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Effects of soluble corn bran arabinoxylans on cecal digestion, lipid metabolism, and mineral balance (Ca, Mg) in rats

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The effects of soluble corn bran arabinoxylans on cecal digestion, lipid metabolism, and mineral utilization [calcium (Ca) and magnesium (Mg)] were investigated in rats adapted to semipurified diets. The diets provided either 710 g/kg wheat starch alone (control) or 610 g/kg wheat starch plus 100 g/kg corn soluble fiber (arabinoxylans) and either 0 or 2 g/kg cholesterol (control + cholesterol and arabinoxylans + cholesterol, respectively). Compared with rats fed the control diets, rats fed the arabinoxylan diets had significant cecal hypertrophy (+50% after 3 days of the fiber adaptation) and an accumulation of short-chain fatty acids, especially propionic acid (up to 45% in molar percentage). Arabinoxylans enhanced the cecal absorption of Ca and Mg (from 0.07 to 0.19 μmol/min for Ca and from 0.05 to 0.23 μmol/min for Mg). Mg balance was enhanced by arabinoxylans (+25%). The arabinoxylan diet markedly reduced the cholesterol absorption from 50% of ingested cholesterol in controls up to approximately 15% in rats adapted to the arabinoxylans diet. Arabinoxylans were effective in lowering plasma cholesterol (approximately −20%). There was practically no effect of the diets on cholesterol in d > 1.040 *lipoproteins (high density lipoproteins) whereas arabinoxylans were very effective in depressing cholesterol in* d < 1.040 *lipoproteins (especially in triglyceride-rich lipoproteins). Corn fermentable fiber decreased the accumulation of cholesterol in the liver. In parallel, the arabinoxylan diet counteracted the downregulation of 3-hydroxy-3-methylglutaryl-CoA by cholesterol. These data suggest that arabinoxylans may have a great impact on intestinal fermentation, mineral utilization, and cholesterol metabolism.* (J. Nutr. Biochem. 10:500–509, 1999)

Keywords: calcium; cecum; cholesterol; fermentation; fiber; magnesium

Introduction

Many common diseases in Western countries are thought to be due to a deficiency in dietary fiber (DF). However, a distinction is established between insoluble DF and soluble DF. The metabolic effects of insoluble DF such as cellulose and a part of hemicellulose are of limited interest because of their low degradability in most monogastric species.[1,2] By contrast, soluble DF is generally broken down by the large intestine microflora, and the resulting production of short-chain fatty acids (SCFA) may be involved in the metabolic effects of fibers,[3] which include a decrease of serum cholesterol[4–9] and an enhancement increase of mineral utilization.[10–13] Arabinoxylan, a soluble DF extracted from

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Table 1 Composition of diets

Ingredients	Diet*			
	Control	Arabinoxylans	Control + cholesterol	Arabinoxylans + cholesterol
Pure wheat starch†	710	610	708	608
Corn soluble fiber‡	—	100	—	100
Milk casein†	150	150	150	150
Peanut oil§	70	70	70	70
Mineral and vitamin mix‖	70	70	7.0	70
Cholesterol**	—	—	2	2

* Measured in g/kg diet.
† Wheat starch and milk casein was purchased from Louis François (Paris, France).
‡ Corn fiber was provided by ULICE (Riom, France). It contained 80.1% arabinoxylans. The sugar composition of the arabinoxylans was 40% xylose, 25.5% arabinose, 7.85% glucuronic acid, and 6.75% galactose.
§ Peanut oil was purchased from C.I.O. (Genay, France).
‖ Mineral and vitamin mix (per kg of diet): thiamine, 20 mg; riboflavine, 15 mg; pyridoxine, 10 mg; nicotinamide, 100 mg; calcium panthotenate, 70 mg; folic acid, 5 mg; biotine, 0.3 mg; cyanocobalamine, 0.05 mg; retinol palmitate, 1.5 mg; DL-α-tocopherol acetate, 125 mg; cholecalciferol, 0.15 mg; menadione, 1.5 mg; ascorbic acid, 50 mg; myoinositol, 100 mg; choline, 1.36 g; $CaHPO_4$, 15 g; K_2HPO_4, 2.5 g; KCl, 5 g; NaCl, 5 g; $MgCl_2$, 2.5 g; Fe_2,O_3, 2.5 mg; $MnSO_4$, 125 mg; $CuSO_4$, 0.2 mg; $ZnSO_4$, 100 mg; KI, 0.4 mg. Purchased from UAR (Villemoisson, Epinay-sur-Orge, France). Mineral content of all diets was checked before the beginning of the experiment.
** Cholesterol was provided by Sigma Chemical (St. Louis, MO USA).

corn bran [Unité de Laboratoire pour l'Innovation dans les Céréales (ULICE), Riom, France], could reduce the level of serum cholesterol in rats fed a cholesterol diet. Moreover, water-soluble arabinoxylan increased the quantities of SCFA in the cecum.[14]

In the present study, the effects of corn bran arabinoxylans on cecal digestion, lipid metabolism, and mineral utilization [calcium (Ca) and magnesium (Mg)] were studied in rats.

Methods and materials

Arabinoxylan preparation

Arabinoxylans were extracted from commercial maize bran and provided by ULICE: 100 g of bran were stirred with 1 L of alkaline solution (KOH 4.5%) in a thermostated reactor (100°C) for 2 hours. The residue was separated by centrifugation (20 minutes; 10,000 *g* 15°C), washed with 200 mL of distilled water, and centrifuged again. Arabinoxylans were finally precipitated with 95% ethanol (2 volumes, 16 hours; 4°C), recovered by filtration (pore diameter <15 μm), and dried by solvant exchange in an oven at 40°C.[15]

Animals and diets

Male Wistar rats, aged approximately 7 weeks, were used. They were derived from the colony of laboratory animals of the National Institute of Agronomic Research (INRA, Clermont-Ferrand/Theix, France). The animals were housed two per cage (wire-bottomed to limit coprophagy) and maintained in a temperature-controlled room (22°C), with a dark period from 8:00 PM to 8:00 AM. For 6 days before the beginning of the experiment, the rats were fed a fiber-free diet (control diet; *Table 1*). After this period, 8 rats were sampled (day 0 of the experiment) and the others were divided into four groups: (1) 16 rats were fed the semi-purified diet (control group); (2) 24 rats were fed a fiber-containing semi-purified diet (arabinoxylans); (3) 8 rats were fed a fiber-free, cholesterol diet (control + cholesterol); and (4) 8 rats were fed the fiber and cholesterol diet (arabinoxylans + cholesterol).

