Effect of diets high or low in unavailable and slowly digestible carbohydrates on the pattern of 24-h substrate oxidation and feelings of hunger in humans[1–3]

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ABSTRACT

Background: The pattern of substrate utilization with diets containing a high or a low proportion of unavailable and slowly digestible carbohydrates may constitute an important factor in the control, time course, and onset of hunger in humans.

Objective: We tested the hypothesis that isoenergetic diets differing only in their content of unavailable carbohydrates would result in different time courses of total, endogenous, and exogenous carbohydrate oxidation rates.

Design: Two diets with either a high (H diet) or a low (L diet) content of unavailable carbohydrates were fed to 14 healthy subjects studied during two 24-h periods in a metabolic chamber. Substrate utilization was assessed by whole-body indirect calorimetry. In a subgroup of 8 subjects, endogenous and exogenous carbohydrate oxidation were assessed by prelabeling the body glycogen stores with [^{13}C]carbohydrate. Subjective feelings of hunger were estimated with use of visual analogue scales.

Results: Total energy expenditure and substrate oxidation did not differ significantly between the 2 diets. However, there was a significant effect of diet ($P = 0.03$) on the carbohydrate oxidation pattern: the H diet elicited a lower and delayed rise of postprandial carbohydrate oxidation and was associated with lower hunger feelings than was the L diet. The differences in hunger scores between the 2 diets were significantly associated with the differences in the pattern of carbohydrate oxidation among diets ($r = -0.67$, $P = 0.006$). Exogenous and endogenous carbohydrate oxidation were not significantly influenced by diet.

Conclusions: The pattern of carbohydrate utilization is involved in the modulation of hunger feelings. The greater suppression of hunger after the H diet than after the L diet may be helpful, at least over the short term, in individuals attempting to better control their food intake. *Am J Clin Nutr* 2000;72:1461–8.

KEY WORDS Dietary fibers, unavailable carbohydrates, dietary carbohydrates, energy expenditure, respiratory quotient, exogenous carbohydrate oxidation, stable isotopes, hunger, appetite, substrate utilization

INTRODUCTION

The availability of dietary carbohydrates depends largely on their physical form and chemical composition, which together determine their fate in the intestinal tract. The available portion of dietary carbohydrates is absorbed in the small intestine, and thus appears in the circulation relatively rapidly in the form of monosaccharides, mainly glucose. Unavailable carbohydrates eventually reach the colon, where they are partly fermented by the colonic microflora, releasing gases, lactate, and short-chain fatty acids (acetate, propionate, and butyrate), the last being metabolized by the colonocytes or passing into the portal circulation for subsequent utilization as energy substrates.

A few short-term studies investigated the relation between carbohydrate availability and energy metabolism (1–8). In general, these studies found that unavailable carbohydrates reduce the thermic response to a meal and delay the postprandial oxidation of carbohydrates measured over 5–6 h. In addition, there is some evidence that the short-chain fatty acids produced during colonic fermentation of carbohydrates may reduce hepatic glucose production (9). However, most of the published studies investigated the effect of unavailable carbohydrates on postprandial nutrient oxidation with single meals over a limited period of time, rather than after 3 meals over a 24-h period.

This study was designed to test the hypothesis that diets with the same macronutrient composition but differing in their content of unavailable and slowly digestible carbohydrates (ie, carbohydrates digested completely in the small intestine but relatively more slowly) will result in different time courses of the 24-h carbohydrate oxidation rate. Specifically, we hypothesized that a diet high in unavailable carbohydrates would result in reduced diurnal postprandial carbohydrate oxidation, altered endogenous glucose oxidation, and a progressive shift of carbohydrate oxidation toward the nighttime. We hypothesized that the sparing of carbohydrates during the daytime would contribute to short-term satiety.

TABLE 1
Physical characteristics of the subjects participating in the study[1]

	Men ($n = 7$)	Women ($n = 7$)
Age (y)	24.4 ± 3.6	22.7 ± 2.4
Weight (kg)	74.5 ± 9.7	63.3 ± 8.1
Height (cm)	181.1 ± 5.2	171.0 ± 6.5
BMI (kg/m^2)	22.7 ± 3.0	21.6 ± 2.2
Body fat (%)	14.2 ± 4.7	26.0 ± 3.6

[1] $\overline{x}$ ± SD.

