pm 8 y old; 41 \pm 8% body fat) consumed a weight-maintaining diet for 3 d; subsequently, they self-selected all food with the use of a computerized vending machine system for an additional 3 d. Mean daily energy intake was calculated from the actual weight of foods consumed and expressed as a percentage of weight-maintenance energy needs (%WMEN). Subjects repeated the study multiple times during 2 y. The within-person reproducibility of energy intake was determined through the calculation of the intraclass correlation coefficients (ICCs) between visits.

Results: Daily energy intake for all subjects was 5020 \pm 1753 kcal during visit 1 and 4855 \pm 1615 kcal during visit 2. There were no significant associations between energy intake and body weight, body mass index, or percentage body fat while subjects used the vending machines, which indicates that intake was not driven by body size or need. Despite overconsumption (%WMEN = 181 \pm 57%), the reproducibility of intake between visits, whether expressed as daily energy intake (ICC = 0.90), %WMEN (ICC = 0.86), weight of food consumed (ICC = 0.87), or fat intake (g/d; ICC = 0.87), was highly significant ($P < 0.0001$).

Conclusion: Although ad libitum energy intake exceeded %WMEN, the within-person reliability of this intake across multiple visits was high, which makes this a reproducible method for the measurement of ad libitum intake in subjects who reside in a research unit. This trial was registered at clinicaltrials.gov as NCT00342732. *Am J Clin Nutr* 2010;91:343–8.

INTRODUCTION

Although energy and macronutrient intakes play important roles in the development of obesity, accurate assessment of these variables in free-living populations is extremely difficult (1). The 24-h recall (2), food-frequency questionnaires (FFQs) (3), and weighed dietary records (4) are the methods generally used. However, these methods do not produce accurate results because most people are not good historians of their intake, and often the mere act of record keeping can cause some individuals to change their eating habits. Moreover, as reported in the Beltsville One-

Year Dietary Intake Study (5), there is considerable variation in long-term intake patterns for most subjects. Not only do these obstacles impede the accurate evaluation of free-living energy and macronutrient intakes but they are inadequate for testing the effects of various interventions for weight loss, such as pharmaceutical agents.

To overcome these difficulties, investigators have developed a number of laboratory methods to assess energy intake and eating behavior under controlled conditions. These methods include allocation systems such as buffet tables, cafeteria lines (6, 7), and challenge meal testing (8, 9). In these systems, measured quantities of food are provided to subjects ad libitum or for a controlled period of time; intake is assessed by weighing waste and calculating the exact amount of food consumed. Although these methods are not valid indicators of free-living energy intake, they provide essential information for testing interventions and examining motivations to eat. For example, Smith et al (9) tested the effects of a weight-control drug on ad libitum food intake with the use of a fast-food challenge and observed decreased intake after drug treatment. In a previous study from our own laboratory Tataranni et al (10) used an automated food-selection system to test the effects of glucocorticoids on ad libitum energy intake and showed that those treated with methylprednisolone ate almost twice the amount of the placebo group and that glucocorticoids induce obesity mostly by increasing energy intake.

Only a few studies (11, 12) have reported the reproducibility of ad libitum energy intake with the use of these laboratory methods; these studies assessed ad libitum intake, one with a buffet meal (11) and the other with a homogeneous meal (12), on 2 occasions and showed significant correlations in intake between the 2 tests. In the present study we report on the reproducibility of ad libitum energy intake over a 3-d period with the use of a computer-

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operated vending machine system in subjects confined to the National Institute of Diabetes and Digestive and Kidney Diseases Clinical Research Unit in Phoenix, AZ.

SUBJECTS AND METHODS

Subjects

Six women and 6 men [Native American ($n = 7$) and white ($n = 5$)] were recruited from the greater Phoenix area. Before participation, volunteers were fully informed of the nature and purpose of the study, and written informed consent was obtained. The experimental protocol was approved by the Institutional Review Board of the National Institute of Diabetes and Digestive and Kidney Diseases.

All subjects were shown to be free of disease on the basis of physical examination, medical history, and laboratory testing. On admission to the metabolic ward, subjects consumed a standard weight-maintaining diet (20%, 30%, and 50% of daily energy provided as protein, fat, and carbohydrate, respectively) for 3 d before testing. Weight-maintenance energy needs (WMEN) while on the metabolic ward were calculated for each subject on the basis of weight and sex [men: $WMEN = 9.5 \times \text{weight (kg)} + 1973$; women: $WMEN = 9.5 \times \text{weight (kg)} + 1745$ (13)]. Body composition was measured by dual energy X-ray absorptiometry (DPX-L; Lunar Corp, Madison, WI), as previously described (14). Glucose tolerance was assessed by a 75-g oral-glucose-tolerance test (15) in accordance with the criteria of the World Health Organization. Only nondiabetic subjects participated in this study.

