Neutral Detergent Fiber, Hemicellulose and Cellulose Digestibility in Human Subjects[1,2]

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ABSTRACT The fate of dietary fiber and its components was examined in seven women consuming low cellulose (LC) and high cellulose (HC) diets, each for about 1 month. The diets were of constant daily composition and differed only in that the HC diet contained an additional 16 g/day non-nutritive fiber (Solka Floc), which increased the neutral detergent fiber (NDF) of the diet from 9.5 to 23.5 g/day and Crampton and Maynard cellulose from 5.4 to 19.3 g/day. When apparent fiber digestibilities during 5-day periods were determined, both NDF and cellulose digestibilities varied greatly and inconsistently in each subject throughout both diet periods. Therefore, samples were pooled to form a single 20–30 day composite for each subject during each diet. Mean apparent NDF digestibility, after correcting for protein contamination in fecal NDF, was 70.4 ± 7.3% during the LC diet and decreased to 23.0 ± 15.0% during the HC diet. Cellulose digestibility was 69.7 ± 10.7% without and 15.7 ± 17.4% with the added cellulose. Hemicellulose was calculated as NDF minus cellulose. When the fecal NDF was corrected for protein contamination, hemicellulose digestibility averaged 71.7 ± 5.4% during the LC diet and 51.0 ± 7.9% during the HC diet. In a separate experiment, 16 g/day Solka Floc was ingested with a semi-purified liquid diet and only 8% of the cellulose was digested. These results suggest that more than half of the fiber in a LC diet containing fruits, vegetables and refined grains is degraded, while the apparent digestibility of refined cellulose is minimal. J. Nutr. *111:* 287–297, 1981.

INDEXING KEY WORDS neutral detergent fiber · hemicellulose · cellulose · dietary fiber digestibility

Information on the fate of dietary fiber in the gut is essential for evaluating the role of fiber in gastrointestinal function and disease. Early determinations of apparent fiber digestibility in man, probably because of inadequate fiber methods (1), yielded estimates of fiber digestibility ranging from 2 to 100% (2–4). Recently, the detergent procedures of Van Soest (5), which have gained acceptance in fiber research, have been used to quantitate fiber digestibility (6–9). Digestibility of water-insoluble dietary fiber is about 80% when a low fiber diet is consumed (6–8) but decreases when bran (6) or cellulose (8) supplements are added to the diet. Hemicellulose appears to be extensively degraded on a low fiber diet, 99% (6) and 96% (7), while cellulose digestion is less, 75% (6) and 80% (7).

Although these data suggest that fiber

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is extensively degraded in the human gut, problems with the design and methods used in these studies leave this conclusion in question. The original neutral detergent fiber (NDF) procedure does not adequately remove starch from human foodstuffs (10); yet, in only one of these studies (8) was an amylase modification (11) of the NDF procedure (5) employed. Sequentially determining acid-detergent fiber (ADF) on an NDF residue, in an effort to obtain a truer estimate of hemicellulose (10), was only done in the Cornell study (8). Finally, the amount of time needed for any adaptation to a particular fiber intake is unknown, and to date, apparent fiber digestibility has been assessed only during short-term studies.

The purpose of the reported experiments was to estimate NDF, cellulose and hemicellulose digestibilities in human subjects consuming low and high cellulose diets. To overcome limitations found in previous fiber digestibility studies, residual starch in NDF food residues was removed by an α-amylase treatment of the NDF residue; cellulose was measured directly in food and feces to avoid problems[3] with the sequential NDF-ADF procedure. Each diet was consumed for about 1 month (20–30 days) to examine changes in fiber digestibility as subjects adapted to a particular fiber intake, and the amount of undigestible nitrogen in fecal NDF was quantitated as a possible source of error in NDF digestibility measurements.

MATERIALS AND METHODS

Eleven healthy women, ages 20–39 years, of normal height and weight participated in two experiments. Informed consent was obtained from each subject and experiments had been approved by the College of Agricultural and Life Sciences' Committee on Research Involving Human Beings, University of Wisconsin-Madison. Experiment 1 was a 2-month study in which seven women consumed a low cellulose diet for 1 month and then a high cellulose diet for an additional month. Experiment 2 was a 1-week study in which four different women ingested a semipurified, fiber-free diet to which 16 g/day nonnutritive fiber (Solka Floc) was added.