SUBJECTS AND METHODS

Subjects

The physical characteristics of the 14 subjects (7 women and 7 men) who participated in this study are shown in **Table 1**. To be admitted to the study, subjects had to be between 20 and 30 y old and have a normal body weight [ie, a body mass index (BMI; in kg/m^2) between 19 and 25]. Athletes, vegetarians, and those with a family history of obesity or diabetes were excluded. We also excluded candidates who smoked, who had known intestinal problems, and who had used antibiotics recently. According to a dietary interview carried out at the time of admission to the study, the subject's habitual diets provided on average 51% of energy as carbohydrates (range: 41–58%) and 36% of energy as fat (range: 26–48%). Consumption of unavailable carbohydrate averaged 18.5 ± 7 g/d (range: 8–31 g/d). Before being admitted to the study, subjects received a detailed written and oral explanation of the different procedures involved in the study and signed an informed consent form. The protocol was submitted to and approved by the Ethical Committee of the Faculty of Medicine of the University of Lausanne.

Experimental design

The aim of the study was to compare the effects on 24-h nutrient oxidation of 2 diets, one high (H diet) and the other low (L diet) in unavailable carbohydrates and slowly digestible carbohydrates. In addition to 24-h carbohydrate oxidation, we aimed to measure the proportion of the oxidized carbohydrates that was of endogenous origin, the importance of colonic fermentation, and subjective feelings of hunger and stomach fullness during the tests. Macronutrient oxidation was measured by indirect calorimetry in a metabolic chamber as described previously (10). Daytime and nighttime urinary collections were also made for total nitrogen analysis by the Kjeldahl method. Energy expenditure and substrate oxidation were computed according to a classic calorimetric formula (11) as outlined by Schutz (*see* the equations in Table 9 of reference 12 for a review). Endogenous carbohydrate oxidation was measured by labeling the body glycogen stores of the subjects with [^{13}C]glucose fed before the test and then measuring the isotopic enrichment in $^{13}CO_2$ in expired air during the tests. An index of colonic fermentation was obtained by measuring breath-hydrogen production. Satiety and stomach fullness were rated with use of visual analogue scales (VASs).

Subjects were measured 3 times in the metabolic chamber: first during a pretest aimed at measuring energy requirements in confined conditions, and then during 2 main tests, during which the H and L diets were compared. The daily energy requirements of the subjects, measured during the first 24-h stay in the metabolic chamber (pretest), were subsequently used to determine energy intakes during the H and L diets in the next 2 tests. This was done to ensure that subjects would be close to zero energy balance during the tests. Each subject participated in the 2 main tests in random order. The subjects performed a set amount of physical exercise during each 24-h stay in the chamber: at 1100 and 1600 each subject walked on a horizontal treadmill at a speed of 4.5 km/h for 30 min.

To standardize as much as possible the conditions under which the measurements were made and to label glycogen stores with ^{13}C, subjects followed a fixed routine during the 4 d preceding each main test as shown in **Figure 1**. The loading procedure with [$^{13}C_6$]-D-glucose (Isotec, Miamisburg, OH) was shown previously to result in stable labeling of hepatic glycogen within 3 d without significant labeling of body fat and protein (13). Only a subset of 8 subjects participated in the [^{13}C]glucose procedure.
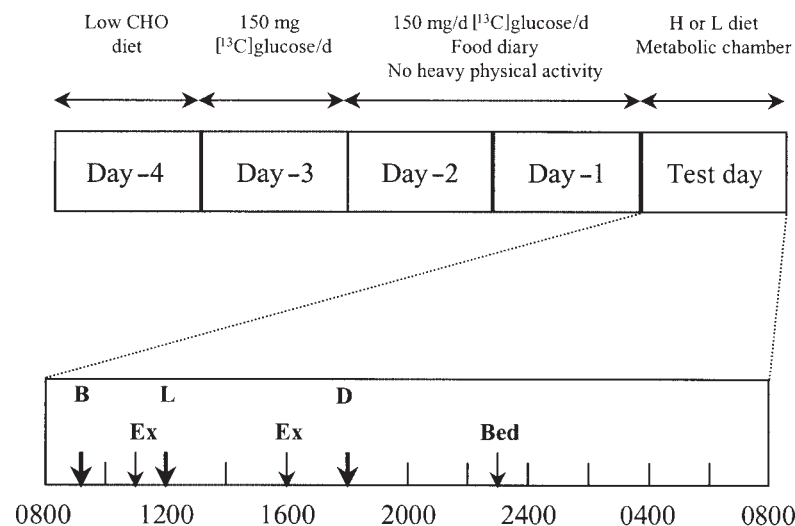

FIGURE 1. The events involved in each main test. The [^{13}C]glucose was added to fruit juices. The food diary obtained before the first test was used to reproduce food intake as closely as possible during the second test. Subjects received the diets high (H diet) or low (L diet) in unavailable carbohydrates in random order. CHO, carbohydrate; B, breakfast; L, lunch; D, dinner; Ex, 30 min of walking on a treadmill at 4.5 km/h.