At days 3 and 11 of the experiment, 8 rats fed the arabinoxylan diet were sampled. After these sacrifices, the 24 remaining rats were sampled at day 20. The rats were provided with fresh food and distilled water daily; these were available ad libitum. Daily food consumption and body weight were recorded twice a week. Feces were collected over 5 consecutive days for Ca, Mg, and sterol studies and were then stored at −20°C. Animals were handled in accompliance with the recommendations of the Institutional Ethics Committee of the University of Clermont-Ferrand.

Sampling

Rats were sampled at the end of the dark period (between 8:00 and 9:00 AM), because cecal fermentation was still very active. They were anesthetized (sodium pentobarbital 40 mg/kg) and maintained on a warming plate at 37°C. An abdominal incision was made. The procedure of blood sampling on anesthesized animals for the measurement of arteriovenous difference across the cecum was described previously.[16] For blood flow measurement, bromosulfophthaleine in saline (4.7 mmol/L) was infused in one of the small veins at the surface of the cecum at a rate of 100 μM/min. The marker's dilution in the vein draining the whole cecum permitted the determination of cecal blood flow. This was roughly proportional to the weight of the cecal wall (ranging from 0.9–1.3 mL/min/g cecal wall). Blood was withdrawn from the cecal vein and the abdominal aorta. The blood was placed in microfuge tubes containing heparin and centrifuged at 10,000 *g* for 2 minutes. Plasma samples were stored at 4°C for lipid and lipoprotein analysis.

After blood sampling, the cecum (complete with contents) was removed and weighed. Duplicate samples of cecal contents were collected into 2-mL microfuge tubes, immediately frozen, and stored at −20°C. The cecal wall was flushed clean with ice-cold saline, blotted on filter paper, and weighed (cecal wall weight). Cecal water was determined as the difference between wet weight and dry weight on aliquots of cecal contents that were dried to constant weight. Before SCFA analysis, supernatants were obtained by centrifuging one of the two microtubes at 20,000 *g* for 10 minutes at 4°C.

A part of the liver was freezed-clamped and stored at −80°C for the measurement of lipid contents. Hepatic microsomes were prepared as previously described[9] and stored at −80°C until 3-hydroxy-3-methylglutaryl-CoA reductase (HMGR) activity

was measured. The protein content of the microsomes was determined using the Pierce BCA reagent kit (Interchim, Montluçon, France).

Analytical procedures

SCFA were measured on aliquots of cecal supernatants by gas-liquid chromatography as previously described.[17] Bile acids and neutral sterols were extracted from feces by a two-step procedure. For this purpose, 1 volume of sample was first dispersed in 10 volumes of ethanolic KOH (0.5 mol/L) using a Polytron desintegrator (Lucerne, Switzerland) and extracted at 70°C for 2 hours. Following this, 1 volume of this suspension (typically 2.5 mL) was redispersed in 4 volumes of ethanolic KOH and reextracted at 70°C for 2 hours. Bile acids were quantified using the reaction catalyzed by 3 α-hydroxysteroid dehydrogenase (EC 1.1.1.50; Sigma Chemical Co., St. Louis, MO USA).[18] Cholesterol concentration was enzymatically determined on this same extract and on plasma using a kit purchased from BioMérieux (Charbonnières-les-Bains, France). Triacylglycerol (Biotrol, Paris, France) was determined in plasma by enzymatic procedure. Liver lipids were extracted with chloroform/methanol (2:1, vol/vol) according to the method previously described.[19]

Plasma lipoproteins were separated by density gradient ultracentrifugation[20] using pooled samples. After centrifugation in a TST 41.14 (Kontron, Zurich, Switzerland) swinging-bucket rotor at 100,000 *g* for 24 hours at 18°C, the gradient was divided into 24 × 500 μL fractions and kept at 4°C for lipid analysis. Due to the low level of low density lipoprotein (LDL) and the relative overlapping of high density lipoprotein (HDL)-1 and HDL-2 fractions in rat plasma, it was decided to present data on the $d < 1.040$ fraction [chiefly triglyceride-rich lipoprotein (TGRLP), with a minor contribution of LDL] and on the $d > 1.040$ fraction (essentially HDL), as previously performed.[21]

The activity of liver microsomal HMGR was measured as described by Wilce and Kroone.[22] Labeled mevalonolactone was separated from unreacted HMG-CoA by column chromatography using AG1-X8 resin (200–400 mesh; Biorad, Paris, France). The activity was expressed as pmol [^{14}C]HMG-CoA transformed in [^{14}C]mevalonolactone/min/mg microsomal protein.

Ca and Mg were determined on the cecal supernatant fractions (soluble) and on the untreated cecal (total) contents, as well as on the fecal materials after dry-ashing (10 hours at 500°C). The resulting ash was redissolved in HCl (6 mol/L) and made up to an appropriate volume with lanthanum solution (1 g/L). After an adequate dilution, mineral concentration was measured by atomic absorption spectrophotometry (Perkin-Elmer 420, Norwalk, CT USA) at wavelengths of 422 (Ca) and 285 (Mg).