Light activities such as playing pool, television and video watching, and arts and crafts projects were available to the subjects during the course of their 10-d admission to the Clinical Research Unit. In addition, supervised outdoor outings within the confines of the hospital campus were scheduled regularly.

Study design

This study was part of a large protocol designed to investigate several aspects of ingestive behavior (which included ethnic differences; eating behavior; taste preferences; metabolic effects, which included energy expenditure and substrate use; hormonal influences; and genotype-phenotype relations), as well as the reproducibility of the method. Accordingly, >150 individuals participated in the larger study, and some data from the first visit of several of the current subjects have been reported previously (16–18).

Assessment of food preferences

After admission to the metabolic ward, subjects were asked to complete a food preferences questionnaire, which consisted of a list of 80 food items presented in random order. On the basis of a model developed by Geiselman et al (19), typical breakfast, lunch, dinner, and snack food items were categorized in accordance with a “macronutrient self-selection paradigm” that varied the fat content of foods as a percentage of energy systematically with other macronutrients. Foods were categorized as high (>45% kcal) or low (<20% kcal) in fat and, within each of these categories, as high in simple sugar (>30% kcal), complex carbohydrate (>30% kcal), or protein (>13% kcal). As part of

this self-administered questionnaire, individuals were asked to assign each food a hedonic rating with the use of a 9-point Likert scale with the following anchors: 1 = dislike extremely; 5 = neutral; 9 = like extremely; an option to indicate that the food item had never been tasted was also included. Several foods on the list, which included hamburgers, french fries, ham and other luncheon meats, doughnuts, cookies, cakes, candies, bread products, muffins, eggs, and cheeses, are among the top 10 sources of dietary fat in the United States; the list also reflects items of intake common to Native Americans and individuals who live in the Southwest.

Ad libitum energy intake with the use of a computerized vending machine system

During the final 3 d of study on the metabolic ward, subjects were asked to self-select all their food with the use of a computer-operated vending machine system as described previously (16, 20). The 40 food items made available to the subjects on each of the 3 d consisted of those foods to which the subject had assigned an intermediate (between 4 and 8) hedonic rating on the food preferences questionnaire. In addition, a core group of condiments was provided to each subject each day, which included butter, peanut butter, cream cheese, and jams; salad items and dressings; crackers, bread, tortillas, and Indian fried bread; spices and salsa; and orange juice, apple juice, milk and a 6-pack of soda of the subject's choice. Subjects had ad libitum access to the vending machines for 23.5 h/d. The refrigerated machines were housed in a separate eating area equipped with a table, chair, microwave oven, and toaster. Subjects were instructed to eat only in the vending room and to eat whatever they wished whenever they desired. Television viewing during food consumption was prohibited. Food wrappers and unconsumed food portions were returned to the vending machines to be weighed by the dietary staff. Uneaten portions and weight of wrappers were subtracted from the initial weight of items for data analysis.

Daily energy, protein, fat, and carbohydrate intakes were calculated from the actual weights of food and condiments consumed with the use of the CBORD Professional Diet Analyzer Program (CBORD Inc, Ithaca, NY), with the database (ESHA, version 10.0.0; ESHA Research, Salem, OR) modified to reflect the nutrient content of specific food items as indicated by the manufacturer. Results are presented as the means \pm SDs of the 3 d. Energy intake is expressed as mean kcal/d and mean percentage of WMEN (%WMEN) on the metabolic ward [(mean daily energy consumed/WMEN) \times 100]. Fat, carbohydrate, and protein intakes are expressed as g/d and as mean percentage of kcal/d.

Eating behavior

The Three-Factor Eating Questionnaire (21), which classifies eating behavior among individuals on the basis of dietary restraint, disinhibition, and perceived hunger, was used to assess eating behavior. The questionnaire was self-administered by each subject before the ad libitum use of the vending machines.

Free-living energy intake

Subjects were asked to complete the 1998 Block FFQ at each visit to assess usual intake in the free-living situation (22).

TABLE 1
Anthropometric characteristics of participants at study visit 1¹

	Men (n = 6)	Women (n = 6)	P value
Age (y)	38 ± 10	35 ± 5	0.1446
Body weight (kg)	98.1 ± 10.7	92.3 ± 13.3	0.1045
Body fat (%)	33.7 ± 4.8	47.4 ± 2.8	<0.0001
BMI (kg/m ²)	32.3 ± 4.1	36.1 ± 4.8	0.0149

¹ All values are means ± SDs. Differences between men and women were determined by Student's *t* test.