Experiment 1

The two diets and experimental protocol of experiment 1 have been described (12). Briefly, the daily diet consisted of normal, typically-consumed food except for the bread which contained 38 g wheat gluten, 40 g lactalbumin and 22 g casein. Because the low cellulose diet served as an experimental diet of another study (13), it was high in protein (% total kcal: 23% protein, 30% fat, 47% CHO). Fiber sources of the low cellulose diet included three servings of fruits, four servings of vegetables and refined grains. The diet contained the Recommended Dietary Allowance (RDA) of all nutrients except calcium, which was 600 mg/day. The high cellulose diet was the same as the low cellulose diet, except that 16 g/day Solka Floc (BW-200, Brown Co., Berlin, NH) was added to the bread. Each diet was ingested by the seven women for 20–30 days.

Brilliant Blue dye was given orally before breakfast every 5 days as a marker for separating feces into composites and for estimating transit time. All stools were collected, divided into 5-day composites, blended and freeze-dried. Four to six 5-day fecal composites were obtained from each subject during each diet. Gastrointestinal transit times, which have been previously published (12), were determined as the time between ingestion and appearance of Brilliant Blue dye and as the time between ingestion and excretion of 80% of 20 small, radiopaque pellets. Dye was ingested by each subject 4–5 times (31 observations) during the low cellulose period and 5–6 times (40 observations) during the high cellulose period. Pellets were taken with the dye, twice during each diet period, except that subject D ingested pellets only once during the low cellulose diet period.

[3] Brauer, P. M. (1979) Apparent digestibility of neutral detergent fiber in young and elderly adults. Master's thesis, University of Wisconsin.

Food composites for fiber analysis were prepared during each dietary period and lyophilized to constant weight. Dietary fiber in food was determined by a modification (14) of the Van Soest neutral-detergent fiber (NDF) procedure (5) and averaged 9.5 g/day during the low cellulose diet and 23.5 g/day during the high cellulose diet. The modified NDF (14) procedure includes glass wool as a filtering aid and an 18-hour incubation of NDF residue with hog α-amylase (#A6880, Sigma Chemical Co., St. Louis, MO.). Fecal NDF analyses were similar to the unmodified procedure (11), except that glass wool was used as a filtering aid.

Cellulose was measured directly in food and feces by a modification (15) of the Crampton and Maynard procedure (16). Acetone extraction was substituted for the benzene, ether and ethanol extractions, a change which did not alter cellulose recovery. The low cellulose diet contained 5.4 g/day cellulose, the high cellulose diet, 19.3 g/day. To estimate hemicellulose in food and feces, cellulose values were subtracted from the respective NDF residue weights. Apparent digestibilities of NDF, cellulose and hemicellulose were calculated as intake minus output and expressed as a percentage of intake for four to six 5-day periods for each subject during each dietary period.

In addition to the 5-day composites, aggregate composites to represent fecal excretion throughout the two experimental diets were prepared for each subject by combining 2 g of each 5-day, dried composite and mixing. Hence, aggregate fecal composites represented the fecal excretions of each subject during each 20–30 day study. Apparent digestibilities of NDF, cellulose and hemicellulose were determined for the aggregate fecal composites. The nitrogen content of the NDF and cellulose residues of each aggregate composite was determined by the macro-Kjeldahl method (17). Fecal NDF and cellulose were corrected for protein [N × 4.3] (18) contamination and apparent digestibilities of NDF, hemicellulose and cellulose were recalculated.

Experiment 2

Four female subjects consumed a semipurified, liquid diet (Ensure, Ross Laboratories, Columbus, OH) along with 16 g/day Solka Floc for 1 week. Average daily intake of the liquid diet was 1,200 kcal (range 800–1,720 kcal/day). Intake of non-fibrous carbohydrate sources (soda pop, fruit-flavored drinks, sugar, hard candy) provided an additional mean 350 kcal/day. Two of the four subjects consumed 6–12 ounces of a cola soda per day. Brilliant Blue dye was given on days 2 and 8 of the study to permit collection of one 5-day fecal composite from each subject. Fecal composites were lyophilized, fecal NDF and cellulose measured, and protein contamination of fecal fiber residues determined, as described in experiment 1. The dietary fiber source, Solka Floc, was analyzed for NDF and cellulose contents which were 14.5 g and 13.5 g per day, respectively, and apparent digestibilities of NDF and cellulose were calculated.

Apparent fiber digestibility for each subject was calculated as the mean of the four to six 5-day composites collected during each of the two levels of fiber intake. Intersubject and dietary differences were assessed by two-way analysis of variance with unweighted means (19). Between-diet and between-subject differences in fiber digestibility of the aggregate composites also were examined by two-way analysis of variance. Correlations between fiber digestibility and transit time were calculated. In all instances, a P value < 0.05 was considered significant.