TABLE 2
Foods included in the 2 experimental diets, which were either low (L diet) or high (H diet) in unavailable carbohydrates

	L diet	H diet
Breakfast	Puffed rice	Breakfast cereals
	Milk	Milk
		Sliced dried apple
Lunch	Dry meat	Dry meat
	Codfish with cress sauce	Codfish with cress sauce
	White rice	Barley
	Strawberry yogurt	Chickpea salad
	Cookie	Dried apricots
Dinner	Gruyère cheese	Gruyère cheese
	Turkey chunks with mushroom sauce	Turkey chunks with mushroom sauce
	Instant mashed potatoes	Buckwheat
	Vanilla custard	Red bean salad
	Marzipan candy bar	Pears in syrup

Diets

The food included in the H and L diets is shown in **Table 2**. For each subject, total energy intake was the same for the 2 diets. The relative macronutrient composition of the 2 diets was identical: 18% of energy as protein, 30% of energy as fat, and 52% of energy as carbohydrate. The composition of the diet was computed from the tables of Favier et al (14) and Souci et al (15).

The unavailable carbohydrate composition of the H and L diets is shown in **Table 3**. The carbohydrate composition was computed from the data of Englyst et al (16). The diets were prepared at 8 energy levels ranging from 7.7 to 13 MJ/d, in steps of 800 kJ. Subjects were required to eat all of the food provided during the tests. Fluid intake was ad libitum, but during meals water intake was restricted to 2 glasses ($\approx$400 mL).

Body composition

The body weight, height, and relative body fat of each subject were measured by the same investigator. Body fat was estimated from the combined results obtained by the skinfold-thickness method according to Durnin and Womersley (17) and the bioelectrical impedance analysis method (18).

Hydrogen production

Breath hydrogen was used as an index of colonic fermentation (19). End-expiration (alveolar) breath samples were collected every 2 h from 0800 until 2200 and again at 0700 the next morning during the calorimetric tests. The samples were analyzed in triplicate within 24 h by using a Quintron Microlyzer hydrogen analyzer (model 12; Quintron Instruments, Milwaukee) calibrated with a standard gas with a hydrogen concentration of 100 ppm.

Endogenous and exogenous glucose oxidation

During the calorimetric tests, expired air samples were collected in quadruplicate in airtight glass tubes every hour for measurement of $^{13}CO_2$ enrichment. In addition, subjects collected 4 samples of expired air in the morning of day -3, before drinking the first fruit juices containing labeled glucose (450 mg/d). These samples were used to measure the baseline abundance of $^{13}CO_2$. Breath $^{13}CO_2$ abundance was measured in duplicate by continuous flow isotope ratio mass spectrometry with a Roboprep G-Tracermass spectrometer (Europa Scientific Ltd, Crewe, United Kingdom).

To calculate endogenous glucose oxidation, we first estimated the glycogen enrichment that was achieved by the labeling procedure as described previously by Gay et al (13). Exogenous glucose oxidation was calculated by subtracting endogenous from total glucose oxidation, the latter being assessed by indirect calorimetry.

After the ingestion of meals containing unlabeled carbohydrate, oxidation of exogenous glucose tends to replace endogenous glycogen utilization. As a result, $^{13}CO_2$ progressively decreases over time. For this period, we computed $^{13}CO_2$ production and [^{13}C]glucose oxidation (20). Because some of the unlabeled carbohydrate eaten during the day of the test was also stored, the glycogen enrichment in ^{13}C decreased throughout the day. Thus, this procedure allowed us to compute the utilization of glucose that was in the body stores at the beginning of the tests and not true "endogenous" glucose utilization. Nevertheless, for simplicity, we will refer to this as endogenous glucose oxidation throughout this article.

Subjective feelings of hunger and satiety

VASs were used throughout the day to assess hunger, desire to eat, and fullness. Subjects completed a 10-cm linear VAS immediately before and after breakfast, at hourly intervals in the morning, before and after lunch, again at hourly intervals in the afternoon, before and after dinner, and at hourly intervals in the evening until going to bed. A final VAS was completed the following morning on waking up. Briefly, subjects were asked to make a single mark on the VAS somewhere between 0-cm and 10-cm extremes to indicate their feelings before and after each meal at each time point. Differences in hunger rating scores between the 2 diets were also quantified.

