Accuracy of the Atwater factors and related food energy conversion factors with low-fat, high-fiber diets when energy intake is reduced spontaneously[1–3]

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ABSTRACT

Background: Systems to calculate metabolizable energy (ME) in foods and diets are often based on Atwater factors. The accuracy of these factors with low-fat diets high in fiber is unknown when food intake is reduced spontaneously.

Objective: The objective was to evaluate the accuracy of Atwater factors and other systems for calculating ME available from low-fat, high-fiber diets when food intake was reduced spontaneously.

Design: The ME contents of a high-fat, low-fiber diet and 2 low-fat diets, one high in fruit and vegetable fiber and the other high in cereal fiber, were determined in a randomized parallel study in humans (n = 27) and compared with various factorial and empirical models for calculating ME.

Results: Food intakes decreased with both the high fruit and vegetable fiber and cereal fiber diets. The difference between ME calculated by using Atwater and similar factors and determined ME values was up to 4% for the refined diet and up to 11% for the low-fat, high-fiber diets. Various factorial and empirical systems for calculating food energy failed to reflect the results of the direct determinations.

Conclusion: Atwater factors were inaccurate with low-fat, high-fiber diets. Although modified Atwater factors may be accurate under standardized conditions of zero-nitrogen and zero-energy balance, they overestimate energy availability from high-fiber fruit and vegetable and cereal diets when food intake is reduced spontaneously in addition to when intake is reduced voluntarily. *Am J Clin Nutr* 2007;86:1649–56.

KEY WORDS Atwater factors, energy density, dietary fiber, digestibility, metabolizable energy

INTRODUCTION

The incidence of obesity and related health disorders in developed nations is a matter of major concern (1). One approach to help combat obesity is the inclusion of low-energy foods in the diet and careful monitoring of dietary energy intakes versus energy expenditures to achieve (zero) energy balance at maintenance or negative energy balance if a person is overweight. To develop such foods and dietary regimens, however, implies a need to determine the available energy content of foods with appropriate accuracy, such that foods or components of food with different energy contents can be differentiated. Moreover, zero energy balance means unchanged energy content in the body rather than zero difference between metabolizable energy (ME) intake and equivalent energy expenditure. This is because some fuels are used inefficiently in metabolism, thereby having physiologic fuel values different from their ME (2).

The Atwater general factors (3), although not originally intended to be used generically, are commonly applied to estimate the ME content of foods (4) and may be used in the United States and other regions for food labeling purposes (5). Atwater described "available" food energy in terms of Physiologic Fuel Value (PFVs). He and Rubner researched food and thermogenesis essentially with a view toward a net ME system. However, PFVs have subsequently been discussed and implemented ignoring thermogenesis (3). Nevertheless, the conversion of ME factors to net ME factors is now well defined with good agreement with theory and with animal and human studies (2, 6). Greater uncertainty arises because of the difficulty in predicting energy losses, which affect metabolizability and ME and therefore is the focus of this study. The Atwater factors have important shortcomings. The gross energy contents of dietary proteins, fats, and carbohydrates are not constants. Other chemical components in foods other than protein, fat, and available carbohydrates contribute energy and may influence the ME of the principal chemical components. The digestibilities of macronutrients are variable, as is the energy per unit nitrogen excretion in urine, and some aspects of analytic methods also raise questions.

There is little published information on low-fat, high-fiber diets when food intakes are not strictly controlled. High-fiber diets or diets of low energy density are generally recommended to lower food intake, and when volunteers deliberately reduce their food intake by consuming a high-fiber diet, current food-energy-assessment systems have poor accuracy and overestimate energy availability (7). The present study, in which ME was determined in subjects consuming a low-fiber, high-fat diet or 2 low-fat, high-fiber diets (cereal or fruit and vegetable based), allowed an assessment to

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TABLE 1
Physical characteristics of each group of subjects receiving 1 of 3 experimental diets[1]

	Refined diet	Fruit and vegetable diet	Cereal diet
No. of subjects			
Total	9	9	9
Women	5	5	5
Men	4	4	4
Age (y)			
$\bar{x}$	35.9	35.2	38.8
SE	2.1	3.7	3.9
Range	26–46	24–59	23–52
Height (cm)			
$\bar{x}$	168.8	168.1	169.6
SE	3.3	2.5	3.5
Range	155.2–188.1	155.4–179	154–180
Body weight (kg)			
$\bar{x}$	73.4	75.8	71.2
SE	6.5	7.2	4.9
Range	54.3–120.4	52.2–123	45.8–91.6

[1] There were no significant differences in physical characteristics between groups.

be made of differences in nutrient digestibility and urinary energy excretion among such diets under conditions in which energy intake was reduced spontaneously (at will or in response to physiologic cues). A comparison of determined ME values with ME values predicted by using Atwater and related factors and several empirical models is described.

SUBJECTS AND METHODS

Subjects

Twenty-seven adult subjects completed the study (**Table 1**). Subjects were visibly healthy, had no gastrointestinal problems, and were not receiving any medication. None of the subjects had received antibiotics for at least 3 mo before the study. Written informed consent was obtained from all participants, and confidentiality was maintained throughout the study. Approval to conduct the study was given by Massey University Human Ethics Committee (HEC 98/123). Subjects were well educated and highly motivated.

