Extrusion Cooking and Dietary Fiber: Effects on Dietary Fiber Content and on Degradation in the Rat Intestinal Tract

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ABSTRACT

Dietary fiber content in raw and in extruded wheat products was measured gravimetrically after enzymatic solubilization of protein and starch. Dietary fiber content of whole grain wheat increased slightly after extrusion cooking, whereas the fiber content in wheat flour only increased after processing under extreme conditions. When the heat-stable α-amylase Termamyl, used in the dietary fiber assay, was excluded, the increase in dietary fiber was more pronounced. A redistribution of insoluble to soluble dietary fiber was observed in all extruded wheat flour samples. In raw wheat flour, 40% was soluble, whereas in extruded wheat flour, 50–75% was soluble. The redistribution in whole grain flour was less pronounced. The degradation of dietary fiber monomers in the rat intestine was very similar with raw and extruded whole grain wheat flour. However, the dietary fiber in extruded wheat flour was more extensively degraded than in the corresponding raw material. Fecal glucan excretion did not increase when extruded materials were fed, which indicated that altered starch was completely absorbed or fermented. Rats fed wheat flour extruded under severe conditions developed diarrhea.

Extrusion cooking is being used increasingly in the processing of cereal-based foods.

Cereals, an important source of dietary fiber, constitute about 40% of the total dietary fiber intake in Sweden (Arnbjörnsson et al 1982). A number of physiological effects have been attributed to dietary fiber, among them increased fecal volume, reduced transit time, improved glucose tolerance, and lowered plasma lipids (Vahouny and Kritchevsky 1982). However, very few data are available on the effects of different food processes on dietary fiber.

Many studies on the relation of physiological effects with the content and chemical composition of fiber have been published (Jenkins et al 1978, Jenkins 1979). The physical state of fiber is also important. For instance, the bile salt-binding capacity decreases with decreasing particle size (Mongeau and Brassard 1982). Furthermore, the milling of cereals increases the availability of digestible carbohydrates both in vitro (Greenberg 1976) and in vivo (O'Dea et al 1980). On the other hand, extrusion-cooked wheat bran was no less beneficial to glucose excretion in alloxandiabetic rats, compared with raw bran.[1]

Thermal processing can make a fraction of the starch less available to enzymes and thus increase the dietary fiber value[2] (Varo et al 1983).

By definition, dietary fiber resists the digestive enzymes in the gastrointestinal tract. In the large intestine, however, fermentation occurs through bacterial enzymes (Nyman and Asp 1982). Different kinds of dietary fiber are fermented to various degrees. Solubility, chemical structure, and particle size are factors that can be expected to influence the susceptibility to bacterial degradation.

The importance of the physical state of the fiber in relation to bacterial fermentation was demonstrated by Brodribb and Groves (1978). The susceptibility to fermentation in the colon of human subjects was inversely proportional to the size of the bran particles. In addition, Berg et al (1972) found that the breakdown of cellulose by highly cellulolytic bacteria was proportional to its surface area. Heller et al (1980) also demonstrated the importance of particle size. The moisture content in feces was significantly higher in humans given a coarse bran diet than in humans given a fine bran diet. Moreover, the bulking effect of bran is less pronounced with cooked bran than with raw (Wyman et al 1976).

Thus, processes such as extrusion cooking that involve heating in combination with homogenization could be expected to affect dietary fiber, in terms of both physiological properties and fiber analyses. A variety of products, including pregelatinized flours, breakfast cereals, crisp-breads and weaning foods, are produced by high-temperature short-time (HTST) extrusion cooking. In the extruder, the raw material is subjected to intense mechanical shear through the action of rotating screws. Cooking occurs at high temperature and pressure and at low water content. The mechanical treatment completely disorganizes the original structure of the raw material. The new structure obtained has been referred to as "uniform plasticized dough" (Kervinen et al 1981). Technical reviews on extrusion cooking have been published by Harper (1981) and by Linko et al (1981).

The purpose of the present investigation was to study the effect of extrusion cooking on dietary fiber in wheat products. The dietary fiber content in raw and in extruded products was measured gravimetrically after enzymatic solubilization of protein and starch. Because all the methods used for determining dietary fiber depend on complete digestion of starch, the efficiency of different enzyme systems for starch degradation was also evaluated. Furthermore, the effect of extrusion cooking on the susceptibility of dietary fiber to bacterial fermentation was studied through balance experiments in rats.

