Chemical and Fluorescence Microscopic Analysis of Fiber Degradation of Oat, Hard Red Spring Wheat, and Corn Bran in Rats†

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The degradation of dietary fiber from hard red spring (HRS) wheat, corn, and oat brans (respectively 25.7, 18.4, or 22.7% in diets) was studied in rats after 28 weeks of feeding. In animals fed the oat bran diet, 76 ± 9% of neutral detergent fiber (NDF) was fermented. Although dietary fiber levels and compositions were similar in HRS wheat and corn bran diets, HRS wheat NDF showed greater fermentative degradation (particularly xylan) than corn NDF (31 ± 3 vs 7 ± 4%) ($P < 0.001$). Dietary fiber degradation observed by fluorescence microscopy was negligible in corn bran, partial in HRS wheat aleurone layer, and extensive in oat aleurone layer, confirming NDF analysis. It is concluded that bran fiber fermentability cannot be predicted from its composition alone.

INTRODUCTION

Fermentation of dietary fiber in the colon is important for several physiological effects including bacterial growth, production of short-chain fatty acids, health of the colonic mucosa, diversion of nitrogen (urea, protein) into microbial protein, and reduction of fecal ammonia levels (Cummings, 1983; Fleming and Arce, 1986; Hellendoorn, 1978; Nauss et al., 1987; Van Soest, 1978).

Cereal brans provide different forms of dietary fiber, and the fermentability of cereal fiber is affected by the chemical and morphological composition of the cell wall components (Yiu, 1989). Fluorescence microscopy, which has the ability to provide both structural and microchemical information, is one of the effective methods to assess the degradation of cereal cell walls (Yiu and Mongeau, 1987; Yiu, 1989). Under short-wavelength excitation, cereal cell walls that contained phenolic compounds, such as ferulic and *p*-coumaric acids, emitted intense autofluorescence (Fulcher et al., 1972).

Using chemical analyses and fluorescence microscopy, the present study aims to compare the chemical and morphological compositions of dietary fiber present in oat, HRS wheat, and corn brans and their degradation in the rat gastrointestinal tract after a long-term bran feeding.

EXPERIMENTAL PROCEDURES

Animals. Fifteen male and 15 female Sprague-Dawley weanling rats (Crl:CD^{R}(SD)BR; Charles River Canada Inc., St. Constant, PQ), weighing 50.9 ± 2.4, 50.4 ± 2.7, and 50.7 ± 2.5 g were assigned to HRS wheat, corn, and oat bran groups, respectively. They were housed individually in wire-bottomed stainless steel cages. Distilled water was provided ad libitum. Illumination was provided automatically from 7 a.m. to 7 p.m. Room temperature was controlled at 22 ± 1 °C and humidity at 45–50%. Females and males were randomly divided into three groups and fed one of the three diets (five males and five females per diet). Each animal was assigned at random to a cage.

Diets. The three purified diets contained 179.7 kcal of basal diet/396.4 kcal of diet (Shah et al., 1990), e.g., 35 g of basal diet/100 g of corn bran diet contained 20% casein, 0.3% DL-methionine, 0.2% choline bitartrate, 3.5% salt mix (AIN mineral mixture 76, ICN Nutritive Biochemicals Ltd., Cleveland OH), 1% vitamin mix (AIN vitamin mixture 76, ICN Nutritive Biochemicals), and 10% corn oil.

The bran was added at the expense of cornstarch, taking into account the caloric contribution. The purified diets were not isocaloric but "fiber adjusted" (CLAD, 1978), assuming 3.8, 2.5, and 1.4 kcal/g for oat bran, HRS wheat bran, and corn bran, respectively (Lockhart et al., 1980). More details have been provided elsewhere (Shah et al., 1990, 1991).

The HRS wheat bran [50.1% total dietary fiber (TDF)], corn bran (63.9% TDF), and oat bran (16.4% TDF) contained, respectively, 16.1, 15.9, and 43% starch, 1.3, 4.5, and 7.1% fat, and 16.6, 8.0, and 21.4% crude protein, some being structural cell wall protein. The HRS wheat bran, corn bran, and oat bran represented 25.7, 18.4, and 22.7 g/100 g of the corresponding diets, respectively (Table I). The diets contained, respectively, 14, 14, and 4.5% TDF, 42, 49.6, and 48% starch, 10.5, 10.8, and 12.7% fat, and 23.0, 19.8, and 25.5% protein. Expressed per 396.4 kcal of diet, the protein contents were, respectively, 22.5, 19.8, and 22.8 g. The same factors (0.977, 1.0, and 0.894, respectively) could be used for the other macronutrients to take into account the caloric density of the diet.

The wheat bran was hard red spring (HRS) wheat bran bought locally. The corn bran was unprocessed corn bran provided by the Kellogg Co., Canada. Oat bran, Mothers Oat Bran, Creamy High-Fiber Hot Cereal, was obtained from the Quaker Oats Co., Barrington, IL. The geometric mean particle size (GMPS) was measured (Mongeau and Brassard, 1982); the latter bran had a GMPS of 554 μm and was used without any further grinding. The HRS wheat and corn brans were ground using a Wiley mill with the 2.0-mm screen. The GMPS was 510 μm for the HRS wheat bran and 523 μm for the corn bran. More details on the diets have been provided elsewhere (Shah et al., 1990, 1991; Mongeau et al., 1991).