Diets

Three diets were formulated with ingredients of stable composition that were also easy to handle, store, and cook. Diet 1, designated the "refined diet," contained mainly high-fat, low-fiber foods (eg, white bread, butter, peanuts, homogenized milk, ham, cookies, chocolate bars, cheese, and mince pie). Diet 2, designated the "fruit and vegetable diet," contained large amounts of fruit and vegetables (eg, dried apricots, sultanas, prunes, fruit bar, and fruit bread). Diet 3, designated the "cereal diet," contained large amounts of cereal-based foods (eg, wholemeal bread, bran cereal, crisp bread, bran and apple muffin). The 27 free-living volunteers were randomly allocated to 3 arms of a study of parallel design, each with 1 of the 3 diets (9 subjects per diet). Each subject was allocated 1 of 5 preset amounts of food according to prior recall of 24-h habitual intake and an estimate of energy requirement based on body weight and activity. After allocation, most of the subjects consuming the 2 high-fiber diets indicated that they were uncomfortable trying to consume the volume of food and were thus reallocated to the next lower preset intake level. Once allocated to a food intake level, the subjects consumed the given amount of food for the duration of the study.

Although dietary intake was individualized for each subject, the proportions of the nutrients within any one diet, and thus the proportion of energy derived from the respective energy-yielding nutrients, remained the same within dietary treatments regardless of differences in absolute intakes. Diet compositions as eaten were the same across participants within diets, whereas they differed between diets (**Table 2**). Subjects were provided

TABLE 2
Determined chemical composition (g/100 g dry food) of the 3 experimental diets[1]

Component	Refined diet	Fruit and vegetable diet	Cereal diet
		%	
Moisture	58.31	55.66	65.96
Crude protein	17.62	13.13	15.83
Fat	27.59	13.13	10.91
Ash	3.21	3.26	4.18
Total CHO by difference[2]	51.57	70.48	69.08
Available CHO as carbohydrate weight[3]	45.87	58.21	55.15
Available CHO as monosaccharide equivalents	49.36	60.93	58.78
Available CHO by difference[4]	46.66	62.59	59.06
Sugars	20.14	34.74	26.56
Starch	25.72	23.47	28.59
Total dietary fiber	4.90	7.89	10.02
Insoluble dietary fiber	4.54	6.83	9.94
Soluble dietary fiber	0.36	1.06	0.07
Nonstarch polysaccharide	3.51	5.64	7.82
Resistant starch	0.45	0.81	0.64

[1] CHO, carbohydrate.
[2] Calculated as 100 − fat (%) − crude protein (%) − ash (%) − moisture (%).
[3] Represents the sum of the individual mono- and disaccharides and starch expressed as the weight of the carbohydrate.
[4] Represents available carbohydrate calculated as total carbohydrate by difference − total dietary fiber (%).

clear instructions, which were reinforced throughout the study, to not eat foods other than those provided and to not imbibe alcoholic or other energy-containing beverages. Tea, coffee, pepper, salt, and sugar were supplied to each subject, and each subject accurately recorded the actual quantities of these items consumed daily. Each subject's actual dietary energy intake was corrected by taking into account the amount of tea, coffee, and sugar ingested and any food not consumed.

Experimental procedures

Diets were eaten for 10 d, including a 4-d preliminary period followed by 6 d of the balance period, when feces and urine were collected. Urine samples were acidified at collection with small quantities of 6 mol/L HCl. Excreta were kept on ice after collection, transferred to the laboratory twice daily, weighed, and stored frozen (−20 °C). Subsequently, feces were thawed, bulked over days, freeze-dried, finely ground (1-mm mesh), and mixed. Urine was also bulked over days. For each subject, representative samples of excreta were freeze-dried before chemical analysis.

On 5 occasions during the experimental period, an entire day's duplicate meals were collected (as eaten), weighed, homogenized, sampled, and frozen (−20 °C). The composite samples were freeze-dried and finely ground (1-mm mesh) before nutrient analysis.

Chemical analysis

Diet, uneaten foods, feces, and urine were analyzed per subject in duplicate for dry matter (DM), ash, total nitrogen, total fat, gross energy, and other constituents as described below.

The DM and ash contents of the feces and food samples were determined after drying the samples in an oven at 105 °C for 16 h, which was followed by ashing in a Muffle furnace (FR-550; Gallenkamp, London, United Kingdom) at 500 °C for 16 h (8). The DM contents of the total diet samples, which contained large amounts of sugar and fat, were determined by drying in a 70 °C vacuum oven until a constant weight was achieved (≈24 h) (8).

Heats of combustion (gross energy) of the samples were determined by using an adiabatic bomb calorimeter with benzoic acid thermochemical standard (Gallenkamp Co Ltd, London, United Kingdom) (9).