Reproducibility protocol

To evaluate the reproducibility of this method for the assessment of ad libitum energy intake, 12 subjects completed the study multiple times over 2 y: 7 individuals completed the study twice; 2 completed the study 3 times; 1 completed the study 4 times; and 2 completed the study 5 times. The reproducibility aspect of the study was open to all volunteers. Subjects were invited to participate until ≥5 Native Americans and 5 whites agreed to do so; however, we continued to allow Native Americans to repeat the study until we had the required number of white subjects. Although the protocol allowed for 5 repeated visits for each individual, the variability in the number of repeats was entirely the result of subject availability.

At each visit, height and weight were measured, body mass index (BMI; in kg/m²) was calculated, body composition was analyzed by dual-energy X-ray absorptiometry, and subjects underwent a 3-d ad libitum intake period with the use of the vending machines, following the same protocol as described above. There was at minimum an interval of 1 mo between visits.

Data analysis

All statistical analyses were performed with the use of SAS software, version 9.1 (SAS Institute, Cary, NC). The data shown here are expressed as means ± SDs, and a *P* value of <0.05 was taken to be significant. Comparisons between groups (men and

women) were made with the use of Student's *t* test with unequal variances. Anthropometric comparisons between visits 1 and 2 were assessed with a paired *t* test. Intraclass correlation coefficients (ICCs) were calculated with the use of analysis of variance to test the reproducibility of the measurements. ICC values measure the proportion of total variation accounted for by the variation between individuals. If the ICC values are larger (closer to 1), this implies there is little variation within the individual (repeated measurements are similar in value) compared with the means between individuals.

RESULTS

The characteristics of the 12 subjects are provided in **Table 1**. Age and body weight did not differ by sex, but, as previously reported (17), women had a greater percentage of body fat and a higher BMI than did men. Mean ad libitum energy and macronutrient intakes for the first and second visits while using the vending machine system are shown in **Table 2**. In general, men ate more than women in absolute calories, as %WMEN, and in total weight of food. As a result, the absolute amount of each macronutrient consumed was also greater in men than in women. Both men and women overate significantly while using the vending machine system (mean %WMEN: 181 ± 57%).

Despite the variability in intake between subjects, mean 3-d energy intake (kcal/d) within subjects was similar between the first 2 visits (**Figure 1**). A Bland-Altman plot that confirmed the agreement between energy intake on the vending machines at the first and second visits is shown in **Figure 2**. The coefficient of reproducibility (CR) from this is ±1500 kcal/d. When the outlier is removed, the CR is substantially decreased to ±800 kcal/d. The ICC values for all the intake variables during the multiple visits with the use of the vending machines are shown in **Table 3**. Energy intake, expressed as both mean kcal/d and %WMEN, was highly consistent across visits (ICC = 0.90 and 0.86, respectively; *P* < 0.0001). Furthermore, good reproducibility was seen in macronutrient intake expressed as a percentage of total intake across multiple visits (protein ICC = 0.80, *P* < 0.0001; carbohydrate ICC = 0.57, *P* = 0.001; fat ICC =

TABLE 2
Intake and eating behavior characteristics of participants at study visit 1¹

	Men (n = 6)	Women (n = 6)	P value
Energy intake (kcal)	5974 ± 1635	4067 ± 1381	<0.0001
Energy intake (%WMEN)	206 ± 53	156 ± 52	<0.0001
Energy intake (g/d)	3788 ± 1247	2915 ± 939	0.0003
Fat intake (g/d)	271 ± 83	184 ± 69	<0.0001
Fat intake (% kcal/d)	41 ± 4	40 ± 3	0.8584
Protein intake (g/d)	170 ± 51	146 ± 42	<0.0001
Protein intake (% kcal/d)	11 ± 2	15 ± 5	0.1683
Carbohydrate intake (g/d)	720 ± 207	486 ± 179	<0.0001
Carbohydrate intake (% kcal/d)	48 ± 5	48 ± 6	0.9070
Energy intake (kcal/d) ²	2970 ± 1963	2524 ± 952	0.44
Fat intake (% kcal/d) ²	42 ± 6	38 ± 5	0.06
Dietary restraint score ³	7.7 ± 4.3	10.3 ± 3.9	0.29
Disinhibition score ³	4.5 ± 3.8	8.5 ± 4.2	0.12
Cognitive hunger score ³	3.0 ± 3.6	5.5 ± 4.1	0.29

¹ All values are means ± SDs for 3 d of study. %WMEN, percentage of weight-maintenance energy needs.

² Block food-frequency questionnaire 1998 (20).