RESULTS

Neutral detergent fiber was significantly ($P < 0.01$) more degraded when the low cellulose diet was consumed than when Solka Floc was added to the diet (table 1). No differences in NDF digestibility among subjects were found. But, digestibility varied greatly among 5-day composites in any subject (fig. 1). The variability in fiber digestibility among composites was less during the low cellulose period; coefficients of variation between 5-day

TABLE 1

Mean digestibility of NDF in healthy women consuming low and high cellulose diets

Subject	Low cellulose		High cellulose	
	Mean[1]	Range	Mean[2]	Range
A	56.6 ± 20.3	32.6–82.1	11.2 ± 28.9	−28.5–56.0
B	56.9 ± 14.7	41.2–78.8	43.5 ± 15.0	22.4–62.4
C	60.9 ± 10.0	46.3–69.1	27.0 ± 7.1	19.7–37.6
D	55.9 ± 13.3	41.6–73.2	24.9 ± 19.0	9.2–56.6
E	72.8 ± 7.5	59.8–78.4	23.2 ± 9.2	15.0–36.6
F	84.7 ± 3.6	83.7–90.6	31.1 ± 20.7	2.5–54.2
G	68.0 ± 17.8	43.0–86.6	−11.3 ± 20.2	−38.9–18.3
Mean ± SD	65.1 ± 10.7		21.4 ± 17.3	

[1] Mean ± SD of five determinations except for Subjects A, C and D, where $n = 4$. [2] Mean ± SD of six determinations except for Subject C, where $n = 5$.

measures of NDF digestibility ranged from 4.3% in Subject F to 35.7% in Subject A. More variation in apparent fiber digestibility among composites occurred when the high cellulose diet was consumed. Coefficients of variation of greater than 100% were seen in Subjects A and G, the two subjects in which negative digestibilities of NDF were observed (table 1).

No consistent trends in digestibility with time were seen (fig. 1). Mean apparent digestibility of NDF during the low cellulose diet was 61% on day 5, after which it increased slightly but insignificantly up to day 25. During the high cellulose diet mean digestibility of NDF was 38% on day 5, decreased to 10% on day 15 and appeared to stabilize at about 20% after day 20.

Digestibility of cellulose also decreased significantly ($P < 0.01$) when Solka Floc was added to the diet while no significant differences among subjects were observed (table 2). Results were similar to those seen with NDF digestibility. Again, wide ranges of digestibility within a subject were observed. Negative digestibility of cellulose during the high cellulose diet was seen once in Subject F, twice in Subjects A and D and 4 times in Subject G; mean cellulose digestibility was negative only in Subject G.

Solka Floc ingestion had no significant effect on apparent hemicellulose digestibility and no differences were seen among subjects (table 3). Ranges of digestibility within a subject were again wide, but negative digestibility during a 5-day period was seen only in Subject G, during two of the six 5-day HC periods.

To determine whether gastrointestinal transit time was a factor responsible for the individual variability in fiber

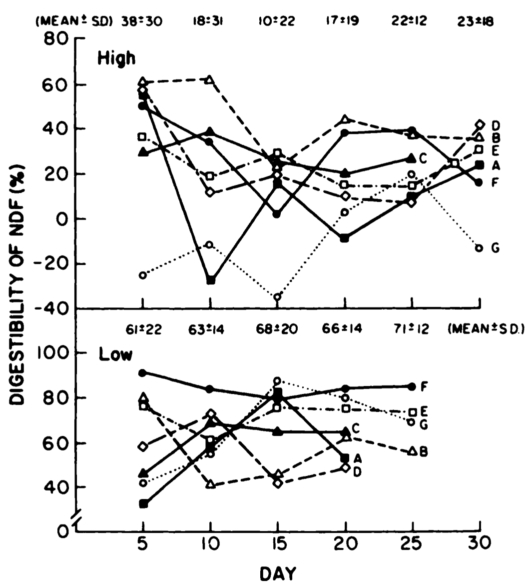

Fig. 1 Changes in NDF digestibility with time in seven women. The top graph shows NDF digestibility during the high cellulose diet and the bottom graph, NDF digestibility during the low cellulose diet. Mean ± SD values of NDF digestibilities (%) for all subjects of each 5-day period are given at the top of each graph. Each subject is identified by a letter at the right side.