Total nitrogen was determined on both food and feces samples by using the Dumas method on a LECO FP3000 CNS auto analyzer (8, 10). The nitrogen content of urine samples was determined on a Kjeltech 1030 auto analyzer (Tecator, Hoganas, Sweden) by following a standard Kjeldahl procedure (8). Crude protein was calculated as total nitrogen × 6.25, with the exception of coffee, for which the conversion factor 5.3 was used (US Department of Agriculture, SR13). Ammonia, urea, uric acid, and creatinine in urine samples were determined on a Cobas Fara II autoanalyzer (Hoffman-La Roche, Basel, Switzerland), following the procedures outlined by Tiffany et al (11), Fossati et al (12), and Larsen (13), respectively. The Soxhlet method (8) was used to measure the fat content of dietary fecal samples. All fecal samples were dried overnight in a 60 °C oven, which was followed by extraction with petroleum spirit (40–60 °C) for 7 h (8). For the dietary samples, the material was acid hydrolyzed (3 mol/L HCl) before fat extraction (8). The fat content of tomato sauce was determined according to the Mojonnier method (8).

A one-step extraction-transesterification procedure was used to determine total fatty acids in the dietary and fecal samples (14). Samples (50–300 mg) of freeze-dried material containing 10–50 mg fatty acids were treated with a solvent mixture consisting of methanol-toluene-acetyl chloride (27:20:3) at 70 °C for 2 h. The organic layer was transferred into a screw-capped tube (Kimax; Kimble Glass Inc, Vineland, NJ) and dried, and the pigments were removed by adding anhydrous sodium sulfate and florisil. The fatty acid composition was subsequently determined by gas chromatography (Shimadzu GC-8A, packed column with 15% Eggs-X on chromosorb W, 100–120 mesh; Shimadzu Corporation, Kyoto, Japan) with nitrogen as the carrier gas, FID as the detector, and pentadecanoic acid (C15:0) as internal standard.

The amount of total carbohydrate (%) in the diets and feces was defined as the difference between 100 and the sum of the percentage of water, protein, total fat, and ash (15). The amounts of total, soluble, and insoluble dietary fiber in the dietary samples were analyzed by using an enzymatic-gravimetric method (8). Total nonstarch polysaccharide (NSP) in the dietary samples was determined as described by Englyst and Cummings (16, 17). Total NSP was equal to the sum of neutral sugars and uronic acids expressed as polysaccharide.

The amount of available carbohydrate in the dietary samples was determined as the sum of the individual mono- and disaccharides, and starch was expressed as the weight of the carbohydrate (18). Sugars were extracted with aqueous alcohol followed by derivatization with Tri-Sil Z (TMS-Imidazole in pyridine; Pierce Ltd, Bonn, Germany), then measured by gas chromatography (Simadzu GC, OV17 column, temperature program 170-240 °C at 5 °C/min, N_2 as carrier gas). Starch was determined by using a commercial kit (Total Starch Kit AA/AMG; Megazyme Australia, Sydney, Australia) following a standard procedure (8). Samples were completely dissolved in dimethylsulfoxide, and hydrolyzed with thermostable α-amalyse and amyloglucosidase (AMG). The amount of released glucose was determined by spectrophotometry with the use of Chromogen reagent glucose oxidase/peroxidase reagent (GOPOD) (Megazyme International Ireland Ltd, Wicklow, Ireland). The level of available carbohydrate was also calculated as the sum of the individual mono- and disaccharides and starch but was expressed as monosaccharide equivalents. Resistant starch in the dietary samples was measured by using a commercial kit (Resistant Starch Kit; Megazyme Australia) following a standard procedure (AOAC 2002.02). Samples (defatted if the fat content was >10%) were incubated at 37 °C in a shaking water bath with pancreatic α-amylase and AMG for 16 h to remove nonresistant starch. The resistant starch was then recovered as a pellet by centrifugation and was dissolved in 2 mol/L KOH. This solution was then neutralized and hydrolyzed with AMG. The resistant starch was quantified by measuring the amount of released glucose with GOPOD (19).

Data analysis

Dietary ME values were calculated by using Equation *1* (3), whereas apparent digestibility of gross energy, fatty acids analyzed, and macronutrients were calculated by using Equation *2*:

$$\text{ME (MJ/kg)} = [\text{GE food (MJ/d)} - \text{GE feces (MJ/d)} - \text{GE urine (MJ/d)}]/\text{food intake (kg/d)} \quad (1)$$

$$\text{Apparent digestibility of analyte (\%)} = 100 \times [\text{analyte food (units/d)} - \text{analyte feces (units/d)}]/\text{analyte food (units/d)} \quad (2)$$

TABLE 3
Nonstarch polysaccharide (NSP) components in each diet

Component	Refined diet	Fruit and vegetable diet	Cereal diet
		% of total NSP	
Arabinose	23.1	19.7	27.5
Xylose	23.6	16.1	35.8
Mannose	5.1	11.5	2.0
Galactose	10.3	15.4	6.8
Glucose	23.6	16.3	19.2
Uronic acid	14.2	20.7	8.7

Data were analyzed by using analysis of variance. If a significant effect of diet was found, differences between the 3 diet groups were compared by using Tukey's test. Student's *t* test was used to compare determined with calculated ME values for each of the 3 diets, respectively. Results were considered statistically significant at $P < 0.05$. All statistical procedures were performed with the use of SAS (version 9; SAS Institute, Inc, Cary, NC).