Calculations and statistical analysis

The total and soluble Ca and Mg cecal pools and total cecal SCFA pools were calculated as follows:

$$\text{total pool (}\mu\text{mol)} = \text{cecal concentration (}\mu\text{mol/g)} \times \text{cecal fresh content weight (g); soluble pool (}\mu\text{mol)} = \text{cecal supernatant concentration (}\mu\text{mol/g)} \times \text{cecal water (g).} \quad (1)$$

The cecal absorption (at the time of the measurement) was determined from the following formula:

$$\text{rate cecal absorption (}\mu\text{mol/min)} = [\text{cecal vein concentration - cecal artery concentration (}\mu\text{mol/mL)}] \times \text{cecal plasma flow (mL/min).} \quad (2)$$

For the determination of mineral balance, food and fecal samples from each pair of rats were homogenized, dried, powdered, and mineralized before mineral analysis.

Values are given as the means ± SEM and, where appropriate, significance of the difference between mean values was determined by analysis of variance coupled with the Student-Newman-Keuls multirange test. *P*-values of less than 0.05 were considered significant.

Results

Kinetics of the changes in rats fed the control diet and rats fed DF diet

The incorporation of 8% corn arabinoxylan did not markedly alter growth: The final weights were practically identical (304 ± 10 g vs. 300 ± 5 g in the arabinoxylan and fiber-free diet groups, respectively). The daily food intake was not significantly different in both groups, although the intake of rats fed the arabinoxylan diet was higher than that of controls (23.5 ± 0.8 g vs. 22.4 ± 0.8 g).

Figure 1 presents the changes in the cecum parameters during the experiment. The cecum weight remained at low and almost constant values in rats fed the control fiber-free diet; a rapid increase of the cecal weight (+80%) was noted from 3 day after the beginning of the arabinoxylan diet, and it remained constant thereafter. By contrast to cecal contents (cecal weight − cecal wall weight), the cecal wall weight increased progressively during the first 10 days of the arabinoxylan diet adaptation, and then became stable. The cecal pH was 7.2 in rats fed the fiber-free diet; in rats fed the arabinoxylan diet, an acidic pH (<6) was reached after 3 days of treatment and remained stable. This pH drop was not due to lactic acid accumulation, which was weak (12 μmol cecum at the third day and 7 μmol at the end of the experiment; data not shown).

The rise of the cecal pool of SCFA in rats fed the DF diet (+280%) could explain the pH drop (*Figure 2*). However, noticeable concentrations of SCFA (close to 100 mmol/L) were also present in the cecum of the rats fed the fiber-free diet (acetate, 66 mmol/L; propionate, 22 mmol/L; and butyrate, 12 mmol/L). The presence of arabinoxylans in the diet involved a progressive increase in the acetate and propionate concentrations (up to 95 mmol/L and up to 80 mmol/L, respectively). The butyrate concentration was particularly weak for DF type (close to 5 mmol/L).

After 10 days of adaptation, the soluble cecal Ca pool increased at day 3 (17-fold; *Figure 3*). The rise of cecal volume and soluble Ca pool may explain the increase of cecal absorption (close to threefold-enhanced; *Table 2*). After an adaptation of 3 days, the soluble Mg pool exhibited an early increase and reached a value of 70 μmol (fivefold the value of the rats fed the fiber-free diet; *Figure 3*). The cecal absorption of Mg was enhanced after switching rats to the arabinoxylan diet (0.05 ± 0.01 for rats fed the fiber-free diet vs. 0.23 ± 0.02 μmol/min for the group fed the DF diet).

Influence of arabinoxylans on lipid metabolism

As shown in *Table 3*, the cholesterol balance was negative in rats fed the cholesterol-free diet. Nevertheless, the arabi-