TABLE 2

Mean apparent cellulose digestibility in healthy women consuming low and high cellulose diets

Subject	Low cellulose		High cellulose	
	Mean[1]	Range	Mean[2]	Range
A	62.1 ± 21.7	32.6–84.4	4.7 ± 33.1	−40.8–55.8
B	58.1 ± 16.2	42.4–76.1	37.7 ± 18.7	13.9–64.2
C	69.0 ± 7.6	57.8–74.4	19.8 ± 7.9	10.6–30.4
D	59.2 ± 19.1	30.7–69.8	15.3 ± 22.5	−4.5–51.7
E	74.0 ± 9.0	59.8–82.4	16.1 ± 9.5	6.1–29.8
F	88.7 ± 2.8	84.6–92.0	25.5 ± 19.6	−4.3–52.4
G	73.0 ± 11.8	59.1–87.0	−18.0 ± 23.0	−44.8–13.1
Mean ± SD	69.2 ± 10.7		14.4 ± 17.5	

[1] Mean ± SD of five determinations except for Subjects A, C and D, where $n = 4$. [2] Mean ± SD of six determinations except for Subject C, where $n = 5$.

digestibility, individual measurements of transit time and fiber digestibility determined during the same 5-day period were correlated (table 4). During the low cellulose diet, NDF, cellulose and hemicellulose digestibilities correlated significantly with dye transit time, while NDF and cellulose digestibilities were significantly correlated to pellet transit time. Neither dye nor pellet transit times correlated with apparent fiber digestibilities during the high cellulose diet.

To examine gastrointestinal transit time as a possible cause of the variability in apparent fiber digestibility among subjects, mean transit times of the pellets or dye of each subject were correlated with mean NDF, cellulose and hemicellulose digestibilities of each subject. Only mean cellulose digestibility and mean pellet transit time during the low cellulose diet were significantly correlated (table 4).

The wide variability between repeated fiber digestibility measurements in an individual suggested that Brilliant Blue dye was an ineffective aid for dividing fecal samples into 5-day composites representative of the residue from five days of intake. Hence, aggregate fecal samples, which represent 20–30 days of excretion for each subject were prepared. As expected, NDF digestibility determined from the aggregate fecal composites was similar to the mean NDF digestibility of 5-day composites of each subject (table 1, fig. 2). During the low

TABLE 3

Mean apparent hemicellulose digestibility in healthy women consuming low and high cellulose diets[1]

Subject	Low cellulose		High cellulose	
	Mean[2]	Range	Mean[3]	Range
A	47.3 ± 23.9	24.8–79.0	33.3 ± 14.7	18.1–51.1
B	64.6 ± 18.3	39.5–82.4	65.9 ± 11.8	47.8–78.1
C	50.1 ± 14.7	31.2–66.1	55.2 ± 7.9	45.1–67.0
D	51.5 ± 34.5	4.6–77.6	64.9 ± 15.6	55.1–88.9
E	70.8 ± 9.6	59.8–81.9	50.4 ± 14.7	28.1–68.4
F	78.0 ± 7.7	71.2–91.2	50.2 ± 19.4	22.7–70.8
G	61.5 ± 26.1	21.9–86.1	8.7 ± 22.7	−26.8–34.9
Mean ± SD	60.5 ± 11.5		46.9 ± 20.1	

[1] Fecal and food hemicellulose determined as NDF minus cellulose. [2] Mean ± SD of five determinations except for Subjects A, C and D, where $n = 4$. [3] Mean ± SD of six determinations except for Subject C, where $n = 5$.

TABLE 4

Relationships between apparent fiber digestibilities and gastrointestinal transit times

	Low cellulose diet		High cellulose diet	
	80% pellets TT[1]	dye TT	80% pellets TT	dye TT
	correlation coefficients of all observations			
Fiber fraction	(n = 13)	(n = 31)	(n = 14)	(n = 40)
NDF	0.559[a]	0.459[b]	0.008	0.139
Cellulose	0.573[a]	0.362[a]	0.045	0.165
Hemicellulose	0.383	0.399[a]	−0.158	−0.055
	correlation coefficients of mean data (n = 7)			
NDF	0.699	0.739	0.188	0.282
Cellulose	0.765[a]	0.741	0.207	0.330
Hemicellulose	0.436	0.625	−0.094	0.023

[1] TT = transit time. [a] Significant at $P < 0.05$. [b] Significant at $P < 0.01$.

cellulose diet, NDF digestibility was 59.4 ± 11.2% when aggregate fecal composites were used to calculate digestibility, compared to 65.1 ± 10.7% (table 1) with 5-day composites. When Solka Floc was ingested, NDF digestibility averaged 19.7 ± 16.2% with aggregate composites and 21.4 ± 17.3% with 5-day composites. Again, no significant difference in digestibility among subjects was seen.