RESULTS

The fruit and vegetable diet and the cereal diet were lower in crude protein and fat than was the refined diet but the former 2 diets had considerably higher fiber contents (Table 2). As expected, the fruit and vegetable diet also had the highest content of uronic acid, and the cereal diet the highest content of neutral saccharides typical of mainly cellulose and hemicellulose (**Table 3**). The full amino acid and fatty acid compositions of the diets were reported elsewhere (20).

When a comparison was made in the percentage difference between estimated and actual GE intakes between the high-fiber diets and the refined diet, subjects consuming the high-fiber diets ingested 17.8% less energy than that predicted to meet their normal energy intake ($P < 0.05$; **Table 4**). With the high-fiber diets of lower energy density, subjects elected to choose a lower food intake than that initially allocated. Food intake was spontaneously reduced. Three of the subjects consuming the high-fiber diets did not elect to choose a lower food intake, and, when the data for these 3 subjects were excluded from the statistical analysis, daily GE intake was also found to be significantly ($P < 0.05$) lower with the high-fiber diets than with the refined diet. The overall results of the study were unchanged when the data for the 3 subjects were excluded. Fecal and urinary energy excretions were highly variable between subjects on a diet (Table 4). Fecal bulking (g fecal dry matter/kg dry food intake) was significantly higher ($P < 0.005$) with the cereal diet than with either the refined or the fruit and vegetable diet (Table 4). Urinary energy excretion did not differ significantly between diets, but urinary nitrogen was lower so that the energy to nitrogen ratio of urine increased with fiber intake, more so with the fruit and vegetable fiber diet than with the cereal fiber diet (**Table 5**). However, the daily food energy intakes were lower than the estimated energy requirements with the high-fiber diets, and subjects who consumed the lower energy intakes may have had a negative nitrogen balance. Urea was the major urinary nitrogen constituent. Urinary creatinine nitrogen excretion was higher with the fruit and vegetable diet than with the other 2 diets ($P < 0.01$ for both diets), whereas the uric acid nitrogen content was significantly higher with the cereal diet than with the refined and fruit and vegetable diets ($P < 0.005$ for both diets).

As expected, the digestibilities of energy and crude protein were lower with the higher-fiber diets ($P < 0.001$) (**Table 6**). The digestibility of fat was lower with the fruit and vegetable diet ($P < 0.001$) than with the refined diet, but this was not so for the cereal diet (Table 6). The digestibility of monounsaturated fatty acids decreased with increasing chain length with all diets (Table 6). Unsaturation improved digestibility of the 18-carbon series of fatty acids from the lower digestible fatty acids (18:O; stearic acid) to the higher digestible fatty acids (18.1,18.2, or C:18.3) (Table 6).

The ME of the high-fiber diets, when calculated by a variety of methods (refer **Table 7**), differed from the experimentally determined values (**Table 8**). However, whether calculated or determined, ME was always lower ($P < 0.001$) with the high-fiber diets than with the low-fiber diet (Table 8), with metabolizabilities (ME/GE) of 0.90, 0.86, and 0.85 for the low-fiber and high fruit, vegetable fiber, and high-cereal-fiber diets, respectively. It is clear (Table 8) that application of the Atwater factors led to statistically significant and practically relevant differences between predicted and determined ME values for the 3 diets tested. The use of Food and Drug Administration (FDA) and British

TABLE 4
Daily food and food energy intakes and energy excretion by the subjects in the 3 experimental diet groups[1]

	Refined diet	Fruit and vegetable diet	Cereal diet
Fresh food intake (g/d)	1244 ± 87	1245 ± 106	1442 ± 156
Food dry matter intake (g/d)	524 ± 40	555 ± 47	492 ± 54
Daily GE intake (MJ/d)	12.250 ± 0.94	10.961 ± 0.93	9.753 ± 1.06
Fecal excretion (MJ/d)	0.801 ± 0.06	1.119 ± 0.16	1.067 ± 0.12
Urinary excretion (MJ/d)	0.388 ± 0.02	0.395 ± 0.03	0.417 ± 0.04
Digestible energy intake (MJ/d)	11.449 ± 0.88	9.842 ± 0.81	8.686 ± 0.95
Difference between estimated and actual GE intake (%)[2,3]	1.4 ± 1.9	−12.3 ± 6.4	−23.3 ± 7.4
Dry fecal bulking (g fecal dry matter/kg dry food intake)	66.2 ± 2.3[a]	82.3 ± 7.3[a]	108.9 ± 2.3[b]
Wet fecal bulking (g wet fecal weight/kg dry food intake)	257.6 ± 25.9[a]	440.4 ± 82.6[a,b]	559.8 ± 32.0[b]

[1] All values are $\bar{x}$ ± SEM; $n = 9$. GE, gross energy. Means in the same row with different superscript letters are significantly different, $P < 0.05$ (ANOVA followed by Tukey's test).