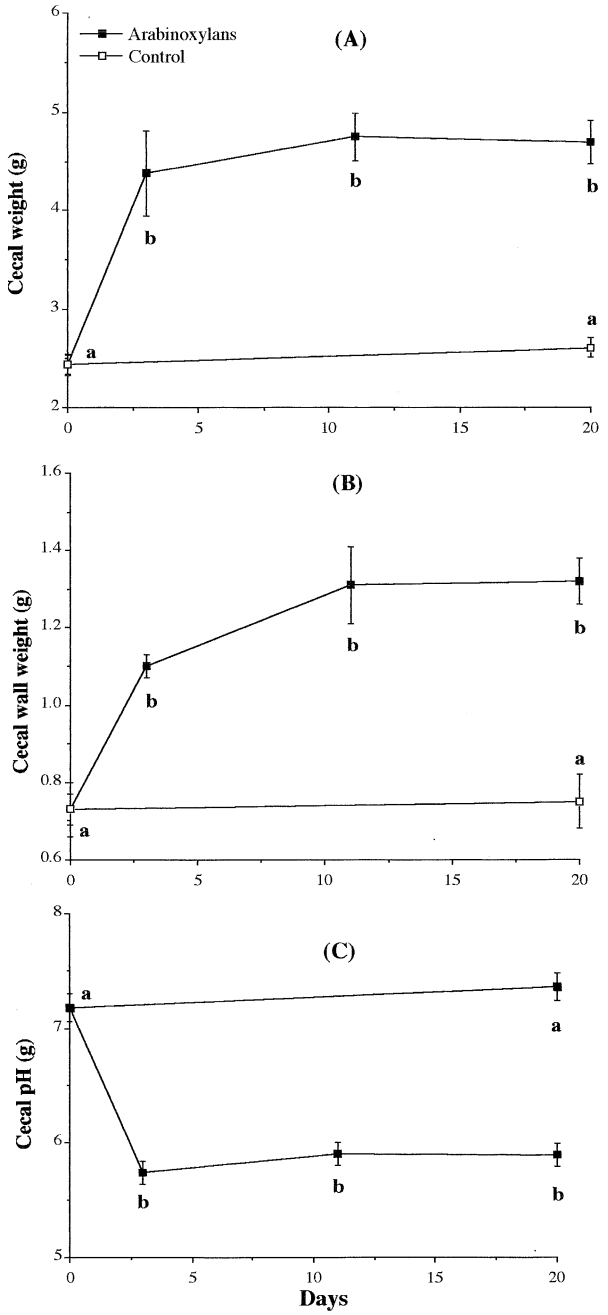

Figure 1 Changes in the weights of the (*A*) cecum (cecal content + cecal wall) and (*B*) cecal wall, and (*C*) the pH of the cecal contents. The rats were first fed a fiber-free, high-carbohydrate diet for 6 days before the beginning of the experiment. Because there was no difference in cecal parameters between the rats fed the cholesterol-free diet and the one fed the cholesterol diet, only the rats fed a fiber-free diet (control) and the one fed an arabinoxylan diet were represented. Moreover, because there were very limited changes in the indices of cecal digestion in rats fed the fiber-free diet, sampling was carried out at days 0 and 20 of the experiment only. Values are means ± SEM for eight rats at each experimental point. Different subscript letters indicate significant differences ($P < 0.05$).

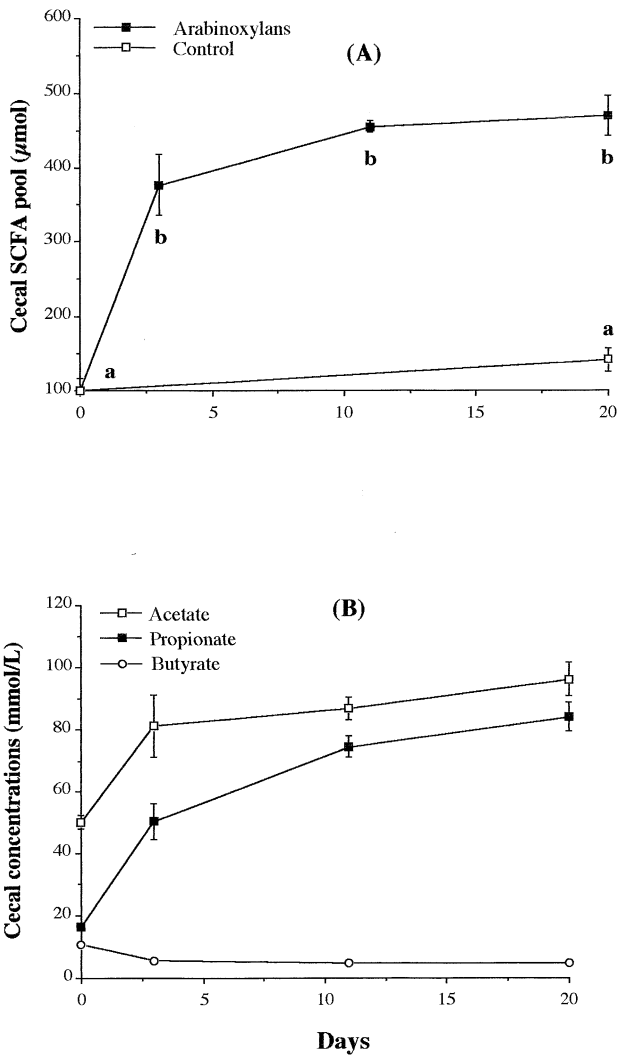

Figure 2 Changes in (*A*) the cecal short-chain fatty acid (SCFA) pool in rats fed the arabinoxylan or the fiber-free diet (control) and (*B*) the kinetics of the changes in the cecal concentrations of acetate, propionate, and butyrate in rats fed the arabinoxylan diet. Values are means ± SEM for eight rats at each experimental point. Different subscript letters indicate significant differences ($P < 0.05$).

noxylan diet allowed elimination of more cholesterol in feces (−26.4 ± 2.7 μmol/d vs. −18.8 ± 1.9 μmol/d with control diet). The daily cholesterol intake in rats fed the control + cholesterol diet was 155 μmol/d, although the intake of rats adapted to the DF + cholesterol diet was 133 μmol/d. This difference was due to the greater food intake of the first diet group. The neutral steroid excretion (fecal cholesterol + fecal coprostanol) in controls (58.9 μmol/d) corresponded to 50% of the daily food supplied. This excretion was markedly important in rats adapted to the arabinoxylan diet (116 μmol/d) and corresponded to 87% of the daily cholesterol intake. If the elimination of fecal neutral steroids was enhanced by the presence of arabinoxylans, the bile acid pool was almost affected by the change of diet (*Figure 4*). However, the total steroid balance was always negative when arabinoxylan was present in the diet.

When the diet contained no cholesterol, the effect of arabinoxylans on bile acid elimination appeared more pronounced than those exerted on neutral steroid losses. When the diet contained cholesterol, the complex carbohydrates