Fecal NDF from the aggregate samples contained 6.23 ± 1.09% nitrogen during the low cellulose diet and 0.92 ± 0.15% nitrogen during the high cellulose diet. When nitrogen was converted to protein with the factor 4.3 (18), the protein content of the fecal NDF fractions from the low cellulose diet ranged from

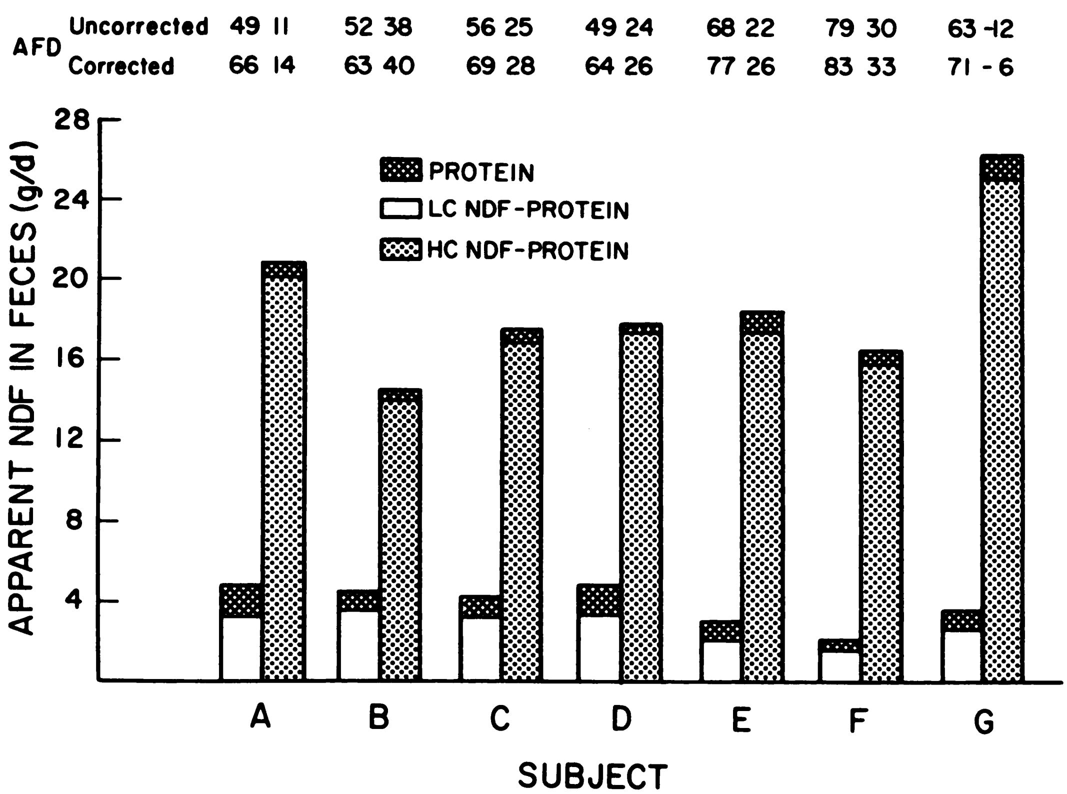

Fig. 2 Fecal excretion of neutral detergent fiber (NDF) before and after correcting for protein contamination (N, g × 4.3). Fecal NDF and fecal NDF protein (▩) for each subject during the low cellulose (LC) diet (□) are indicated on the left and during the high cellulose (HC) diet (▨) on the right. Fecal NDF of each subject was quantitated in two aggregate fecal samples, one which represented excretion throughout the low cellulose period and the other throughout the high cellulose period. Uncorrected and corrected apparent NDF digestibility (AFD, %) is shown above each bar. NDF digestibility during the LC diet increased significantly ($P < 0.01$) when corrected.

TABLE 5

Digestibility of cellulose and hemicellulose determined from aggregate composites[1]

Subject	Cellulose		Hemicellulose			
	LC	HC	LC[2]	LC[3]	HC[2]	HC[3]
A	65.6	4.5	27.6	66.1	33.8	53.8
B	58.1	35.5	44.4	70.5	43.5	58.9
C	65.6	23.4	43.7	74.4	25.9	44.9
D	62.0	19.4	31.0	66.3	37.6	52.2
E	74.1	18.3	60.2	81.5	31.4	55.4
F	90.7	26.5	63.2	73.4	38.4	55.9
G	71.9	−17.6	51.2	69.8	4.6	36.2
Means:	69.7 ± 10.7	15.7 ± 17.4	45.9 ± 13.5	71.7 ± 5.4	30.7 ± 12.8	51.0 ± 7.9

[1] Fiber analysis done on aggregate fecal composites representing 20–30 days of excretion by each subject during each diet. [2] Hemicellulose determined by difference (NDF minus cellulose). [3] Fecal hemicellulose determined by difference (NDF corrected for protein contamination minus cellulose).