[2] Percentage difference = (actual daily GE intake − estimated daily GE intake)/actual daily GE intake × 100.

[3] None of the differences between diets for intakes or fecal and urinary excretions were significant ($P > 0.05$), except for the percentage difference between estimated and actual GE intakes, for which there was a significant ($P < 0.05$) difference between the high-fiber diets (combined) and the refined diet.

TABLE 5
Daily food total nitrogen (N) intakes and excretions, the composition of urinary N, the ratio of urinary energy to urinary N, and the ratio of urinary energy to food N for subjects in the 3 experimental diets groups[1]

	Refined diet	Fruit and vegetable diet	Cereal diet
Intake and excretion of N			
Daily intake (g/d)	14.74 ± 1.15[a] (10.85–20.22)	11.63 ± 1.00[a] (6.97–13.99)	12.45 ± 1.35[a] (9.29–18.67)
Fecal excretion (g/d)	1.45 ± 0.31[b] (1.12–1.87)	2.18 ± 0.23[a] (1.11–3.03)	2.13 ± 0.22[a] (1.41–3.41)
Urinary excretion (g/d)	11.48 ± 2.06[a] (8.26–14.33)	8.94 ± 0.55[b] (6.43–11.25)	11.11 ± 1.14[a,b] (6.96–17.63)
Urinary nitrogenous constituent (g/100 g total urinary N)			
Creatinine N	3.5 ± 0.14[a] (3.0–4.2)	4.4 ± 0.16[b] (3.8–5.5)	3.7 ± 0.15[a] (2.9–4.4)
Ammonia N	3.8 ± 0.10[a] (3.2–4.3)	3.9 ± 0.27[a] (2.9–5.2)	3.9 ± 0.26[a] (2.9–5.4)
Uric acid N	0.8 ± 0.09[a] (0.5–1.5)	0.8 ± 0.07[a] (0.5–1.2)	1.3 ± 0.08[b] (0.9–1.6)
Urea N	87.4 ± 0.33[a] (86.0–89.4)	85.4 ± 1.95[a] (80.3–96.1)	85.0 ± 0.75[a] (82.2–89.9)
Urinary energy:urinary N (kJ/g N)	33.9 ± 0.33[a] (32.5–35.4)	44.1 ± 0.90[b] (39.1–47.7)	37.6 ± 0.39[c] (35.2–39.1)
Urinary energy:food N (kJ/g N)	26.9 ± 1.22[a] (19.8–30.8)	34.9[b] ± 1.81[b] (23.8–42.9)	33.9 ± 1.20[b] (28.3–39.6)

[1] All values are $\bar{x}$ ± SE; range in parentheses. $n = 9$. Means in the same row with different superscript letters are significantly different, $P < 0.05$ (ANOVA followed by Tukey's test).

modified Atwater factors, for which dietary carbohydrate is corrected for insoluble dietary fiber (FDA) or is determined as available carbohydrate (British), gave better agreement but practically important differences (4%) remained. In general, the empirically derived prediction equations that were tested did not lead to a higher level of accuracy of prediction compared with the factorial models.

DISCUSSION

We sought to understand variation in energy availability and the predictive accuracy of Atwater factors (3) for a range of complex mixed diets in healthy persons. We focused on 3 aspects: analysis of dietary carbohydrate (available and unavailable), digestibility and metabolizability, and the importance of the amount of food consumed. Our results confirm that the Atwater calculation system can overestimate the ME content of diets by up to 11%, a finding consistent with others (3, 7, 29, 30). A new observation from this study was that energy availability is particularly low in association with spontaneously reduced energy intakes from high-fiber diets. The spontaneous reduction in food energy may have been secondary to keeping a constant intake of dry mass per kg body weight (Table 4) or to physiologic cues other than energy. The considerable degree of variability across diets for macronutrient digestibility (Table 6) and urinary energy excretion per unit nitrogen (Table 5) highlights a shortcoming of calculation factors, such as the Atwater factors, and also underscores the potential to explore such variation in the development of weight-loss foods.

TABLE 6
Apparent digestibility of gross energy, crude protein, fat, total carbohydrate, and individual fatty acids for the 3 experimental diets[1]