Protocol. The animals were fed one of the bran diets for 28 weeks. During week 26 or 27, animals were placed in large Nalgene (Nalgene Co., Rochester, NY) metabolic cages for a 3-day adaptation and then a 4-day collection of feces. NDF was measured in diet and feces. Food intakes were recorded daily. After 28 weeks on the diets, the fed animals were killed by exsanguination while under anaesthesia (Somnotol, MTZ Pharmaceuticals, Mississauga, ON) in oxygen within 4 h after the end of the dark cycle. The digesta were collected in the distal ileum (1–6 cm from the cecum). The major part of the large intestine of the animals in the three groups was filled with well-formed fecal pellets. The two pellets [large intestinal content (LIC)] which were the most distally situated were collected in plastic scintillation vials, freeze-dried, and stored at −70 °C until microscopic examination. These relatively dry pellets were

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similar in characteristics to excreted fecal pellets, and their composition was assumed to be close to that of feces.

Dietary Fiber Analysis. Dietary fiber in the brans was measured by two methods: total dietary fiber was measured according to the method of Mongeau and Brassard (1986) and nonstarch polysaccharides (NSP) according to the method of Englyst (1982). The former method includes a soluble fiber procedure which is complementary to the enzyme-neutral detergent fiber (NDF) procedure. Soluble fiber was extracted at 100 °C in acetate buffer at pH 4.5 and precipitated with 4 volumes of alcohol. In the NDF procedure, the residue was incubated at 55 °C with porcine pancreas α-amylase, and it was fractionated in hemicelluloses, cellulose, and lignin according to the Van Soest system as described by Mongeau and Brassard (1982).

The diet and feces were analyzed according to the NDF procedure, which well discriminates between plant cell walls and bacterial cell walls. This permitted evaluation of the NDF degradation in the gastrointestinal tract. The NDF residues from the diet and feces were also subjected to acid hydrolysis, and polysaccharidic components were analyzed by GC as in the Englyst method. Data for males and females were grouped since there was no difference in their fermentability.

The actual dietary fiber content of the diets measured during weeks 26–27 includes small amounts of dietary fiber from other ingredients, e.g., starch. Disappearance data were calculated using the actual amounts fed during week 26 or 27.

Fluorescence Microscopy. All samples were first encapsulated in molten 2% agar in a Petri dish according to a previously described method by Yiu and Mongeau (1987) and were cut into 1–2-mm blocks after the agar was set firm. They were then fixed in 3% glutaraldehyde (in 0.01 M phosphate buffer, pH 7.0) for 24 h. Fixed samples were dehydrated through methyl cellosolve, ethanol, *n*-propanol, and *n*-butanol followed by infiltration with glycol methacrylate monomer for 3–5 days at room temperature prior to polymerization at 55 °C in gelatin capsules. Sections were cut 2 μm thick using an ultramicrotome (Sorvall Inc., Newtown, CT) equipped with a glass knife. All sections were affixed to glass slides, air-dried, mounted in immersion oil, and examined without staining by fluorescence optics using a Zeiss universal research photomicroscope (Carl Zeiss Ltd., Montréal, PQ). The microscope was equipped with a III RS epi-illuminating condenser combined with an HBO 100-W mercury arc burner for fluorescence analysis. The III RS condenser contained a fluorescence filter system with a dichromatic beam splitter and an exciter/barrier filter set for maximum transmission at 365 nm/418 nm. Micrographs were recorded on 35-mm Ektachrome 400 daylight film from which black and white prints were obtained.

Statistics. The Mann and Whitney nonparametric test was used to determine the statistical significance of differences among groups (Stat Plus, 1982).

RESULTS AND DISCUSSION

Contrary to the HRS wheat and corn bran diets which contained 14% dietary fiber, the 22.7% oat bran diet contained only 4.5% dietary fiber because oat bran contains less dietary fiber than wheat and corn brans (Table I).

The mean daily intakes from week 8 to week 28 were 19.2, 18.9, and 17.7 g/rat for the HRS wheat bran, corn bran, and oat bran diets, respectively. The difference in food intake were not significant ($P > 0.26$). The mean body weight gain for the same 20-week period varied from 1.49 (corn bran) to 1.69 (oat bran) g per rat per day, but the differences were not significant.

The daily food intake during the 4-day collection period (week 26 or 27) was 19.0 ± 2.9, 20.2 ± 1.5, and 19.4 ± 4.7 g/rat in males, and 11.4 ± 1.9, 11.0 ± 2.3 and 12.2 ± 2.0 g/rat (±SD) in females fed HRS wheat bran, corn bran and oat bran diets, respectively. The daily fecal fresh weights during the corresponding period were 6.22 ± 0.96, 6.76 ± 0.47, and 3.02 ± 0.38 for males and 3.37 ± 0.47, 3.47 ± 0.80, and 1.71 ± 0.33 g/rat for females fed the HRS wheat bran, corn bran, and oat bran diets, respectively. The fecal dry weights were, respectively, 3.00 ± 0.39, 3.37 ± 0.19, and 1.30 ± 0.17 for males and 1.70 ± 0.47, 1.77 ± 0.36, and 0.75 ± 0.07 for females.