21 (Subject F) to 33% (Subject A). Protein contamination of fecal NDF residues from the high cellulose period was less (about 3–4%), although the absolute amount of protein in the fecal NDF fraction was the same for both diets (~1 g/day). When the fecal NDF results from the low cellulose diet were corrected for protein (fig. 2), digestibilities of NDF increased significantly ($P < 0.01$). Digestibility increased the most in Subject A and the least in Subject F (fig. 2), while mean apparent NDF digestibility of the group increased from 59.4 ± 11.2% to 70.4 ± 7.3% with the correction. Correcting the fecal NDF residues from the high cellulose diet for protein content had little effect on digestibility, which was 19.7 ± 16.2% without and 23.0 ± 15.0% with correction (fig. 2).

Apparent cellulose digestibility determined from the aggregate fecal samples (table 5) agreed well with the means of cellulose analyses performed on the 5-day composites (table 2). The effect of diet on cellulose digestibility was significant ($P < 0.01$), while again there were no significant differences among subjects in cellulose digestibility. The modified Crampton and Maynard procedure effectively removed nitrogen from fecal cellulose fractions obtained from the aggregate fecal samples. Fecal cellulose samples contained less than 2% protein during the low cellulose diet and less than 0.5% protein during the high cellulose diet so no correction for protein contamination was necessary.

Apparent hemicellulose digestibility was recalculated using aggregate fecal NDF and cellulose values (table 5). When the fecal NDF values were not corrected for protein contamination, mean hemicellulose digestibility was 45.9 ± 13.5% during the low cellulose diet and decreased nonsignificantly to 30.7 ± 12.8% during the high cellulose diet. Hemicellulose was recalculated with corrected fecal NDF values; hemicellulose digestibility was 71.7 ± 5.4% during the low celulose diet and decreased significantly to 51.0 ± 7.9% during the high cellulose diet. Measures of hemicellulose digestibility obtained from the 5-day composites (table 3) fall between the corrected and uncorrected hemicellulose digestibility values.

When Solka Floc was the sole fiber source in the diet (experiment 2), it was largely undegraded in the human gastrointestinal tract (fig. 3). Digestibilities of NDF ranged from 2.0 to 15.5% (mean: 10.0 ± 6.6%), while cellulose digestibilities ranged from 0.5 to 14.1% (mean: 8.1 ± 6.1%). Calculation of apparent hemicellulose digestibility was impossible because of the small amount of hemicellulose (1 g) in the 16 g of Solka Floc. The nitrogen contents of fecal NDF residues were below detection level (<0.5%) when the Solka Floc was ingested with the semipurified diet.