Data analysis

Unless indicated otherwise, values are expressed as means ± SEs. Statistical analysis was carried out by using SPSS 7.0 for WINDOWS (SPSS Inc, Chicago). Comparisons of 24-h mean values between diets were done by using paired t tests, after testing for normality. The overall difference between hourly profiles of carbohydrate oxidation was tested by a repeated-measures analysis of variance (ANOVA) and by a run test. This was done because the expected effect of unavailable and slowly digestible carbohydrates on carbohydrate oxidation was limited mainly to the postprandial periods and consisted of a reduced and delayed rise in carbohydrate oxidation. Thus, the temporal profiles of

TABLE 3
Composition of the diets low (L diet) and high (H diet) in unavailable carbohydrates for an energy intake of 10 MJ/d[1]

	L diet	H diet
Fat (MJ/d)	3.0	3.0
Protein (MJ/d)	1.8	1.8
Carbohydrate (MJ/d)	5.2	5.2
Gross energy density (kJ/g)	4.5	4.6
Unavailable carbohydrates (g/d)	3	60
RAG (g/d)	284	231
SDS (g/d)	24	63
RS (g/d)	4	18

[1] The values given constitute a rough estimate based on food-composition tables (14–16). RAG, rapidly available glucose; SDS, slowly digestible starch (starch completely digested at a slow rate); RS, resistant starch (starch degradation products escaping digestion, becoming available for fermentation in the large intestine).
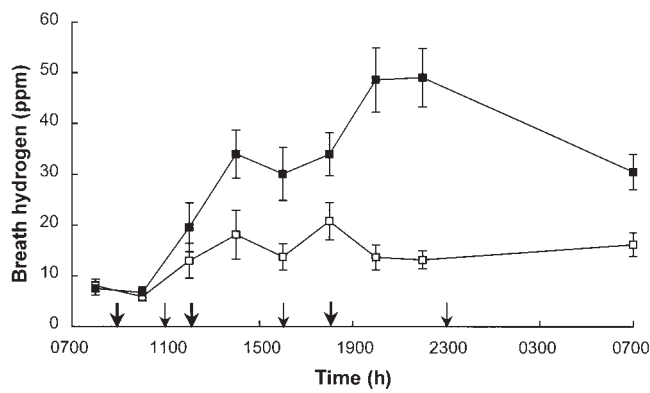
FIGURE 2. Mean (±SE) breath-hydrogen concentrations in the 14 subjects during the 24-h calorimetry tests with consumption of a diet either low (L diet; □) or high (H diet; ■) in unavailable carbohydrates. A repeated-measures ANOVA showed a significant time effect ($P < 0.001$), a significant diet effect ($P = 0.001$), and a significant time × diet interaction ($P < 0.001$). The bold arrows indicate meals and the small arrows indicate the 2 exercise periods and the beginning of sleep.

carbohydrate oxidation for the 2 diets were expected to crisscross repeatedly. The run test would test for the existence of a nonrandom structure in this pattern. The difference between diets at each time point was tested by paired t tests with the Bonferroni correction. The effect of diet on endogenous carbohydrate oxidation was tested by a repeated-measures ANOVA. The VASs were compared by Wilcoxon rank tests (with Bonferroni correction) because the assumption of normality was not satisfied. The association between carbohydrate oxidation and hunger score was tested with Spearman's rank correlation coefficient.

RESULTS

The analysis of the food diaries showed that food intake during the 2 d preceding each test was similar. The average energy intake was 10.3 ± 0.2 and 10.0 ± 0.2 MJ/d before the L and H test, respectively, and the mean within-subject CV was 5.5%. Carbohydrate intake averaged 336 ± 72 g/d before the L test and 342 ± 60 g/d before the H test. The within-subject CV was 5.6%.

During the tests in the metabolic chamber, the average energy intake was 10.0 ± 1.7 MJ/d for both the L and H diets. Macronutrient intakes were also not significantly different between the 2 diets and averaged 112 ± 20 g protein, 82 ± 14 g fat, and 318 ± 52 g carbohydrates. The average weight of food ingested was almost identical for the 2 diets ($\bar{x} \pm SD$): 2.243 ± 0.44 kg/d and 2.240 ± 0.44 kg/d for the L and H diets, respectively.

During both diets, breath hydrogen was low in the morning 1 h before breakfast and was still low 1 h after breakfast. However, starting from 1200, breath hydrogen was significantly higher with the H diet than with the L diet (**Figure 2**). The next morning, breath hydrogen with the H diet was still significantly higher than with the L diet.

During the L diet period, subjects expended on average 9.5 ± 0.4 MJ/d. Carbohydrate oxidation amounted to 4.3 ± 0.3 MJ/d and fat oxidation to 3.4 ± 0.2 MJ/d. The corresponding values for the H diet were 9.5 ± 0.4, 4.7 ± 0.3, and 3.3 ± 0.3 MJ/d, none of which were significantly different from the values for the L diet.