Table I. Dietary Fiber Content and Composition of Bran Diets

component	g/100 g of diet: HRS wheat bran 25.7%[a]	corn bran 18.4%	oat bran 22.7%
total dietary fiber[b]	14.0	13.9	4.5
soluble fiber	1.3	1.0	2.0
insoluble fiber (NDF)	12.7	12.9	2.5
hemicelluloses	8.6	9.7	1.7
cellulose	2.9	2.9	0.2
lignin	1.0	0.3	0.5
nonstarch polysaccharides (total)[c]	10.1	11.3	3.5
rhamnose	0.1	0.1	ND[d]
arabinose	2.4	2.5	0.5
xylose	4.2	4.4	0.6
mannose	0.1	0.1	<0.1
galactose	0.2	0.7	0.1
glucose	2.8	3.0	2.2
uronic acid	0.3	0.5	0.1

[a] Bran dietary level. [b] Rapid method (Mongeau and Brassard, 1986). NDF, neutral detergent residue treated with porcine α-amylase. Mean of four determinations. [c] GC method of Englyst (1982). Mean of duplicate analyses. [d] Not detected.

The chemical analysis showed that the water-soluble fiber content of the oat bran diet was higher than that in other diets but its insoluble fiber (NDF) content was much lower (Table I). Glucose was the major component of NSP in oat bran diet, but most of it was part of the noncellulosic polysaccharides as indicated by the lower cellulose content (Table I). On the other hand, the HRS wheat and corn bran diets had similar levels of total dietary fiber, soluble fiber, hemicellulose, and cellulose as well as NSP components (Table I); the latter components agreed within 0.2 g/100 g except for galactose (0.5 g). The arabinose:xylose:glucose ratios of NSP were 0.86:1.5:1 and 0.83:1.5:1 for the HRS wheat and corn bran diets. Similar ratios (0.89:1.5:1) were reported by Stevens et al. (1988) for wheat bran cell wall. Olson et al. (1983) reported the same arabinose:xylose ratio for corn bran fiber.

Chemical analysis applied to the LIC and calculation of fiber intake and excretion showed that corn bran, HRS wheat bran, and oat bran insoluble fiber were fermented to different degrees (7, 31, and 76%, respectively). The differences were attributable to the hemicellulose fraction ($P < 0.001$; Table II). Arabinose, xylose, and glucose accounted for about 90% of the polysaccharidic constituents of NDF of the three brans (Table III). During passage through the gastrointestinal tract, a maximum of 6% disappeared from the corn fiber while more than 80% disappeared from the oat fiber. The high fermentability of oat bran fiber is in agreement with its estimated available energy of 3.8 kcal/g in rats (Lockhart et al., 1980). HRS wheat bran NDF lost 16–17% arabinose and glucose but 45% xylose (Table III). These latter figures are in agreement with the preferential loss of xylose reported in wheat bran during fermentation in the rat (Bertrand et al., 1981) and pig (Roberston et al., 1986; Bach Knudsen and Hansen, 1991) or after a 24-h in vitro incubation with human fecal bacteria (Stevens et al., 1988).

The similar fiber compositions of HRS wheat and corn bran diets were associated with dissimilar degrees of fermentation (Tables I–III), and this does not substantiate the assumption that the degree of fiber fermentation depends upon the polysaccharide components of the fiber (Cheng et al., 1987). The low fermentability of uronic

Table II. Disappearance of Bran Insoluble Fiber[a] in the Gastrointestinal Tract of Rats after 26 Weeks on Diets

fraction		HRS wheat	corn	oat
total NDF	IN[b]	1927	2010	390
	EX	1334	1865	93
	% D[c]	31 ± 3[d]	7 ± 4[e]	76 ± 9[e]
hemicellulose	IN	1304	1510	263
	EX	771	1408	31
	% D	41 ± 3[d]	7 ± 4[e]	88 ± 10[e]
cellulose	IN	444	445	30
	EX	394	414	15
	% D	11 ± 4[e]	7 ± 4[e]	50 ± 17[d]
lignin	IN	158	45	81
	EX	147	40	40
	% D	7 ± 8[e]	12 ± 17[e]	50 ± 8[d]

[a] Enzyme-neutral detergent fiber (Mongeau and Brassard, 1982). [b] IN, amount ingested (milligrams per rat per day); EX, amount excreted in feces (milligrams per rat per day); % D, percentage disappearance (mean for 10 animals ± SD); duplicate analysis for each animal. [c] Disappearance data with different superscripts are significantly different ($P < 0.001$).

Table III. Disappearance of Monosaccharide Components of Bran Insoluble Fiber[a] in the Gastrointestinal Tract of Rats after 26 Weeks on Diets

		mg per rat per day		
constituent sugar		HRS wheat	corn	oat
ARA[b]	IN[c]	387	384	48
	EX	325	359	9
	% D	16	6	81
XYL	IN	570	635	69
	EX	312	603	12
	% D	45	5	83
GAL	IN	17	106	2.3
	EX	12	98	0.3
	% D	29	8	87
GLU	IN	526	508	80
	EX	436	485	13
	% D	17	5	84

[a] Enzyme-neutral detergent fiber (Mongeau and Brassard, 1982). [b] ARA, arabinose; XYL, xylose; GAL, galactose; GLU, glucose. [c] IN, amount ingested; EX, amount excreted in feces; % D, percentage disappearance. Mean of a duplicate determination in diet or feces pooled in each group.

acids in whole vegetables contrasts with that of pure pectins, indirectly supporting the view that the architecture of the dietary fiber polymers has an important impact on fermentability and physiological effects (Nyman et al., 1990; Bach Knudsen and Hansen, 1991). The present work provides more direct evidence in HRS wheat and corn bran that the fiber fermentability is dependent on the specific architectural structures. Undigested food nitrogen participates in the equilibrium between nitrogen and fermentable energy for bacterial fermentation in the cecum (Kaufmann, 1986). Part of the protein provided by HRS wheat bran or oat bran could have favored conditions for bacterial growth. The extent of fermentation of fiber also depends on other factors.