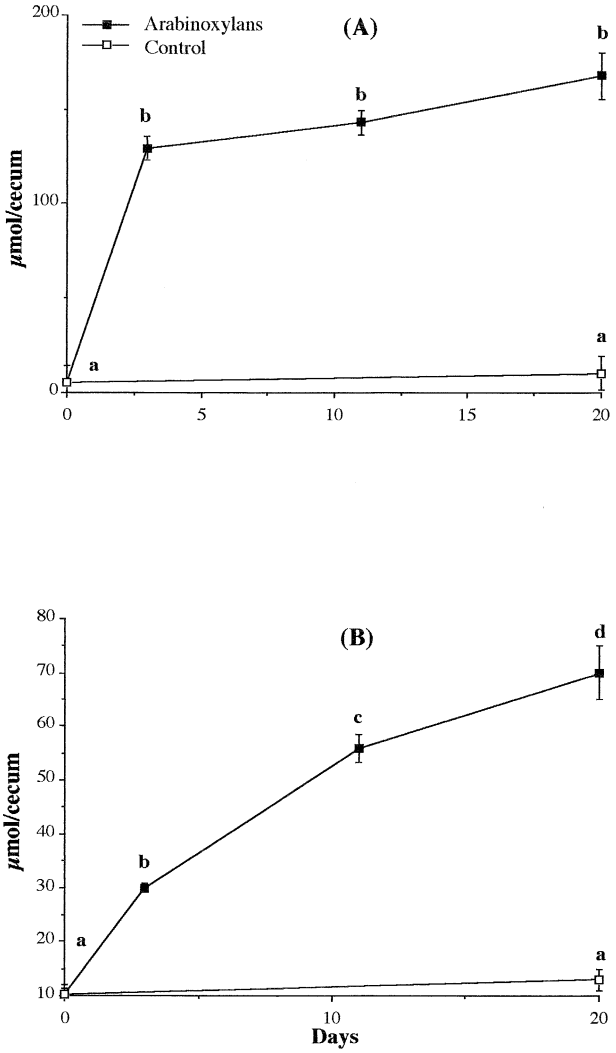

Figure 3 Changes in (*A*) the soluble cecal calcium pool and (*B*) the soluble cecal magnesium pool. Values are means ± SEM for eight rats at each experimental point. Different subscript letters indicate significant differences ($P < 0.05$).

reduced cholesterol absorption (approximately 13% in rats adapted to arabinoxylan diet vs. 50% in control rats). In so far as cholesterol is less absorbed when diet contains arabinoxylans, cholesterol transformation into bile acids in the liver is reduced. Under these conditions, it was difficult to observe a significant effect of arabinoxylans on fecal bile acid excretion.

Rats fed the arabinoxylan diet had a significantly lower plasma cholesterol concentration than control rats although the plasma triglyceride concentration was not affected by the diet (*Table 4*). Analysis of the plasma lipoprotein profile by gradient density ultracentrifugation (*Figure 5*) showed that there was a drastic reduction of cholesterol in the $d <$ 1.040 kg/L fractions (TGRLP) in rats fed the DF diet. By contrast, there was no significant change in the $d > 1.040$ cholesterol (essentially HDL) in rats adapted to the arabinoxylan diet. In the liver, the dietary cholesterol increased the hepatic cholesterol and triglyceride concentrations. When the rats were fed the arabinoxylan + cholesterol diet, the incorporation of arabinoxylans had a significantly lower effect on the liver cholesterol (−40%) compared with rats fed control + cholesterol diet.

As shown in *Figure 6*, microsomal HMGR activity was practically nonexistent when the diet contained cholesterol. By contrast, as the complex carbohydrates lead to a 70% elevation of total steroid losses, HMGR activity was markedly higher in rats fed the arabinoxylan diet.

Discussion

The incorporation of soluble corn bran arabinoxylan in the diet elicited striking effects on cecal fermentation as well as on cholesterol and mineral balances. The first effect of fermentable hemicelluloses was to cause an enlargement of the cecum and hypertrophy of the cecal wall. Enlargement of cecum in rats consuming unavailable carbohydrates has been reported consistently.[4,9,10,13,15,23–25] The effects of complex carbohydrates on cecal hypertrophy tends to be proportional to their fermentability rather than to their accumulation in the cecum.[24] Thus, the arabinoxylans diets induced high bacterial proliferation; in particular it has been shown by an increase of total nitrogen present in the cecum but also an increase of fecal nitrogen losses (data not shown).

In rats fed the diet containing 8% arabinoxylans, the weight of cecal wall rapidly increased from the first days of the experiment (+50% after 3 days). This displays a large stimulation of the cellular division. It has been shown that this hyperplasia is concomitant with an elevation of ornithine decarboxylase and thymidine kinase in rats fed the soybean fiber.[23] The decrease in pH and the increase of the SCFA pool play essential roles in inducing cellular division, because low fermentable fibers that accumulate in the cecum have little hypertrophic effect.[24]

One of the most striking effects of corn bran arabinoxylan is a very high percentage of propionate (up to 45% in molar percentage), together with a low percentage of butyrate, observed in the cecal content. In respect to this, corn bran arabinoxylan seems to have similar effects to those of soybean fiber.[23] Extensive conversion of fiber into propionate is an interesting feature, because propionate is the only neoglucogenic SCFA. Furthermore, propionate or its acylCoA derivatives affect various metabolic pathways (e.g., gluconeogenesis, ureagenesis, ketogenesis).[3]

Fermentable carbohydrates are able to modify the bivalent cation utilization and conversely, these cations may play a role in SCFA neutralization. When the Ca in the diet is adequate, only a part of this Ca is absorbed through the small intestine, so that it accumulates in the large intestine in form of insoluble Ca phosphate.[25] Arabinoxylan fermentation in the cecum decreases pH by raising SCFA production and increases Ca solubility. Furthermore, cecal hypertrophy allows to enlarge the volume where Ca from ileum may accumulate. Consequently, there is an important increase in concentrations of soluble Ca (8 times) and in concentrations of soluble Ca pool present in the cecum (16 times). The solubilization of approximately 60 mM of soluble Ca may play a role in the maintenance of the physiologic pH (near 6) as described by Rémésy et al.[25] It must be noted that in the presence of arabinoxylans, more

Table 2 Effect of arabinoxylans on calcium and magnesium (*A*) cecal parameters and (*B*) ca and mg balances*

(A)

	Calcium				Magnesium			
	Total (mmol/L)	Soluble (mmol/L)	Soluble cecal pool (μmol/cecum)	Cecal absorption (μmol/min)	Total (mmol/L)	Soluble (mmol/l)	Soluble cecal pool (μmol/cecum)	Cecal absorption (μmol/min)
Control	435.4 ± 31.0[a]	8.0 ± 1.1[a]	10.3 ± 0.8[a]	0.07 ± 0.01[a]	63.7 ± 2.8[a]	9.1 ± 0.9[a]	13.4 ± 1.3[a]	0.05 ± 0.01[a]
Arabinoxylans	409.2 ± 18.3[a]	63.8 ± 4.7[b]	167.7 ± 12.3[b]	0.19 ± 0.03[b]	35.6 ± 2.3[b]	26.2 ± 1.9[b]	68.9 ± 4.9[b]	0.23 ± 0.02[b]