Energy and macronutrient balances measured over the 24-h period were not affected by diet. Energy balance was positive

under both conditions (0.54 ± 0.17 and 0.49 ± 0.17 MJ/d for the L and H diets, respectively). Fat balance was slightly negative during both diets (-0.44 ± 0.16 and -0.32 ± 0.29 MJ/d for the L and the H diets, respectively) and carbohydrate balance was positive (0.77 ± 0.21 and 0.40 ± 0.23 MJ/d for the L and the H diets, respectively).

The profile of carbohydrate oxidation over the 23-h tests is shown in **Figure 3**. Carbohydrate oxidation increased after each meal and during the exercise periods on the treadmill. Fat oxidation increased during the 2 periods of walking and decreased after breakfast and after lunch (data not shown). The run test showed that the difference between the temporal profiles of carbohydrate oxidation obtained for the 2 diets was significantly different from a random arrangement ($z = -2.13$, $P = 0.03$). This implied that the dietary treatment affected the temporal profile of carbohydrate oxidation. The carbohydrate oxidation measured after lunch and after dinner was significantly higher during the L diet than during the H diet ($P < 0.05$). The carbohydrate oxidation measured during the night was significantly lower during the L diet than during the H diet ($P < 0.05$).

In a subsample of 8 subjects, breath $^{13}CO_2$ abundance at baseline was 1.0818 ± 0.0003 atom% before the L diet and 1.0815 ± 0.0003 atom% before the H diet. The consumption of the fruit juices enriched in [$^{13}C_6$]glucose for 3 d increased breath $^{13}CO_2$ enrichment to 1.0898 ± 0.0009 atom% for the L diet and to 1.0896 ± 0.0008 atom% for the H diet. This corresponded to an enrichment of the endogenous carbohydrates of 0.018 ± 0.005 atom percent excess (APE) for the L diet and of 0.015 ± 0.002 APE for the H diet. About 70% of the variance in the initial enrichment of endogenous carbohydrates was explained by the differences in body weight among subjects. Breath $^{13}CO_2$ enrichment decreased throughout the day during both test diets (**Figure 4**), corresponding with the progressive replacement of the initial labeled endogenous glycogen stores with unlabeled carbohydrates of exogenous (dietary) origin as oxidative fuel. By the next morning, most subjects had reached a breath $^{13}CO_2$ enrichment value close to the baseline value recorded before the loading procedure.
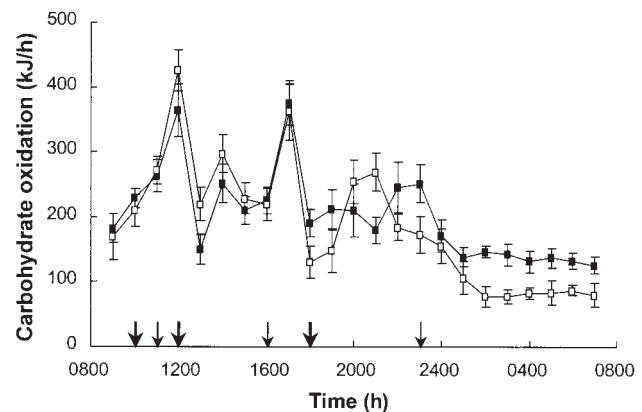

FIGURE 3. Mean (±SE) carbohydrate oxidation rates in the 14 subjects during the calorimetry tests with consumption of a diet either low (L diet; □) or high (H diet; ■) in unavailable carbohydrates. A repeated-measures ANOVA showed a significant time effect ($P < 0.001$), a nonsignificant diet effect ($P = 0.2$), and a significant time × diet interaction ($P < 0.001$). The bold arrows indicate meals and the small arrows indicate the 2 exercise periods and the beginning of sleep.
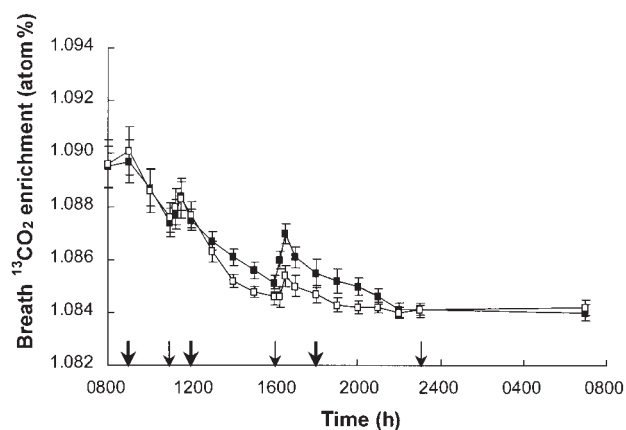
FIGURE 4. Mean (±SE) breath $^{13}CO_2$ enrichment during the calorimetry test for 8 subjects who consumed a diet either low (L diet; □) or high (H diet; ■) in unavailable carbohydrates. There were no significant effects by repeated-measures ANOVA, except for the time effect ($P < 0.001$). The bold arrows indicate meals and the small arrows indicate the 2 exercise periods and the beginning of sleep.