³ Three-Factor Eating Questionnaire (19).

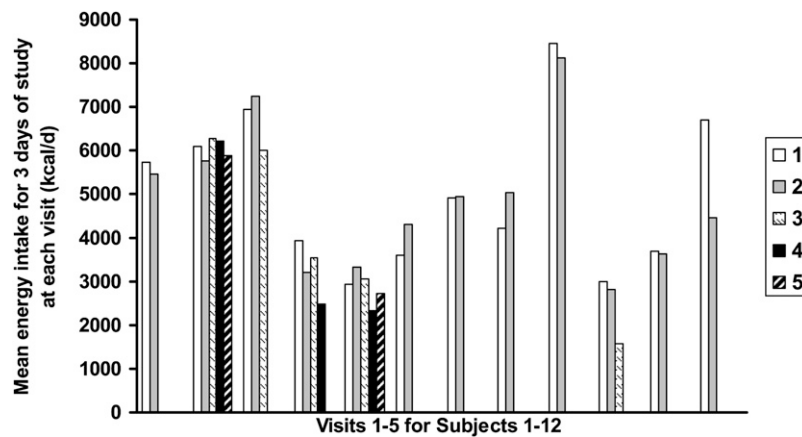


FIGURE 1. Energy intake in kcal. Values are the mean of 3 d ad libitum intake while the computerized vending machine system was being used. Subjects had between 2 and 5 repeat visits to the clinical research unit.

0.42, $P = 0.012$). The ICC value for energy intake determined from the Block FFQ was 0.79 ($P < 0.0001$), whereas the percentage of energy from fat determined from the Block FFQ showed lower reproducibility (ICC = 0.34, $P = 0.06$). The ICCs were analyzed separately by race and sex. The results were generally similar in these smaller subsets, although the ICCs for energy intake and %WMEN were slightly lower for women but still highly significant (results not shown).

The association between ad libitum energy intake and anthropometric variables indicated that, at visit 1, there was no significant correlation between body weight, BMI, or percentage body fat and energy intake with the use of the vending machines (mean kcal/d or %WMEN), which indicated that energy intake was not driven by body size or need only (data not shown). Although the responses to the Three-Factor Eating Questionnaire were highly reproducible (Table 3), there were no significant relations between ad libitum energy intake and dietary restraint, disinhibition, or cognitive hunger (data not shown).

DISCUSSION

In the current study we assessed the within-person reproducibility of ad libitum energy intake over a 3-d period with the use of a computerized vending machine system. The results of this study show that energy intake, expressed as mean kcal/d or %WMEN, macronutrient intake, and the weight of food consumed was highly consistent within subjects across visits. Although this method does not provide an assessment of the usual intake of free-living subjects, we believe it is useful for the assessment of ad libitum intake in subjects confined to a metabolic research unit.

The need for an accurate and precise method to assess ad libitum energy intake is a major concern in nutritional research. Consequently, various laboratory methods have been developed so that interventions might be tested and behavioral aspects of ingestion examined. Numerous studies have sought to validate the reliability of various instruments to assess energy intake, but, to our knowledge, few studies have evaluated the reproducibility of actual measured food consumption to this exact degree over a period extended for more than a single meal. Arvaniti et al (11)

observed a high degree of reproducibility in energy and macronutrient intake in a single ad libitum buffet-style meal, which indicated that energy intake tended to remain consistent from one session to the next over the short term. In a more recent study Gregersen et al (12) evaluated the reproducibility of ad libitum energy intake with and without prior diet standardization. Although there was considerable individual variation in energy intake between the groups depending on whether they had consumed a standardized diet beforehand, the use of an ad libitum test meal to measure energy intake was reproducible within subjects. The CR in our study was ± 1500 kcal but decreased considerably with the removal of one outlier (to ± 800 kcal). However, our results represent average daily intake over 3 d and thus compare favorably to the single meal CR of ± 353 kcal reported by Gregersen et al. Moreover, the ICCs enable us to incorporate all the available data, which allows for multiple visits, and were nearly identical to those reported by Arvaniti and Gregersen.