(B)

	Calcium				Magnesium			
	Daily intake (DI) (mg/d)	Fecal excretion (FE) (mg/d)	DI-FE difference (mg/d)	DI-FE difference (% of intake)	DI (mg/d)	FE (mg/d)	DI-FE difference (mg/d)	DI-FE difference (% of intake)
Control	118.0 ± 7.0[a]	52.7 ± 1.4[a]	65.3 ± 2.8[a]	55	13.1 ± 0.7[a]	6.8 ± 0.2[a]	6.3 ± 0.3[a]	48
Arabinoxylans	137.1 ± 15.0[a]	79.6 ± 2.6[b]	57.5 ± 1.5[a]	42	14.9 ± 0.9[a]	6.0 ± 0.3[a]	8.9 ± 0.3[b]	60

* Values are the means ± SEM; $N = 8$ rats. Values in a column not sharing a common superscript are significantly different at $P < 0.05$.

Ca reaches the large intestine; this might result in a lower utilization in the small intestine. Such an effect can be ascribed to direct interactions between Ca and arabinoxylans or to an osmotic effect due to fermentable carbohydrates. Nevertheless, in terms of total balance, digestive absorption does not decrease, and cecal absorption may play a compensating role. Furthermore, a high rate of Ca absorption in the large intestine could trigger a feedback mechanism involving an inhibition of duodenal absorption, because there is a control of the digestive balance of Ca by endocrine factors.[26,27] The rat cecum presents the highest density of Ca transport sites (responsive to vitamin D metabolites)[28,29]; however, Ca absorption is restricted when Ca is in an unabsorbable form.[26,30] Thus, fermentable carbohydrates could favor Ca absorption in the distal part of the digestive tract in several ways: hypertrophy of the cecal wall and larger surface exchange area, increase of soluble Ca, and accelerated blood flow. It is also possible that the SCFA directly influence Ca absorption by modifying various electrolyte exchanges (Ca-H), and Trinidad et al.[31] have suggested that Ca could pass through the cell membrane more readily in the form of a less-charged complex $(Ca\ acetate)^{+}$. Lutz and Scharrer[32] have also reported a stimulatory effect of SCFA on Ca absorption (cecal pH, SCFA concentration, Ca itself). The question is whether the effects of arabinoxylans on the cecal absorption of Ca is mainly due to the hypertrophy of the cecum or to the increasing production of SCFA. Moreover, Ohta et al.[12] reported that dietary fructooligosaccharides (FOS) change the concentration of calbindinD9K differently in the mucosa of the small intestine and large intestine of rats. Thus, a part of the stimulatory effect of FOS relates to the transcellular route of Ca absorption in the large intestine of rats. In humans, a role for the colon is supported by the observation that the large intestine is able to maintain a near-normal rate of Ca absorption in case of small intestine resection.[33] The increase of soluble Ca in the large intestine may also decrease bile acids solubility and thus make their fecal elimination easier. It was reported that Ca could exert a protective effect on the colon epithelium[34] and inhibit the cytotoxicity of potential carcinogens, such as bile acids or fatty acids.[35,36]

The importance of the distal part of the digestive tract for Mg absorption is well documented.[37,38] In contrast to Ca, arabinoxylans strongly stimulate Mg absorption. The possibility of a negative feedback in response to a highly effective absorption in the large intestine seems less likely for Mg than for Ca. It was shown previously that various resistant starches or oligosaccharides stimulate Mg absorption.[10,11,13,25,39] Fermentable arabinoxylans raise the cecal pool of soluble Mg by acidifying digestive contents. The

Table 3 Effects of arabinoxylans on cholesterol balance*

	Cholesterol intake (μmol/d)	Fecal cholesterol (μmol/d)	Fecal coprostanol (μmol/d)	Balance (intake − excretion)	Cholesterol excreted (% ingested)
Control	—	5.3 ± 0.5[a]	13.5 ± 1.4[a]	−18.8 ± 1.9[a]	—
Arabinoxylans	—	8.3 ± 0.5[a]	18.1 ± 2.2[a]	−26.4 ± 2.7[b]	—
Control + cholesterol	115.0 ± 12.1[a]	24.2 ± 1.3[b]	34.7 ± 2.0[b]	56.1 ± 2.5[c]	51
Arabinoxylans + cholesterol	132.9 ± 14.2[a]	52.2 ± 7.9[c]	63.8 ± 8.1[c]	16.9 ± 0.2[d]	87

* Values are the means ± SEM; $N = 8$ rats. Values in a column not sharing a common superscript are significantly different at $P < 0.05$.