	Refined diet	Fruit and vegetable diet	Cereal diet
Digestibility of energy (%)	93.5 ± 0.19[a] (92.4–94.1)	90.0 ± 0.79[b] (85.4–93.4)	89.1 ± 0.23[b] (87.9–90.0)
Digestibility of protein (%)	90.0 ± 0.44[a] (88.4–92.6)	81.4 ± 0.92[b] (78.7–85.6)	82.7 ± 0.73[b] (80.3–86.7)
Digestibility of fat (%)	95.7 ± 0.29[a] (94.3–97.3)	87.0 ± 1.00[b] (81.7–91.6)	95.1 ± 0.33[a] (93.4–96.9)
Digestibility of total CHO (%)	94.4 ± 0.39[a] (92.9–96.1)	95.5 ± 0.66[a] (91.1–97.4)	91.1 ± 0.26[b] (89.9–92.1)
Digestibility of individual fatty acids (%)			
Saturated			
10:0	99.9 ± 0.08[a] (99.3–100.0)	87.4 ± 1.46[b] (81.6–93.0)	98.2 ± 0.89[a] (94.1–100.0)
12:0	98.7 ± 0.75[a] (93.1–100.0)	80.7 ± 1.29[b] (76.4–86.7)	99.7 ± 0.18[a] (98.3–100.0)
14:0	99.0 ± 0.20[a] (98.3–100.0)	79.2 ± 1.16[b] (75.4–85.4)	99.4 ± 0.23[a] (98.2–100.0)
16:0	94.7 ± 0.58[a] (92.7–97.6)	87.8 ± 0.58[b] (85.6–91.2)	96.4 ± 0.11[c] (95.8–96.9)
18:0[2]	86.3 ± 2.24[a,b] (75.2–96.8)	84.0 ± 2.16[a] (74.4–92.1)	91.1 ± 1.03[b] (85.5–96.2)
Monounsaturated			
16:1[2]	99.6 ± 0.42[a] (96.2–100.0)	100.0 ± 0[a] (100.0–100.0)	100.0 ± 0[a] (100.0–100.0)
18:1[2]	94.3 ± 0.55[a,b] (92.5–96.9)	93.1 ± 1.04[a] (87.1–96.4)	95.9 ± 0.24[b] (94.7–97.1)
Polyunsaturated			
18:2[2]	94.2 ± 1.29[a] (88.3–98.6)	92.2 ± 2.22[a] (77.6–97.7)	96.7 ± 0.50[a] (94.5–98.7)
18:3[2]	93.2 ± 0.78[a] (88.7–96.5)	96.8 ± 0.65[b] (93.2–98.8)	97.7 ± 0.38[b] (95.8–99.3)

[1] All values are $\bar{x}$ ± SE; range in parentheses. $n = 9$. CHO, carbohydrate. Means in the same row with different superscript letters are significantly different, $P < 0.05$ (ANOVA followed by Tukey's test).

[2] Digestibilities for the 18-carbon series of fatty acids were compared between groups by using a 2-factor ANOVA (including factors for diet and degree of unsaturation). The digestibility of 18:0 was significantly lower ($P < 0.005$) than the digestibilities of 18:1, 18:2, and 18:3 for all 3 diets. The digestibilities of monounsaturated fatty acids were compared between groups by using a 2-factor ANOVA (including factors for diet and chain length). The digestibility of 18:1 was significantly lower ($P < 0.001$) than that of 16:1 with all 3 diets.

TABLE 7
Models used to predict the metabolizable energy values (kJ/g) of the diets[1]

Model and reference	Model
Factorial model	
Atwater, 1910 (21)	$ME_{Atwater} = 16.7P + 37.6F + 16.7C$
British food tables, 1991 (22)[2]	$ME_{British} = 16.7P + 37.6F + 15.7Cm$
FDA, 1993 (23)	$ME_{FDA} = 16.7P + 37.6F + 16.7\ (C - isDF)$
Atwater, modified, 1998 (7, 24)	$ME_{Atwater\ modified} = 16.7P + 37.6F + 16.7\ AC + 8.4UC$
Empirical model	
Levy et al, 1958 (25)	$ME_{Levy} = 0.976E - 33.3N - 250$
Miller and Payne, 1959 (9)	$ME_{M\&P} = 0.95E - 31.4N$
Southgate, 1975 (26)	$ME_{Southgate} = 0.977E - 16.7UC - 27.6N$
Miller and Judd, 1984 (27)	$ME_{M\&J} = (0.95E - DF\%) - 31.4N$
Livesey, 1991 (28)	$ME_{Livesey} = 0.96E - 8.4U - 30N$

[1] ME (kJ/g), metabolizable energy; P (g), dietary protein; F (g), dietary fat; C (g), total carbohydrate by difference; Cm (g), determined available carbohydrate expressed as equivalent weight of monosaccharide; isDF (g), insoluble dietary fiber; AC, available carbohydrate (determined by difference); UC (g), unavailable carbohydrate determined as Southgate dietary fiber or total dietary fiber; E (kJ/g), gross energy of diet; N (g), dietary nitrogen; DF%, total dietary fiber as a percentage of the dry weight of the diet; U (g), unavailable complex carbohydrate; FDA, Food and Drug Administration.
[2] For legislative purposes, the Atwater approach is used in the European Union; fiber has zero energy by default (C = total carbohydrate minus total dietary fiber).

The calculation of food energy assumes accurate analysis of food components. Currently, the approaches used to calculate such differ between regions in relation to total, available, and unavailable carbohydrates. Total carbohydrate in foods and diets can be derived in at least 3 ways (**Table 9**). With both of the present high-fiber diets, direct measurements gave lower values than did indirect measures determined from differences. Should the direct measures be used, a discrepancy of ≈5% of the dry weight of food arises and would lead toward a lower food energy value of ≈5%. For this reason, care needs to be taken over the approach used to analyze carbohydrate.