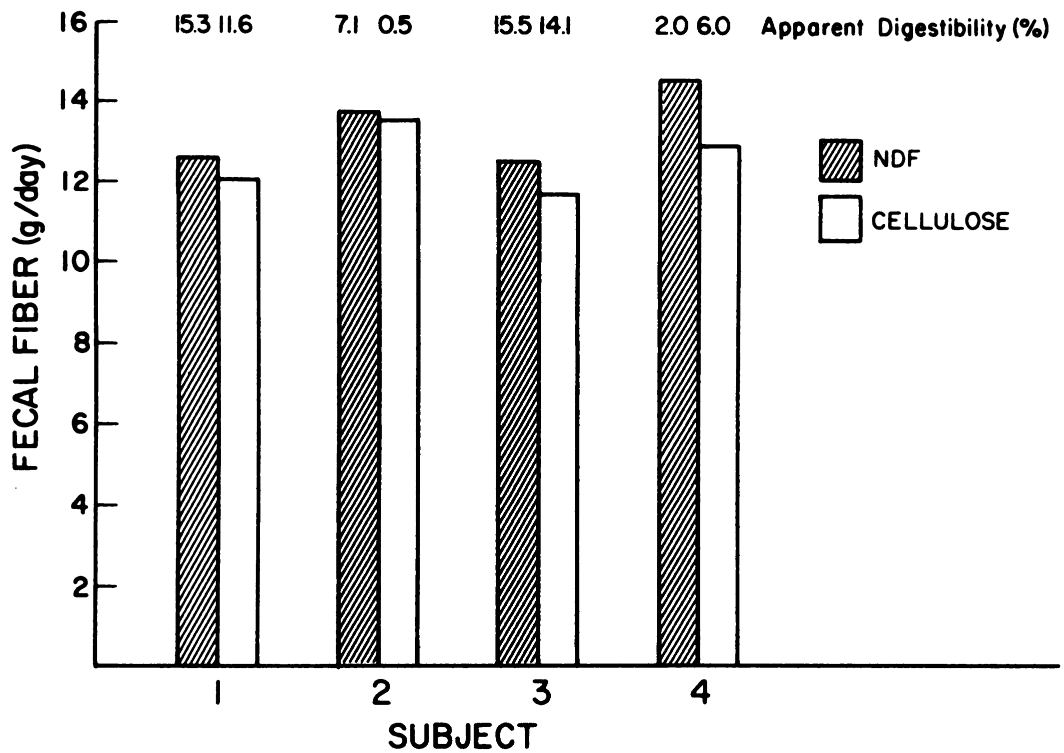

Fig. 3 Fecal fiber excretion per day when Solka Floc was the sole fiber source in a semipurified diet (experiment 2). The left bar represents NDF excretion (▨) and the right bar represents cellulose excretion (□). Apparent digestibilities (%) of NDF and cellulose are given above each bar. Daily fecal fiber was determined as fiber excreted during a 5-day collection period divided by 5.

DISCUSSION

Cummings (20) has suggested that at least half of the fiber in a low fiber, Westernized diet is degraded in the human gut. With our low cellulose diet, digestibility of NDF calculated from aggregate composites was 59% and 70% when fecal NDF residues were corrected for protein. Mean NDF digestibility calculated from 5-day composites was 65% during the low cellulose period. Other researchers (6–8) have reported digestibility of NDF to be about 80% when subjects consumed a low fiber diet. Food NDF residues were not treated with amylase in two of these studies (6, 7); hence, digestibility estimates are probably inflated. Indeed, Farrell et al. (6) recognized that the food NDF was probably contaminated with starch and analyzed the food with an enzymatic modification of the NDF procedure (21). Calculating fiber digestibility using this lower food fiber value yields an NDF digestibility of 73%, as compared to 80% when no amylase modification for food NDF was used. Fiber digestibility during a low fiber diet, as measured with the Southgate method (22), which measures both water-soluble and insoluble fiber, ranges from 70 to 80% (23). Hence, fiber digestibility data generated using available fiber methods agree that more than half of ingested fiber is degraded when subjects consume a low fiber diet.

Digestibility of NDF decreased significantly when Solka Floc was added to the diet. Fiber digestibility also decreases when bran is added to a low fiber diet (6). Neither bran nor refined cellulose appear to be highly fermented in human subjects (24), so this apparent decrease in fiber digestibility is not unexpected. Whether the digestibility of a more fermentable fiber source decreases also as it is consumed in increasing amounts has never been examined. Further, it is unclear what effect either a fermentable or an unfermentable fiber supplement would have on the apparent digestibility of the food-derived fiber.

Large within-subject variations in fiber digestibility were observed in the present study and that of Hummell (3), but no consistent trends in digestibility with time were evident in either study. The negative fiber digestibilities during the high cellulose diet, though, suggest that wide within-subject variations may be caused in part by the inability of dye to adequately divide fecal samples into composites corresponding to a 5-day intake. During the low cellulose diet, Subject F's feces were divided without the aid of a marker. Yet the most consistent fiber digestibility among composites was observed in Subject F during the low cellulose period (mean: 84.7 ± 3.6%).

Reasons for the consistently negative fiber digestibility in Subject G are obscure. During the high cellulose intake Subject G's feces were about 50% dry matter, while the feces of all other subjects were about 30% dry matter (12). Yet, approximately 45% of the dry matter of all feces from all subjects, including G, during the high cellulose diet was NDF. Thus, Subject G appeared to excrete almost twice as much NDF as the other subjects during the high cellulose diet.

Another source of within-subject variation in fiber digestibility may be the ability to adapt to a particular diet. Mean digestibility of NDF with the cellulose supplement was 38% on day 5, decreased to 10% on day 15 and then stabilized at about 20%. An individual's microflora react differently to the ingestion of a novel fiber source (23) and thus, the amount of time needed for any adaptation to a particular fiber intake is not known. Recent evidence (25, 26), though, implies that the microflora are not influenced by the fiber composition of the diet.