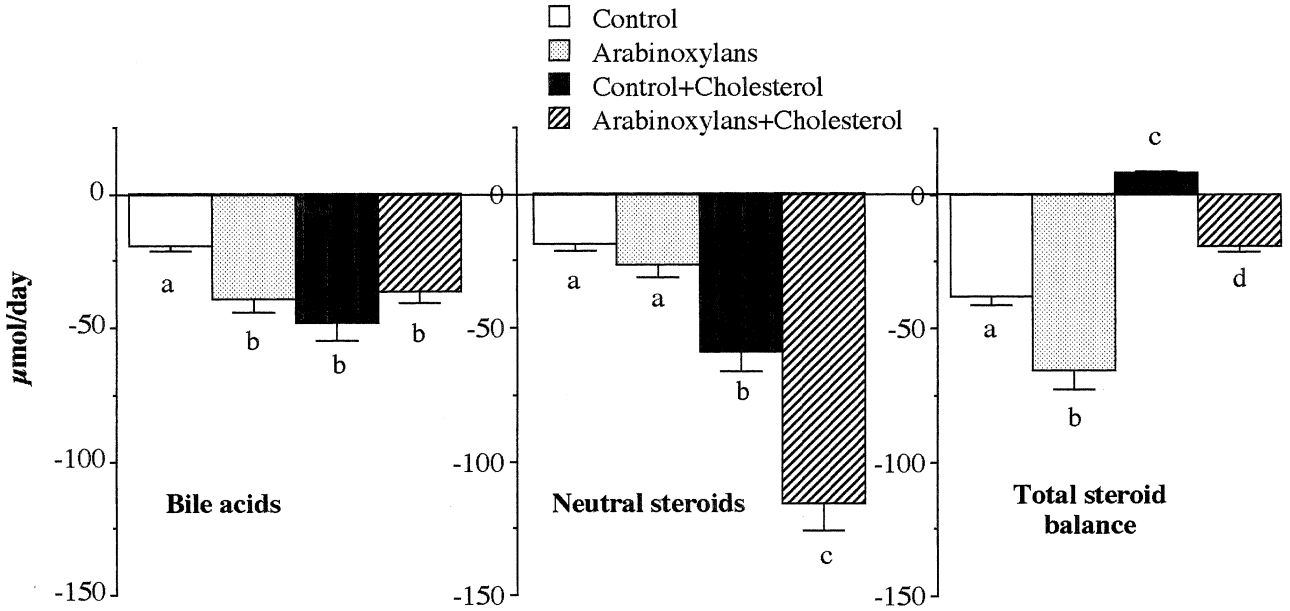

Figure 4 Changes in the fecal excretion of bile acids and neutral steroids and in the total steroid balance. The total steroid balance was calculated as: [daily cholesterol intake − (fecal excretion of bile acids + fecal excretion of neutral steroids)]. Values are means ± SEM for eight rats in each diet. Different subscript letters indicate significant differences ($P < 0.05$).

increase of the cecal absorption may arise from cecal hypertrophy, Mg solubilization, and possibly a specific effect of SCFA.[40] In particular, SCFA absorption at an acidic pH would supply more protons to the exchangers, resulting in a higher transport rate.[32] Fermentable carbohydrates may play a notable role by increasing mineral absorption in the large intestine, and this effect may be of particular interest when the overall process of digestive absorption is inefficient, such as in elderly subjects.[41] Because fiber-rich plants also contain many minerals, the effects of fermentable carbohydrates are beneficial for mineral status unless vegetables contain an high percentage of phytic acid.

Soluble and fermentable fibers do not only exert a role in maintaining symbiotic fermentation, but they also participate in neutral sterol elimination. When the diet does not contain cholesterol, arabinoxylans clearly increase the elimination of bile acids and neutral sterols. Nevertheless, the effect on bile acids appears more pronounced. Thus, the effects of arabinoxylans lead to a 70% elevation of total steroid losses; as a result, there was a marked induction of the liver HMGR. This induction of HMGR in parallel to a cholesterol-lowering effect has been observed in rats fed guar gum, pectin, or psyllium.[42–44] With a cholesterol-free diet, this induction is the result of the fiber-mediated diversion of the cholesterol body pool toward fecal steroid excretion. However, in spite of this adaptative response, arabinoxylans exert a significant plasma cholesterol lowering effect. When the diet contains cholesterol, the hypocholesterolemic mechanisms of arabinoxylans are different. The major effect of these complex carbohydrates is to reduce cholesterol absorption at a weak level (approximately 13% in rats adapted to arabinoxylan diet vs. 50% in control rats). In so far as cholesterol is less absorbed when the diet contains arabinoxylans, cholesterol transformation into bile acids in the liver is reduced. Under these conditions, one does not observe a significant effect of arabinoxylans on fecal bile acid excretion. On the other hand, in terms of total steroid excretion, the effect of arabinoxylans is noteworthy because this excretion is twice as high. This induces a slight HMGR induction although the diet contains cholesterol. The mechanism of induction of the rate-limiting enzyme of cholesterologenesis by fiber is probably connected to a depletion of cholesterol from the liver. The

Table 4 Effects of arabinoxylans on plasma and hepatic lipid concentration*

	Plasma		Liver	
	Cholesterol (mmol/L)	Triacylglycerols (mmol/L)	Cholesterol (mg/g liver)	Triacylglycerols (mg/g liver)
Control	1.88 ± 0.04^{a}	1.11 ± 0.14^{a}	2.10 ± 0.13^{a}	15.79 ± 0.81^{a}
Arabinoxylans	1.45 ± 0.09^{a}	1.21 ± 0.16^{a}	2.08 ± 0.17^{a}	16.67 ± 1.65^{a}
Control + cholesterol	2.34 ± 0.14^{c}	1.39 ± 0.11^{a}	5.81 ± 0.62^{b}	25.61 ± 2.32^{b}
Arabinoxylans + cholesterol	1.89 ± 0.11^{a}	1.40 ± 0.12^{a}	3.54 ± 0.40^{c}	24.04 ± 2.04^{b}

* Values are the means ± SEM; $N = 8$ rats. Values in a column not sharing a common superscript are significantly different at $P < 0.05$.