The time profiles of endogenous and exogenous glucose oxidation are shown in **Figure 5**. Endogenous oxidation tended to be higher during the H diet throughout the day, but not significantly so (only the time effect was significant). Endogenous glucose oxidation measured during the waking hours (0900–2300) amounted to 1.89 ± 0.29 MJ/14 h for the H diet and to 1.55 ± 0.30 MJ/14 h for the L diet and did not differ significantly. These values corresponded to 55 ± 6% and 44 ± 7% of the total carbohydrate oxidation measured over the same time period for the H and the L diets, respectively. The exogenous carbohydrate oxidation calculated between 0900 and 2300, ie, the difference between total and endogenous oxidation, was 1.61 ± 0.34 and 1.86 ± 0.21 MJ/14 h for the H and L diets, respectively. These values were not significantly different from each other. Exogenous carbohydrate oxidation represented on average 32% and 37% of the carbohydrate intake for the H and the L diets, respectively.

We calculated that we would need 20 subjects to detect a difference of 10% in substrate oxidation (power of 85% and statistical significance set at $P < 0.05$). With the limited size of the subsample ($n = 8$), we were close to the limit of the statistical power and were able to detect a difference in exogenous carbohydrate oxidation of ≈20%.

The effect of the H and L diets on the temporal profiles of the ratings of hunger and stomach fullness are shown in **Figure 6**. The H diet tended to be more satiating than the L diet, particularly in the afternoon and the evening. The H diet also had a definite effect on stomach fullness, with subjects showing higher scores after lunch and after dinner.

We looked for a possible association between the differential hunger scores and differential carbohydrate oxidation rates observed between the 2 dietary treatments (**Figure 7**). As shown in the figure, there was an inverse association between the 2 variables.

DISCUSSION

Use of the breath-hydrogen test allowed us to provide evidence of the difference in unavailable carbohydrate composition between the 2 diets. As indicated by the results of the test, there was a clear difference in colonic fermentation between the H and L diets:

breath hydrogen was already higher with the H diet than with the L diet after lunch, and was even more so after dinner. Breath hydrogen with the H diet was still higher the next morning. Thus, 4 h after the first meal, unavailable carbohydrates had reached the colon and were being fermented by the microflora. The increase in breath-hydrogen production observed in the present study suggests a lower digestibility of the diet containing unavailable carbohydrate, confirming previous balance studies in humans (21).

The presence of unavailable carbohydrates did not affect overall energy and macronutrient balances because total macronutrient oxidation was not significantly different between diets. Note, however, that a small uncertainty remains as to whether true metabolizable energy intake (which was not measured in the present study) was markedly different between the diets because the apparent digestibility of the H diet was lower.

The time courses of the carbohydrate and fat oxidation rates suggested a modest effect of diet. Less carbohydrate and more fat was oxidized in the postlunch and postdinner periods with the H diet than with the L diet. These differences were compensated for (at least partially) by an inverse effect during the nighttime.

Because colonic fermentation is an incomplete combustion, the calculation of nutrient oxidation by use of the classic equations of indirect calorimetry may give erroneous results when large amounts of unavailable carbohydrates are ingested. However, in
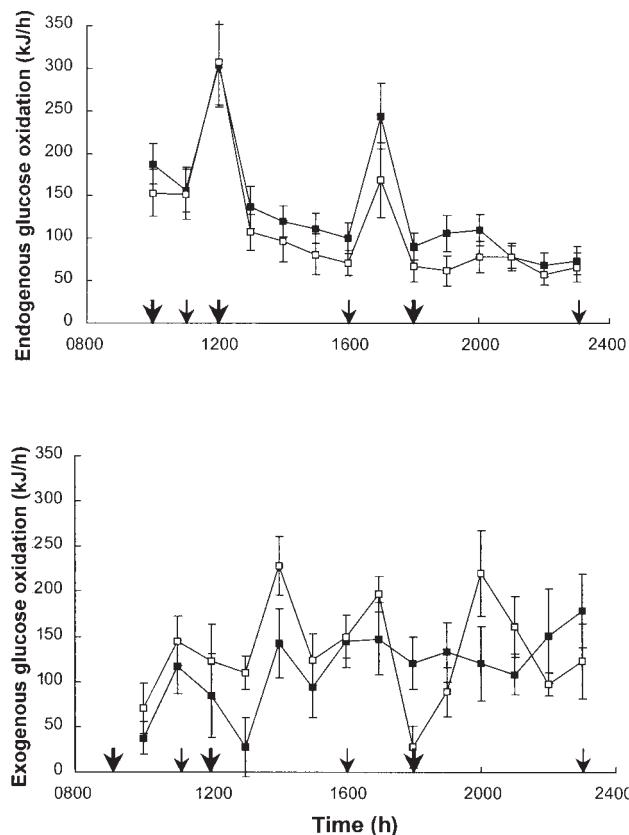