The high extent of fermentability of oat bran fiber compared to that of HRS wheat and corn bran was not attributable to the lower fiber level (4 vs 14%) because the fermentability of HRS wheat bran at the 4% level in the diet remained moderate (45%) in rats in similar conditions (Mongeau et al., unpublished results). This degree of fermentation was still lower than the 76% observed for oat bran fiber (Table II).

Ileal digesta and LIC obtained from rats fed the corn bran, oat bran, or wheat bran diet were analyzed by fluorescence microscopy. When examined under short-wavelength illumination at 365 nm, all three brans were composed of cell walls that emitted blue to bluish white autofluorescence, an observable phenomenon not commonly displayed by other fecal matters. Corn bran fragments detected among the ileal digesta (Figure 1A) and LIC (Figure 1B) were numerous and emitted intense autofluorescence. Only minor reduction in fluorescence intensity was observed as corn bran passed through the gastrointestinal tract of the rat. Furthermore, most of the pericarp tissue remained structurally intact. Microbial degradation on the corn cell walls was not evident.

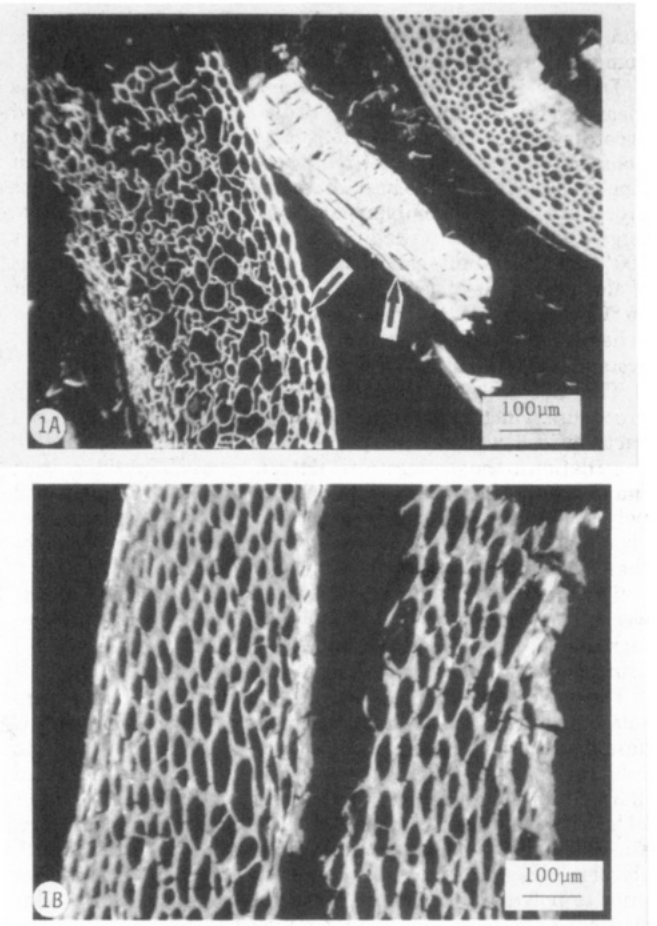

Figure 1. (A) Undegraded corn pericarp tissues in a section of the ileal digesta. (B) Undegraded corn pericarp tissues in a section of the large intestine contents.

A reduction in autofluorescence intensity as well as a partial degradation of cell wall was observed in wheat bran: parts A and B of Figure 2 illustrate differences in the structure and autofluorescence intensity of HRS wheat bran before and after it passed through the cecum, respectively. Both the pericarp and aleurone cell wall contained phenolic compounds that autofluoresced under ultraviolet (UV) light. After passing through the rat cecum, the majority of the pericarp tissue remained structurally intact whereas a considerable portion of the aleurone cell wall, especially the part that was close to the inner endosperm, was degraded. Similar microscopic observations were reported for soft wheat bran fiber recovered in human feces, where most of the aleurone cell wall was removed (Dintzis et al., 1979; Moss and Mugford, 1986). The partially degraded HRS wheat bran remained autofluorescent when examined under UV light (Figure 2B). Results of chemical characterization of the HRS wheat cell wall indicated that the major constituent of the HRS wheat aleurone was heteroxylans (Bacic and Stone,