Also important is the method for estimating unavailable carbohydrate. NSP, resistant starch, and the sum of these 2 components each underestimates total dietary fiber according to the methods used (**Table 10**). Total dietary fiber most closely represents the measure used in the derivation of food energy factors for unavailable carbohydrate (2, 28). The ratio of total dietary fiber to NSP in the refined, the fruit and vegetable, and the cereal diets was similar at about an expected value of 1.3 (Table 10). This is of parenthetical interest because the lack of variability suggests that neither NSP nor total dietary fiber would have demonstrable superiority over the other in indicating a healthful diet, which is of particular interest at

TABLE 8
Determined metabolizable energy (ME) values, calculated ME values based on the application of different models, and differences between determined ME and calculated ME for the 3 experimental diets[1]

	Refined diet		Fruit and vegetable diet		Cereal diet	
	Value	Difference[2]	Value	Difference[2]	Value	Difference[2]
		%		%		%
Determined (kJ/g DM diet)[3]						
GE	23.397 ± 0.03[a]	—	19.741 ± 0.02[b]	—	19.840 ± 0.01[c]	—
ME	21.111 ± 0.06[a]	—	17.043 ± 0.14[b]	—	16.814 ± 0.05[b]	—
Calculated with factorial models (kJ/g DM diet)[4]						
$ME_{Atwater}$	21.884	3.7[4]	18.873	10.8[5]	18.274	8.3[5]
ME_{FDA}	21.134	0.1	17.738	4.1[5]	16.616	−1.2[4]
$ME_{British}$	21.057	−0.3	16.809	−1.3	16.122	−4.1[5]
$ME_{Atwater\ modified}$	21.520	1.9	18.245	7.1[5]	17.450	3.8[5]
Calculated with empirical models (kJ/g DM diet)						
ME_{Levy}	21.398	1.4[4]	18.084	6.2[5]	17.966	6.9[5]
$ME_{M\&P}$	21.344	1.1[4]	18.096	6.2[5]	18.052	7.4[5]
$ME_{M\&J}$	21.295	0.9[6]	18.018	5.8[5]	18.030	7.2[5]
$ME_{Southgate}$	21.486	1.8[5]	17.761	4.3[5]	17.378	3.4[5]
$ME_{Livesey}$	21.211	0.5	17.661	3.7[5]	17.445	3.8[5]

[1] Means in the same row with different superscript letters are significantly different, $P < 0.001$ (ANOVA followed by Tukey's test).
[2] Calculated as $100 \times (ME_{calculated} - ME_{determined})/ME_{determined}$.
[3] Values are $\bar{x} \pm$ SEM; $n = 9$.
[4] $P < 0.01$ (Student's t test).
[5] $P < 0.001$ (Student's t test).
[6] $P < 0.05$ (Student's t test).

TABLE 9
Three different approaches to calculating total carbohydrate (g/100 g dry food)[1]

Method of analysis	Refined diet	Fruit and vegetable diet	Cereal diet
A) Total CHO by difference	51.6	70.5	69.1
B) Available CHO[2] + total dietary fiber	50.8	66.1	65.2
C) Available CHO + NSP + RS	49.8	64.7	63.6
Difference A minus B	1.6	6.2	5.7
Difference A minus C	1.7	5.8	5.5

[1] Refer to Table 2 for individual components. CHO, carbohydrate; NSP, nonstarch polysaccharide; RS, resistant starch.
[2] Determined directly and expressed as the weight of the carbohydrate (18).

the present time to WHO/FAO/Codex deliberations on the definition of dietary fiber.

The calculation of food energy values by factorial approaches, such as the Atwater system, assumes also that the gross energy in fat, carbohydrate, and protein is reasonably well represented by those gross energies used in the derivation of Atwater factors (5.65 kcal/g protein, 9.3 kcal/g fat, and 4.1 kcal/g total carbohydrate; 1 kcal = 4.184 kJ). With the use of these factors, the calculated gross energy contents of the 3 diets were 23.747, 20.303, and 19.838 kJ/g for the refined, fruit and vegetable, and cereal diets, respectively, which differ from the determined values for gross energy in the diets by 1.5%, 2.8%, and 0.0% respectively. These differences appear to be within experimental error, although the overestimation for the fruit and vegetable diet may have resulted because of the lower gross energy of the protein in the fruit and vegetables (with a higher proportion of free amino acids of low energy density), the higher proportion of sugars with a lower gross energy value than starch (Table 2), the higher proportion of organic acids (of lower energy density than carbohydrate), and the higher uronic acid content of fiber (Table 3) and thus the lower gross energy content of the fiber (≈16.5 kJ/g on average for the fruit and vegetable fiber diet compared with ≈17.5 kJ/g on average for the cereal fiber diet) (31).