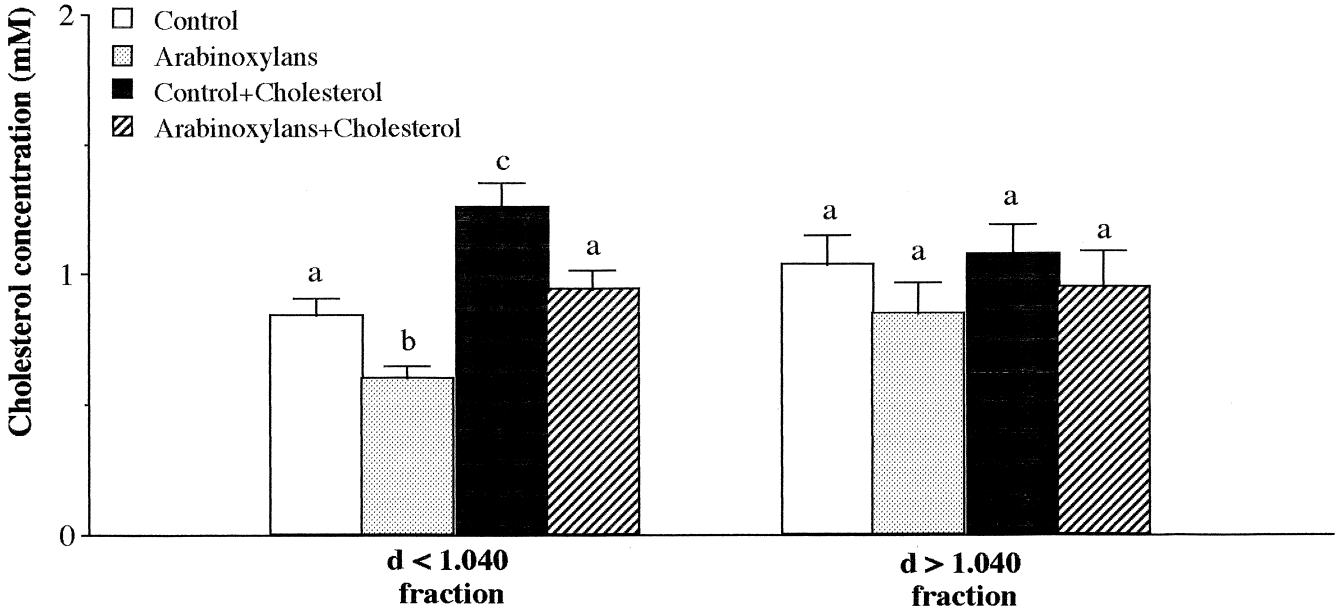

Figure 5 Changes in the repartition of cholesterol in the various plasma lipoprotein fractions in rats adapted to the control, arabinoxylans, control + cholesterol, and arabinoxylans + cholesterol diets. Each value is a mean ± SEM of a triplicate analysis of a pool of eight plasmas. The fractions with a density lower than 1.040 kg/L corresponded chiefly to triglyceride-rich lipoproteins, with a minor contribution of low density lipoproteins. The fractions with a density higher than 1.040 kg/L corresponded essentially to high density lipoproteins. Different subscript letters indicate significant differences ($P < 0.05$).

cholesterol-lowering effect of arabinoxylans was highly pronounced in TGRLP fraction, in keeping with the inhibition of cholesterol absorption, in particular when diet contained cholesterol.

With cholesterol-free diets, cholesterol oxidation for bile acid synthesis is accelerated, but HMGR induction is not sufficient enough to maintain a normal plasma cholesterol rate. Favier et al.[4] and Moundras et al.[44] showed that soluble fibers increase bile acid secretion and reabsorption from the ileum and the large intestine. It is possible that accelerated bile acid turnover plays a role in counteracting HMGR induction. Morand et al.[45] showed that the substitution of a part of wheat starch by fermentable carbohydrates decreased hepatic lipogenesis. This raises the question of whether SCFA, particularly propionate, potentiate the consequences of an enhanced fecal steroid excretion.[46] A putative role of SCFA in mediating the cholesterol-lowering effect of fiber has been proposed, probably in relation with the inhibition of the metabolism of the major lipogenic precursors, such as acetate and lactate. Demigné et al.[47] showed that proprionate, the production of which is high in animals fed the arabinoxylan diet, inhibits cholesterologenesis and lipogenesis from acetate. Relatively low insulinemia, a high rate of SCFA absorption, and low glucose absorption have been observed in rats fed fiber. Taken together, these factors may account for a depressed lipid synthesis.[48]

Even if a direct extrapolation of the present results to humans is still questionable due to differences in digestible tract structure and in colonic microflora, soluble corn bran

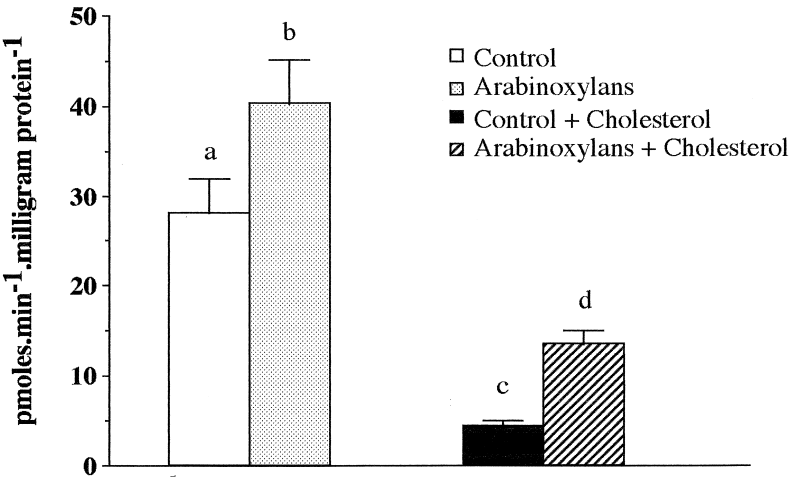

Figure 6 Changes in the hepatic activity of 3-hydroxy-3-methylglutaryl-CoA reductase. Values are means ± SEM for eight rats in each diet. Different subscript letters indicate significant differences ($P < 0.05$).

arabinoxylans have a great impact on intestinal fermentation, mineral utilization, and cholesterol metabolism in rats. Because these fibers are entirely soluble, they may be incorporated into foodstuffs (dairy products for instance) such as FOS. Moreover, arabinoxylans have an important molecular weight that delays their degradation rate, leading to physiologic fermentation at a moderately acidic pH. Thus arabinoxylan ingestion presents many attractive digestive and metabolic effects for preventive nutrition.

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