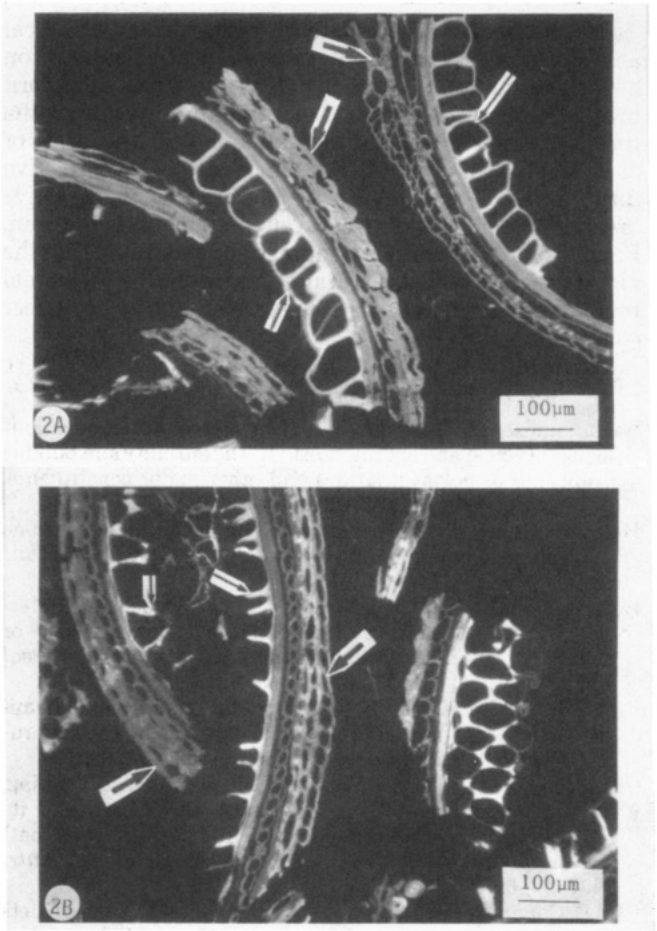

Figure 2. (A) Structural integrity of the pericarp tissues (large arrows) and aleurone layer (small arrows) of HRS wheat bran in the ileal digesta. (B) Relatively intact structures of the pericarp tissues (large arrows) and degraded structures of the aleurone layer (small arrows) of HRS wheat bran in the large intestine contents.

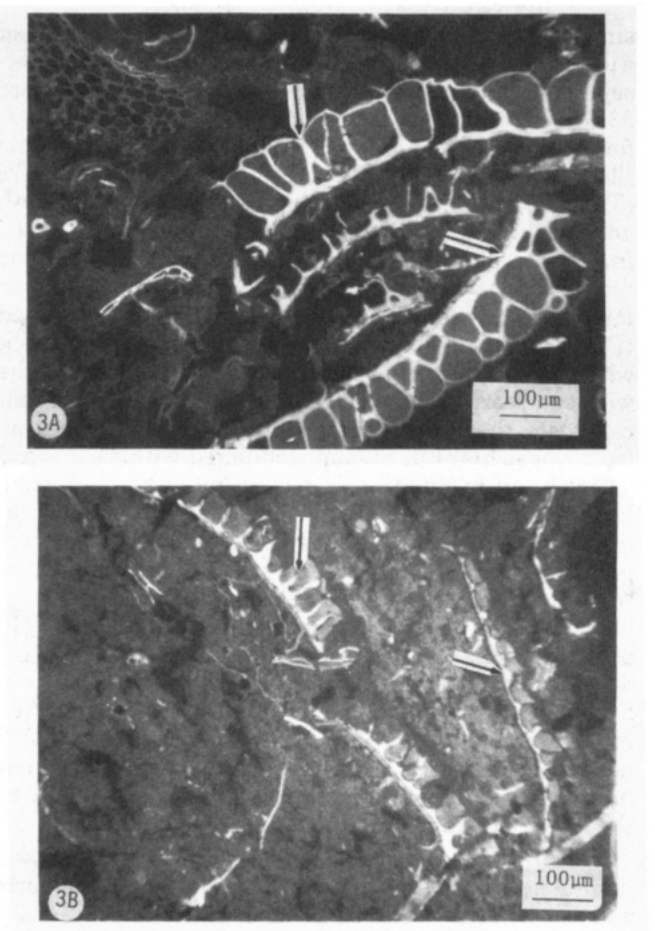

Figure 3. (A) Relatively intact aleurone (arrows) cell wall of oat bran in the ileal digesta. (B) Extensively degraded aleurone (arrows) cell walls of oat bran in the large intestine contents.

1981) cross-linked with phenolic compounds such as ferulic acid (Fulcher et al., 1972).

Oat bran fiber, on the other hand, was more fermentable than HRS wheat bran fiber and had a slightly different degradation pattern. Size reduction and tissue degradation were most obvious in oat bran fiber that had passed through the gastointestinal tract of the rat. The autofluorescent cell wall of the oat aleurone layer was detected among the ileal digesta (Figure 3A) but virtually disappeared as the bran reached the distal portion of the colon (Figure 3B). Having a higher soluble fiber content than HRS wheat bran (Frolich and Nyman, 1988), cell wall components of oat bran were degraded differently, depending on the gastrointestinal environment.

Microscopic examination detected qualitative differences among corn, oat, and HRS wheat brans in terms of the distribution of autofluorescent cell walls. Although comparative figures on the phenolic contents of corn, oat, and HRS wheat brans were unavailable, results of the microscopic examination indicated that corn bran, which contained mostly cell walls that emitted intense autofluorescence under ultraviolet light, was most resistant to microbial fermentation. The pericarp tissues of HRS wheat bran, which had high lignin and phenolic contents (Ring and Selvendran, 1980) as well as cutin (Schwarz et al., 1988), were not affected by the microbial action. Oat bran fiber, on the other hand, consisted of the smallest portion of phenolic bound, insoluble cell wall components and was the most degraded product of the three.