The ME values for the high-fiber diets were not calculated accurately by any of the various systems of food energy assessment (Table 8). At first this seems surprising; however, a combination of the present results with those of Brown et al (7) provides useful insight (**Figure 1**). Brown et al used a modified Atwater approach in which total carbohydrate is separated into its component parts of available carbohydrate and unavailable carbohydrate, with assignment of separate energy values. The application of this system to food items provides results that are little different from those obtained with the use of the food-specific system of food energy assessment (3, 25). The results of the present study combined with those of Brown et al (7) (Figure 1) indicate that the modified Atwater approach may be suitable for application with high-fiber diets, but not when food intake is reduced. When food intake decreases, as it may with consumption of high-fiber diets, fecal excretion exceeds that predicted by the Atwater modified system. This also indicates a need to maintain the use of standardized methodology during food energy evaluations, for which zero nitrogen balance and zero energy balance have been suggested (2, 6). It also could explain some of the variability in results with unavailable carbohydrates found in the literature (reviewed by Livesey; 30). In the present study, gross energy was expressed as kJ/kg body weight (Figure 1). It remains to be seen, however, whether body weight, the departure from maintenance energy intakes, or some other factor was the key determinant of the variability; whether energy intakes differ between men and women; and the extent to which the slope (Figure 1) might vary with the amount and type of fiber. Importantly, matching energy requirements and energy intake should take account of this response. It will also be important to ascertain whether the lower than expected energy availability from the high-fiber diets taken deliberately or spontaneously at submaintenance levels persists in the long term.

TABLE 10
Contrasting approaches to the assessment of unavailable carbohydrate (g/100 g dry food)[1]

Component	Refined diet	Fruit and vegetable diet	Cereal diet
A) TDF	4.9	7.89	10.02
B) NSP	3.51	5.64	7.82
C) RS	0.45	0.81	0.64
D) Sum NSP + RS (B plus C)	3.96	6.45	8.46
A minus D	0.94	1.44	1.56
A:B	1.396	1.399	1.281

[1] TDF, total dietary fiber; NSP, nonstarch polysaccharide; RS, resistant starch.

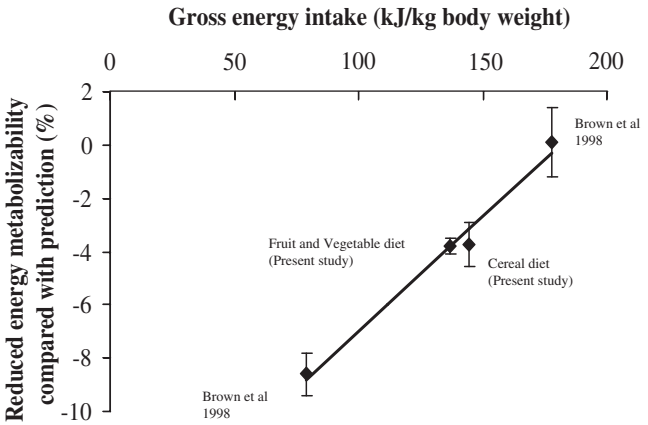

FIGURE 1. Mean (±SEM) reduction in available metabolizable energy associated with low food intakes from high-fiber diets calculated by using a modified Atwater system (*see* Table 7) with correction for errors in predicted gross energy so as to view the change in metabolizable energy due to biological processes alone:

$$100/ME_{determined} \times [(ME_{calculated} - ME_{determined}) - (GE_{calculated} - GE_{determined})] \quad (3)$$

Values shown are for high-fiber maintenance and submaintenance diets from Brown et al (7) combined with the present results with the high-fiber fruit and vegetable diet and the cereal fiber diet.

A further issue for matching food energy with energy requirements concerns differences in thermogenesis between different food components (2, 32). In particular, protein and fiber are more thermogenic than is available carbohydrate and this contributes an energy loss equivalent to 20% of the ME in protein and 25% of the ME in fiber (above that for available carbohydrate) (2). The sum of absolute errors in the ME system of food energy on such account, for the present study, amounts to 2.4% of ME corrected for thermal losses (net ME). However, in the present study there was a decrease in protein intake simultaneously with an increase in fiber intake, so that we would not expect important differences between the refined and high-fiber diets in the present cases. Indeed, we estimate a difference of only 0.2% of net ME. This differs from many specialized foods intended for obesity control, which use a high proportion of both fiber and protein (2).

In developing and evaluating specialized low-calorie foods, for which very small differences in ME may be of practical significance, the use of Atwater or modified Atwater factors is likely to be too inaccurate. Fiber preparations of very high fermentability, very low fermentability, or particularly viscous fiber and gel-forming fibers are expected to differ from the general trend for foodstuffs, which have a narrower range of fermentability, viscosity, and gelling characteristics. For an accurate evaluation of the "available" energy content, especially of novel formulated weight-loss foods, it would be more accurate to determine digested and fermented nutrients (at both the ileal and fecal levels), to predict potential ATP production using stoichiometric relations, to predict urinary energy losses, and thus derive a net ME (6) value.

In conclusion, we confirm lower energy availability from high fiber diets. We also show modest (spontaneous) lower food intake is sufficient to make food energy assessment systems inadequate as predictors of food energy value in high fiber diets, thus extending similar prior findings made with sub maintenance high fiber diets. In this study we found that the high-fiber fruit and vegetable diets and the cereal diets were not distinguishable. However, we did not invalidate the modified Atwater factor system for comparison of ME values of foods in general when consumed at zero nitrogen balance and zero energy balance (meaning energy intake minus energy expenditure). The system does not account for differences in thermal energy losses associated with the metabolism of the macronutrients.

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