Although statistically we could not detect differences in fiber digestibility among subjects, mean NDF digestibility calculated from 5-day composites, ranged from 56 to 85% during the low cellulose diet and from −11 to 43% during the high cellulose diet. Wide ranges of fiber digestibility have been previously described (3, 8, 27) and may be due to differences in response of an individual's microflora to a fiber source (23) or to differences in gastrointestinal rate among individuals (8). Others, however, find no relationship between fiber digestion and transit time when pectin is the fiber source (28). In our study when apparent fiber digestibility was low (HC period), fiber digestibility and transit time were not correlated, whereas when more than half of the fiber was digested (LC diet), fiber digestibility and transit time may have been related. Thus, it appears that the relationship between gut transit and fiber digestibility may depend on either the level or the kind of fiber.

Recent work (6, 7, 9) lends support to the early observation by Williams and Olmstead (4) that hemicellulose is more digestible than cellulose in human subjects. Because these investigators (6, 7, 9) did not sequentially determine ADF on an NDF sample to eliminate pectins (10) and also did not treat the food NDF with amylase, it is unlikely that hemicellulose and cellulose measures in food and feces are reliable. Van Soest (8) found that cellulose in a low fiber diet and also cellulose in a cabbage diet were more digestible than the hemicellulose. Our results suggest that when food NDF starch and fecal NDF nitrogen are considered in the calculation, cellulose and hemicellulose have comparable digestibilities, about 70% (table 5) when a low fiber diet is ingested.

Estimates of hemicellulose in the present study also may not be reliable. Because NDF contains hemicellulose, cellulose and lignin and the Crampton and Maynard method isolates only cellulose, calculated hemicellulose values include lignin. Human foodstuffs are low in lignin and Solka Floc contains less than 1% lignin so the error would be small. But, correcting for the protein in NDF before calculating hemicellulose had a marked effect on hemicellulose digestibility, increasing it from 46 to 71% on the low cellulose diet and from 31 to 51% with the added cellulose. These conflicting results could be caused by the crude gravimetric schemes for quantitating hemicellulose and cellulose and could illustrate the need for a better means of separating and characterizing the components of fiber.

Comparison of apparent cellulose digestibility determined when a solid food diet was consumed, 14% (experiment 1, table 2) versus the consumption of a liquid diet, 8% (experiment 2, figure 3), suggests that little Solka Floc is degraded, independent of the form of the rest of the experimental diet. Other studies (8, 29) also have reported that digestion of Solka Floc is much less than that of fiber in foods (6–8). Refined celluloses are chemically processed and hence differ markedly from natural cellulose in physical and biological properties (24). Van Soest's preliminary data (8) suggest that Solka Floc may have a negative and inhibitory effect upon fecal microbial action. Prolonged feeding of Solka Floc did not induce cellulolytic fermentation but appeared to depress fiber digestibility during the sequential diet (8).

The fecal NDF fractions collected during the low and high cellulose diets in experiment 1 contained a significant quantity of nitrogen while the fecal NDF fractions collected when Solka Floc was ingested with a semi-purified diet contained minimal nitrogen. These results suggest that the nitrogen found in fecal NDF residues originated from food sources rather than from endogenous gut secretions. Probably, the nitrogen is the Maillard product, an indigestible compound formed during the non-enzymatic browning reaction between amino acids and the degradation products of sugars (30). Although Maillard products are a small part of most diets, they are indigestible and hence become concentrated in the feces. The Maillard product has a high nitrogen content, about 11% (31); thus, if the nitrogen in the fecal NDF fraction is the Maillard product, the factor used to convert nitrogen to protein, 4.3, would underestimate nonfibrous, nitrogenous contamination of the fecal NDF samples.

When fecal NDF values from the aggregate samples during the low cellulose period we corrected for protein, NDF digestibility was significantly increased from 60 to 70%. Because of the substantially larger proportion of fecal NDF during the high cellulose period, correction for fecal NDF protein had virtually no effect on apparent NDF digestibility, which for the group was 20% without and 23% with correction. The validity of correcting for the nitrogen in NDF, however, can be argued. The Maillard product is indigestible and is isolated in the lignin fraction during fiber analysis (31). The nitrogenous matrix isolated with fiber in the form of Maillard products (1) or as indigestible protein (32) may be responsible for some of the effects associated with fiber in the gut. True lignin contains no nitrogen, though, and is in low concentration in most human foodstuffs, so other fiber chemists feel that "artifact lignin" should not be isolated as dietary fiber (33).

Independent of this controversy, however, the findings of this study suggest that substantial quantities of unprocessed food fiber are digested during transit through the human gastrointestinal tract whereas little or no digestion of Solka Floc occurs.

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