The results of the current study must be considered in the context of several potential limitations. First, because the study design constituted an artificial setting on a metabolic research

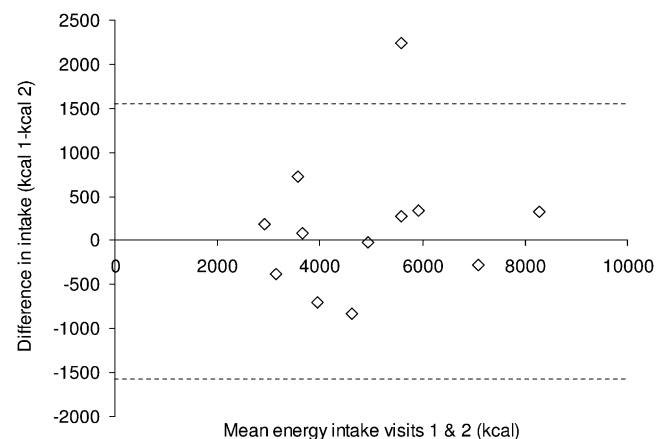


FIGURE 2. Bland-Altman plot that confirms agreement between energy intake with the use of the vending machine system at visits 1 and 2. The x axis represents the mean intake of both visits, whereas the y axis is the difference in intake between the visits. The dashed lines represent ± 2 SD.

TABLE 3

Intraclass correlation coefficients (ICCs) for the intake and questionnaire variables ($n = 12$)¹

	ICC	<i>P</i> value
Energy intake (mean kcal/d)	0.90	<0.0001
Energy intake (%WMEN)	0.86	<0.0001
Energy intake (g/d)	0.84	<0.0001
Fat intake (g/d)	0.87	<0.0001
Fat intake (% kcal/d)	0.42	0.0124
Protein intake (g/d)	0.74	<0.0001
Protein intake (% kcal/d)	0.80	<0.0001
Carbohydrate intake (g/d)	0.88	<0.0001
Carbohydrate intake (% kcal/d)	0.57	0.0010
Habitual energy intake (kcal/d) ²	0.79	<0.0001
Habitual fat intake (% kcal/d) ²	0.34	0.0597
Dietary restraint ³	0.75	<0.0001
Disinhibition ³	0.70	<0.0001
Cognitive hunger ³	0.79	<0.0001

¹ %WMEN, percentage of weight-maintenance energy needs.

² Block food-frequency questionnaire 1998 (13).

³ Three-Factor Eating Questionnaire (12).

ward, there is some concern in viewing food intake under these experimental conditions as representative of actual eating behavior in free-living conditions. However, the question of whether eating in the laboratory is representative of usual dietary intake was posed >25 y ago by Obarzanek and Levitsky (23), who showed that the correlation between energy intake evaluated from 4-d dietary records kept at home and 4-d ad libitum energy intake in the laboratory was highly significant. Moreover, they observed no changes in body weight during either period, which suggests that eating in the laboratory under controlled conditions is a reasonable approximation of free-living consumption.

Second, the foods made available in the vending machines were customized to the subjects' food preferences, and an overabundance of food was provided. Although one might argue that this system allowed for overeating, we believe that the system allowed for the free expression of eating behaviors by the study participants, behaviors that might normally be governed by social pressures such as disinhibition that inhibit usual food intake. Indeed, the withdrawal of social inhibitions likely gave way to underlying drives to eat, which resulted in the marked overconsumption of food relative to body mass. Overconsumption might also have resulted from diet standardization. In their study Gregersen et al (12) observed that diet standardization for 2 d significantly increased ad libitum intake when subjects were presented with a homogeneous meal. In the present study not only was the diet standardized for ≥ 3 d before any metabolic testing but the standard diet period actually lasted for ≈ 7 d, the entire period before the subjects used the vending machines. In addition, because the subjects were largely confined to the research unit during the study period, overconsumption may have resulted from boredom. Finally, although we showed that energy intake was very stable in our system, this study was unable to discern whether the biological mechanisms that underlie the intake are stable.

Despite these limitations, there are many positive features, which include an extremely accurate assessment of ad libitum intake over several days and the knowledge of meal timing and

frequency. We have shown it to be a useful method for the assessment of the psychological aspects of eating behavior, which include nighttime eating behavior (18), and for the evaluation of the physiologic effects of excess intake (16, 17).

In conclusion, although ad libitum energy intake exceeded both habitual intake (FFQ) and %WMEN, the within-person reliability of intake and macronutrient distribution for 3-d periods across multiple visits while this computerized vending machine system was used was highly significant. These direct observations make validation of the method difficult because observation is the gold standard. However, the results indicate that this model is useful for the assessment of ad libitum energy intake when food is abundant and freely available on a metabolic ward and for the assessment of interventions that might alter energy intake.

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The authors' responsibilities were as follows—SBV, PWF, JK, and ADS: study design; CAV: menu planning; CAV and ADS: data collection; CAV, SBV, PWF, JK, and ADS: data analysis; SBV, PWF, and JK: study manuscript composition; and CAV and ADS: manuscript preparation. All authors helped prepare the manuscript for submission. None of the authors reported a conflict of interest.

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