FIGURE 5. Mean (±SE) exogenous and endogenous glucose oxidation for 8 subjects who consumed a diet either low (L diet; □) or high (H diet; ■) in unavailable carbohydrates. There were no significant effects by repeated-measures ANOVA, except for the time effect ($P < 0.001$). The bold arrows indicate meals and the small arrows indicate the 2 exercise periods and the beginning of sleep.
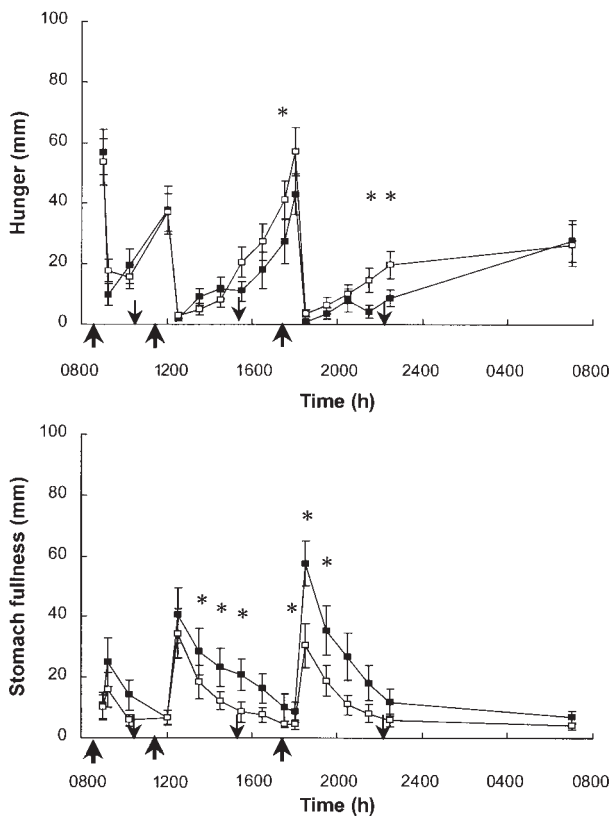
FIGURE 6. Mean (±SE) subjective feelings of hunger and stomach full-ness for the 14 subjects who consumed a diet either low (L diet; □) or high (H diet; ■) in unavailable carbohydrates. The bold arrows indicate meals and the small arrows indicate the 2 exercise periods and the beginning of sleep. *Significant difference between diets, $P < 0.05$ (Wilcoxon test).

an experiment designed to quantify the indirect calorimetry error due to the presence of fermentation, Poppitt et al (22) estimated the maximal error in carbohydrate oxidation after the ingestion of 58 g unavailable carbohydrates to be 2%.

It may be legitimate to ask whether the effects on nutrient uti-lization found in the present study were an artifact resulting from the effects of colonic fermentation on gas exchange measure-ment. To answer this question, we estimated the oxygen uptake and carbon dioxide production that could be attributed to the fermentation process and the subsequent oxidation of the short-chain fatty acids produced by assuming that 75% of the unavail-able carbohydrates were fermented (23) and then using the stoichiometry of carbohydrate fermentation proposed by Miller and Wolin (24). The application of this correction reduced the carbohydrate oxidation rate by 17% on average. However, this factor tended to enhance (rather than decrease) the difference between diets in the postprandial periods. In contrast, the esti-mation of endogenous carbohydrate oxidation was virtually unaf-fected by the correction (an ≈3% difference). Therefore, we considered that the potential error introduced by the presence of fermentation did not invalidate our results.

Examination of the carbohydrate oxidation profiles suggests that with the H diet carbohydrate oxidation was slightly reduced during the postlunch period but peaked at approximately the same time as with the L diet. In contrast, after the evening meal, the effect of the H diet was to delay carbohydrate oxidation. This may

have been because the nature of the carbohydrates ingested at each meal lead to different gastric-emptying rates as a result of differences in the viscosity of the digesta (25). The delay observed in carbohy-drate oxidation after the evening meal may have been associated with this meal's high content of slowly digestible starch (Table 2).