It is assumed that fermentation does not occur in the small intestine. Some upward migration of bacteria occurs through the ileocecal valve to the small intestine, but the transit is so rapid that little dietary fiber is fermented before it has reached the large intestine. Nevertheless, fluorescence and light microscopy indicated that apparent degradation of the subaleurone layer (β-glucan) of oat bran took place in the small intestine of rats (Yiu and Mongeau, 1987); the presence of bacteria was also observed among the oat bran particles, suggesting that the disappearance of β-glucan was not simply due to its solubilization but the latter is not excluded. Bach Knudsen and Hansen (1991) measured oat β-glucan and bacterial activity in the gastrointestinal tract of pigs fed wheat and oat fiber diets. In the small intestine, only 12–23% of oat β-glucan was found in the liquid phase but up to 88% of it was degraded by bacterial fermentation; thus, the fermentation of a significant portion of oat β-glucan occurred in the terminal ileum (10 cm from cecum) of pigs. It is likely that β-glucan was fermented in the terminal ileum (4 cm from cecum) of rats as indicated by fluorescence microscopic observations in the present work. Partial depolymerization (molecular weight loss) of oat β-glucan in the upper gastrointestinal tract of rats has also been reported (Wood et al., 1991).

Although the gastrointestinal tract of the human and rat are not exactly comparable, they share certain common characteristics (Mongeau and Brassard, 1985) including their abilities to ferment various fibers. A low fermentability of corn bran fiber has been reported in the human gastrointestinal tract (Olson et al., 1983). Nyman and Asp (1985) studied factors affecting dietary fiber fermentation in the rat intestinal tract and concluded that various sources of dietary fiber including bran are fermented to

similar extents in man and in rats. The rat is considered a useful model for quantitative fermentation studies (Livesey, 1990). Stephen and Cummings (1980) reported that 36% of HRS wheat fiber added to the human diet is fermented. In the present experiment, 31% of insoluble fiber was fermented by rats during the 26th and 27th weeks (Table II), and the fermentability was 37% during the 9th and 10th weeks (results not shown). In human subjects, practically all of the NDF of the corn bran ingested was recovered in feces and appeared unchanged under electron microscopy; wheat bran NDF was substantially degraded (Dintzis et al., 1979). The present results are in agreement with the conclusions of Dintzis et al. (1979), even if the wheat and corn brans are different. For wheat bran hemicelluloses, the latter authors reported 60% fermentation (soft wheat bran) in human, compared with 41% (hard wheat bran) in rats (Table II). In rats, the NDF from HRS wheat bran was less extensively fermented than that from soft wheat bran (unpublished data). Another experiment in rats showed an average 47% (dry weight basis) "digestibility" for seven wheat brans, but these measurements were not NDF degradation (Saunders, 1978). In pigs, Stanogias and Pearce (1985) reported a 48% NDF fermentation for wheat bran. Using human fecal inoculum in vitro (24-h incubation), McBurney (1990) reported NDF fermentations of 39% for AACC wheat bran (hardness not specified), 6.9% for corn bran, and 78.1% for oat bran. NDF fermentation figures in Table II are close to the latter values.

The phenolic constituents of bran fiber which emitted intense autofluorescence under UV light are *p*-coumaric and ferulic acids. The latter components are the main constituents of noncore lignin (Hartley, 1972). Core lignin has been studied more than noncore lignin and has been negatively correlated with fiber fermentation in forage, but there is generally a positive correlation between core and noncore lignin concentration (Van Soest, 1982; Jung, 1989). The core lignin is that type of material retained as lignin in the acid detergent fiber, and concentrations in diets are shown in Table I: the lignin level was lowest (0.3%) in the corn bran diet and highest (1%) in the HRS wheat bran diet. The regulating effect of HRS wheat bran on colonic function is attributable both to its fermentable material and to its resistant material. The association of the hemicellulose with lignin could be important in helping to maintain some of the structural integrity of HRS wheat bran fiber, providing a physical resistance to compacting and drying of colonic contents (Brice and Morrison, 1982; Cummings, 1982; Nyman and Asp, 1982; Robertson et al., 1986; Wrick et al., 1983). The degree of resistance to fermentation observed in the three brans examined here was not related to the lignin content of the bran. However, microscopic evidence indicated that lignification was directly linked to the resistance of the pericarp tissue when the digestive breakdown was compared among the cell wall components of HRS wheat bran. This observation in HRS wheat bran is in agreement with that of Stevens et al. (1988), who reported that the aleurone layer degraded by fecal bacteria in vitro does not contain lignin while the outer lignified layers are much less degradable; the degradation of the latter is prevented by the degree of cross-linking between polymers and not by the degree of branching of individual polysaccharides. Corn bran, on the other hand, contained little lignin. Hence, lignification could not be the major factor that prevents the fermentation of the corn fiber. Strong linkage among its polysaccharide molecules may result in the low fermentability of the corn fiber.

Results of the present study indicate that chemical analysis was necessary to obtain a quantitative comparison of fiber fermentability among oat, HRS wheat, and corn brans. However, differences in fermentability among the three products could not be explained on the basis of chemical data alone. Microscopic analysis was effective for comparing the qualitative differences in digestive breakdown among various cell wall components of the bran. Furthermore, microscopic findings demonstrated that the morphological and structural organization of the cereal bran fiber strongly influences the fermentability of its fiber components.