To our knowledge, <10 experimental studies examining the effect of unavailable carbohydrates on energy metabolism have been published (1–8, 26). Of those, only one measured respira-tory gas exchange for 24 h in a metabolic chamber (26). The other studies measured the response to a single meal over 5–6 h (1–8). Most studies reported a slight reduction in postprandial thermogenesis associated with the unavailable carbohydrate meal. In the present study, we could not confirm this difference in energy expenditure between the 2 diets. However, the magni-tude of the difference found in the short-term studies (80–90 kJ/6 h or ≈0.05 kcal/min) may have been too small to be detected with a metabolic chamber. Indeed, the only other study that used a metabolic chamber did not show an effect of unavailable carbo-hydrates on postprandial thermogenesis (26).

The effects of unavailable carbohydrates on postprandial car-bohydrate oxidation are complex. The studies of Raben et al (5) and Ranganathan et al (6) showed that adding fiber to a meal has no effect on postprandial carbohydrate oxidation. Several authors found that the presence of resistant or slowly digestible starch reduces or delays the peak rate of carbohydrate oxidation (1, 3, 8). In contrast, Ritz et al (4), who studied the effect of a highly digestible starch with a low glycemic index, found pro-longed carbohydrate oxidation, which was attributed to a lower fatty acid concentration and lower rate of fat oxidation. In our study, we observed both a reduction in the peak oxidation rate and increased carbohydrate oxidation of longer duration.

The presence of unavailable carbohydrates in the diet resulted in decreased feelings of hunger and increased feelings of full-ness, particularly during the evening. Decreased hunger associ-ated with the consumption of dietary fiber was described by several authors (27–31). Several mechanisms may be involved in the satiating effect of dietary fiber. Viscous polysaccharides were shown to delay emptying of the stomach and thus to prolong sati-ety signals related to gastric distention (32). The increased vis-cosity of the luminal fluid in the small intestine may also slow
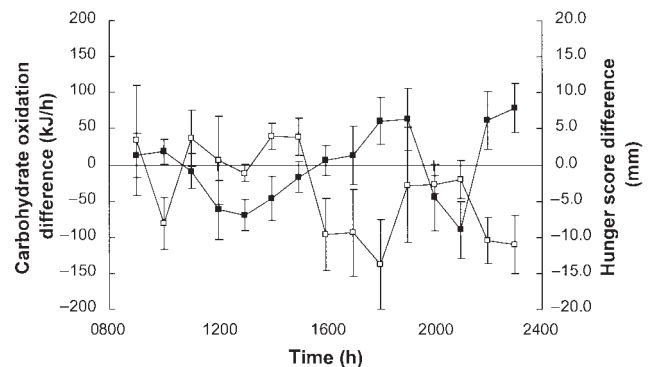

FIGURE 7. Mean (±SE) difference in carbohydrate oxidation (■) between the diets either high (H diet) or low (L diet) in unavailable car-bohydrates compared with the mean difference in hunger score (□) between the H and L diets for the 14 subjects. The Spearman rank corre-lation coefficient calculated for the dietary difference in carbohydrate oxi-dation and the dietary difference in hunger score was −0.67 ($P = 0.006$).

intestinal transit time and thus prolong the contact between nutrients and intestinal receptors (28). The decreased insulin response after a high-fiber meal was shown to be significantly associated with increased satiety (33). Finally, propionate, which is produced during colonic fermentation of carbohydrates, was shown to promote satiety (34).

In our study, the difference in satiety scores between the H and L diets was significantly associated with the difference in carbohydrate oxidation (Figure 7). Because the difference in satiety measured with the 2 diets was higher in the late postprandial periods, it is likely that it was related to the delayed and prolonged increase in carbohydrate oxidation observed after the H meals. This finding is consistent with the results of a study showing that differences in hunger sensations between diets are negatively correlated with differences in glucose metabolism, ie, postprandial glycemia and insulinemia and glucose oxidation (35). This is in keeping with both the glucostatic theory of Mayer (36), which suggests that peripheral carbohydrate utilization produces signals that influence short-term energy intake, and the glycogenostatic theory proposed by Flatt (37), which states that energy intake is determined mainly by changes in carbohydrate balance.

In summary, by using 2 diets with very different contents of unavailable and slowly digestible carbohydrates, but otherwise similar in macronutrient composition, we showed an effect of unavailable carbohydrates on the time course of the carbohydrate oxidation rate. The difference between diets was noted mainly during the postprandial periods, at which time postprandial carbohydrate oxidation with the H diet reached a lower peak than with the L diet and the increase lasted longer. The difference in carbohydrate utilization was negatively associated with the difference in hunger sensations. It is known that differences in subjective hunger sensations do not always translate into different food intakes. However, reductions of hunger in the late afternoon and late evening periods induced by meals with a high content of unavailable and slowly digestible carbohydrates may contribute to reduced evening snacking in persons trying to control their food intake. Longer-term studies are needed to explore the potential importance and the persistence of this phenomenon over a prolonged period.

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