LITERATURE CITED

Bach Knudsen, K. E.; Hansen, I. Gastrointestinal implications in pigs of wheat and oat fractions. 1. Digestibility and bulking properties of polysaccharides and other major constituents. *Br. J. Nutr.* **1991**, *65*, 217–232.

Bacic, A.; Stone, B. A. Chemistry and organization of aleurone cell wall components from wheat and barley. *Aust. J. Plant Physiol.* **1981**, *8*, 475–495.

Bertrand, D.; Brillouet, J. M.; Rasper, V. F.; Bouchet, B.; Mercier, C. Effect of rat digestion upon native, enzymatically or chemically modified wheat brans and native oat bran. *Cereal Chem.* **1981**, *58*, 375–380.

Brice, R. E.; Morrison, I. M. The degradation of isolated hemicellulose and lignin-hemicellulose complexes by cell free rumen hemicelluloses. *Carbohydr. Res.* **1982**, *101*, 93–100.

Cheng, B.-Q.; Trimble, R. P.; Illman, R. J.; Stone, B. A.; Topping, D. L. Comparative effects of dietary wheat bran and its morphological components (aleurone and pericarp-seed coat) on volatile fatty acid concentration in the rat. *Br. J. Nutr.* **1987**, *57*, 69–76.

CLAD, Committee on Laboratory Animal Diets. Control of diets in laboratory animal experimentation. In ILAR News; National Academy of Sciences: Washington, DC, 1978; Vol. 21, No. 2, pp A1–A12.

Cummings, J. H. Polysaccharide fermentation in the human colon. In *Colon and Nutrition*; Kasper, H., Goebell, H., Eds.; MTP Press: Lancaster, U.K., 1982.

Cummings, J. H. Fermentation in the human large intestine: evidence and implications for health. *Lancet* **1983**, *1* (8335), 1206–1209.

Cummings, J. H.; Branch, W. J. Fermentation and the production of short-chain fatty acids in the human large intestine. In *Dietary fiber*. Basic clinical aspects; Vahouny, G. V., Kritchevsky, D., Eds.; Plenum Press: New York, 1986.

Dintzis, F. R.; Legg, L. M.; Deatherage, W. L.; Baker, F. L.; Inglett, G. E.; Jacob, R. A.; Reck, S. J.; Munoz, J. M.; Klevay, L. M.; Sandstead, H. H.; Shuey, W. C. Human gastrointestinal action on wheat, corn, and soy hull bran-preliminary findings. *Cereal Chem.* **1979**, *56*, 123–127.

Englyst, H.; Wiggins, H. S.; Cummings, J. H. Determination of the non-starch polysaccharides in plant foods by gas-liquid chromatography of constituent sugars as alditol acetates. *Analyst* **1982**, *107*, 307–318.

Fleming, S. E.; Arce, D. S. Volatile fatty acids: their production, absorption, utilization, and roles in human nutrition. *Clin. Gastroenterol.* **1986**, *15*, 787–814.

Frolich, W.; Nyman, M. Mineral, phytate and dietary fibre in different fractions of oat grain. *J. Cereal Sci.* **1988**, *7*, 73–82.

Fulcher, R. G.; O'Brien, T. P.; Lees, J. W. Studies of the aleurone layer. 1. Conventional and fluorescence microscopy of the cell wall with emphasis on phenol-carbohydrate complexes in wheat. *Aust. J. Biol. Sci.* **1972**, *25*, 23–34.

Hartley, R. D. p-Coumaric and ferulic acid components of cell walls of ryegrass and their relationships with lignin and digestibility. *J. Sci. Food Agric.* **1972**, *23*, 1347–1354.

Hellendoorn, E. W. Fermentation as the principal cause of the physiological activity of indigestible food results. In *Topics in dietary fiber research*; Spiller, G. A., Ed.; Plenum Press: New York, 1978.

Jung, H. G. Forage lignins and their effects on fiber digestibility. *Agron. J.* **1989**, *81*, 33–38.

Kaufmann, W. Fermentation in the forestomach and hind gut, a comparison. *Arch. Tierernaehr.* **1986**, *36* (2-3), 205-212.
Livesey, G. Workshop report: dietary fibre and energy balance. In *Dietary fibre: chemical and biological aspects*; Southgate, D. A. T., Waldron, K., Johnson, I. T., Fenwick, G. R. Eds.; Royal Society of Chemistry: Cambridge, U.K., 1990.
Lockhart, H. B.; Lee, H. S.; O'Mahony, S. P.; Hensley, G. W.; Houlihan, E. J. Caloric value of fiber-containing cereal fractions and breakfast cereals. *J. Food Sci.* **1980**, *5*, 372-374.
McBurney, M. I.; Thompson, L. U. Fermentative characteristics of cereal brans and vegetable fibers. *Nutr. Cancer* **1990**, *13*, 271-280.
Mongeau, R.; Brassard, R. Insoluble fiber from breakfast cereals and brans: bile salt binding and water-holding capacity in relation to particle size. *Cereal Chem.* **1982**, *59*, 413-417.
Mongeau, R.; Brassard, R. Dietary fiber and fecal characteristics in rats: effect of level and particle size of bran. *J. Food Sci.* **1985**, *50*, 654-656.
Mongeau, R.; Brassard, R. A rapid method for the determination of soluble and insoluble dietary fiber: comparison with AOAC total dietary fiber procedure and Englyst's method. *J. Food Sci.* **1986**, *51*, 1333-1336.
Mongeau, R.; Brassard, R.; Malcolm, S.; Shah, B. G. Effect of dietary cereal brans on body weight and blood lipids in a long term rat experiment. *Cereal Chem.* **1991**, in press.
Moss, R.; Mugford, D. C. Analysis and Microscopic examination of faecal residues and insoluble dietary fibre from wheat bran and other wheat products. *J. Cereal Sci.* **1986**, *4*, 171-177.
Nauss, K. M.; Jacobs, L. R.; Newberne, P. M. Dietary fat and fiber: relationship to caloric intake, body growth and colon tumorigenesis. *Am. J. Clin. Nutr.* **1987**, *45*, 243-251.
Nyman, M.; Asp, N.-G. Fermentation of dietary fibre components in the rat intestinal tract. *Br. J. Nutr.* **1982**, *47*, 357-366.
Nyman, M.; Asp, N.-G. Dietary fibre fermentation in the rat intestinal tract: effect of adaptation period, protein and fibre levels, and particle size. *Br. J. Nutr.* **1985**, *54*, 635-643.
Nyman, M.; Schweizer, T. F.; Tyrén, S.; Reimann, S.; Asp, N.-G. Fermentation of vegetable in the intestinal tract of rats and effects on fecal bulking and bile acid excretion. *J. Nutr.* **1990**, *120*, 459-466.
Olson, A. C.; Gray, G. M.; Csiu, M.-C.; Fleming, S. E. Cellulose, xylan, corn bran, and pectin in the human digestive process. In *Unconventional sources of dietary fiber. Physiological and in vitro functional properties*; Furda, I., Ed.; ACS Symposium Series 214; American Chemical Society: Washington, DC, 1983.
Ring, S. C.; Selvendran, R. R. Isolation and analysis of cell wall material from beeswing wheat bran (Triticum aestivum). *Phytochemistry* **1980**, *19*, 1723-1730.
Robertson, J. A.; Murison, S. D.; Cheeson, A. Loss of selected water-insoluble polysaccharides and component neutral sugars from swede (Brassica napus (cv Danestone)) and cereal bran measured during digestion in the pig caecum. *J. Sci. Food Agric.* **1986**, *37*, 359-365.
Saunders, R. M. Wheat bran: composition and digestibility. In *Topics in dietary fiber research*; Spiller, G. A., Amen, R. J., Eds.; Plenum Press: New York, 1978.
Schwarz, P. B.; Kunerth, W. H.; Youngs, V. L. The distribution of lignin and other fiber components within hard red spring wheat bran. *Cereal Chem.* **1988**, *65*, 59-64.
Shah, B. G.; Malcolm, S.; Belonje, B.; Trick, K. D.; Brassard, R.; Mongeau, R. Effect of dietary cereal brans on the metabolism of calcium, phosphorus and magnesium in a long term rat study. *Nutr. Res.* **1990**, *10*, 1015-1028.
Shah, B. G.; Malcolm, S.; Belonje, B.; Trick, K. D.; Brassard, R.; Mongeau, R. Effect of dietary cereal brans on the metabolism of trace elements in a long term rat study. *Cereal Chem.* **1991**, *68*, 190-194.
Stanogias, G.; Pearce, G. R. The digestion of fibre in pigs. 1. The effects of amount and type of fibre on apparent digestibility, nitrogen balance and rate of passage. *Br. J. Nutr.* **1985**, *53*, 513-530.
Stat Plus. In *General statistics program for the Apple II*; Human Systems Dynamics: Northridge, CA, 1982.
Stephen, A. M.; Cummings, J. H. Mechanism of action of dietary fiber in the human colon. *Nature* **1980**, *284*, 283-284.
Stevens, B. J. H.; Selvendran, R. R.; Bayliss, C. E.; Turner, R. Degradation of cell wall material of apple and wheat bran by human faecal bacteria in vitro. *J. Sci. Food Agric.* **1988**, *44*, 151-156.
Van Soest, P. J. Dietary Fibers: their definition and nutritional properties. *Am. J. Clin. Nutr.* **1978**, *31*, S12-S20.
Van Soest, P. J. In *Nutritional ecology of the ruminant*; O&D Books: Corvallis, OR, 1982.
Wood, P. J.; Weisz, J.; Mahn, W. Molecular characterization of cereal β-glucans. II. Size-exclusion chromatography for comparison of molecular weight. *Cereal Chem.* **1991**, in press.
Wrick, K. L.; Robertson, J. B.; Van Soest, P. J.; Lewis, B. A.; Rivers, J. M.; Roe, D. A.; Hackler, L. R. The influence of dietary fiber source on human intestinal transit and stool output. *J. Nutr.* **1983**, *113*, 1464-1479.
Yiu, S. H. Cereal structure and its relationship to nutritional quality. *Food Microstruct.* **1989**, *8*, 99-113.
Yiu, S. H.; Mongeau, R. Fluorescence and light microscopic analysis of digested oat bran. *Food Microstruct.* **1987**, *6*, 143-150.

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Registry No. ARA, 147-81-9; GAL, 59-23-4; GLU, 50-99-7; xylan, 9014-63-5; hemicellulose, 9034-32-6; cellulose, 9004-34-6; lignin, 9005-53-2.