MATERIALS AND METHODS

Materials

Wheat starch (A-starch, Raisio Factories Ltd, Finland), wheat flour (extraction rate approximately 80%), and whole-grain wheat flour (Vaasa Mills Ltd, Finland) were the materials used. The products were processed in a Creusot-Loire BC-45 twin-screw extruder under conditions described in Table I. The feed rate was 200 g/min except in one case in which a higher feed rate was used. Feed moisture content was 15 or 20%. Screw speed varied between 100 and 200 rpm. Set temperature of barrel was 150°C in all experiments. Mass temperature was from 161 to 180°C and was measured with a thermocouple inserted just before the die. The extruded materials and the raw whole grain wheat flour were ground to pass a 0.5-mm sieve. The extruded products were shaped like expanded ribbons, and the grinding was performed to enable comparison with the corresponding raw materials. The most severely processed wheat flour (WF4), as judged from the degree of browning, is considered overcooked.

Methods

Determination of dietary fiber. The dietary fiber content was analyzed gravimetrically after enzymatic solubilization of protein and starch. Two different enzymatic systems for starch degradation were used. One system, based on the method by Hellendoorn et al (1975), used only physiological enzymes. After gelatinization for 15 min at 100°C, enzyme digestion was performed with pepsin (Merck No. 7190) at pH 1.5 for 1 hr and with pancreatin (Sigma No. P-1750) at pH 6.8 for 1 hr. The dietary fiber was precipitated with

[1] C. Nygren, G. Hallmans, L. Jonsson, and N.-G. Asp. 1982. Effects of processed rye and wheat bran on the glucose metabolism. Poster presented at International Symp. Fiber in Human and Animal Nutrition. Palmerston North, New Zealand, Abstr. 176.

[2] C.-G. Johansson, M. Siljeström, and N.-G. Asp. 1984. Dietary fibre in bread and corresponding flours—Formation of resistant starch. Unpublished data.

four volumes of 95% ethanol for 1 hr. Filtration in G-2 crucibles with Celite (0.5 g) as a filtering aid was used to separate the dietary fiber. The other method was described by Asp et al (1983). In addition to incubation with physiological enzymes, as above, a thermostable bacterial α-amylase (Termamyl 120L, Novo A/S, Denmark) was added during gelatinization. Insoluble fiber was recovered by filtration (G-2 crucibles, Celite as filtering aid). Soluble fiber was precipitated with four volumes of 95% ethanol and recovered by another filtration.

TABLE I
Process Conditions[a] During Extrusion Cooking of Starch, Wheat Flour, and Whole Grain Wheat Flour

	Wheat Starch	Wheat Flour				Whole Grain Wheat Flour		
		WF1	WF2	WF3	WF4	WGF1	WGF2	WGF3
Mass feed rate including moisture (g/min)	200	350	200	200	200	200	200	200
Feed moisture content (%)	15	15	15	15	15	20	20	20
Screw speed (rpm)	200	150	100	150	200	100	150	200
Mass temperature (°C)	180	161	161	171	171	164	166	166

[a] Creusot-Loire BC-45 twin-screw extruder. Set temperature of barrel, 150°C. Die: diameter, 5 mm; capillary length, 27 mm; clearance die/endplate, 2 mm. Screw: combination Die-RCCCC-Feed; R, Reverse flight screw element; C, Compression screw element; corotating intermeshing screws.

TABLE II
Composition of the Diets (% dry matter)

	Wheat Starch		Wheat Flour		Whole Grain Wheat Flour	
Component	Raw	Extruded[a]	Raw	Extruded[b]	Raw	Extruded[c]
Wheat product	69.3	69.3	74.2	76.3	81.6	81.2
Casein	9.9	9.9	...	...	...	...
Sucrose	10.0	10.0	15.0	12.9	7.6	8.0
Corn oil	5.0	5.0	5.0	5.0	5.0	5.0
Minerals[d]	4.8	4.8	4.8	4.8	4.8	4.8
Vitamins[e]	0.8	0.8	0.8	0.8	0.8	0.8
Choline chloride	0.2	0.2	0.2	0.2	0.2	0.2

[a] Process conditions described in Table I.
[b] Flour WF4 with process conditions described in Table I.
[c] Flour WGF3 with process conditions described in Table I.
[d] Containing, in grams: $CuSO_4 \cdot 5\,H_2O$ 8.6, $ZnSO_4 \cdot 7\,H_2O$ 32.0, KH_2PO_4 7780, $NaH_2PO_4 \cdot 2\,H_2O$ 4024, $CaCO_3$ 7600, KI 1.6, $MgSO_4 \cdot 7H_2O$ 2000, $FeSO \cdot 7\,H_2O$ 18, $MnSO_4 \cdot H_2O$ 80, $CoCl_2$ 0.46, NaCl 2382.
[e] Containing, in grams, menadione 25.0, thiaminhydrochloride 10.0, riboflavin 10.0, pyridoxin hydrochloride 5.0, calcium pantothenate 25.0, nicotinic acid 25.0, folic acid 1.0, inositol 50.0, *p*-aminobenzoic acid 5.0, 0.2, vitamin B12 cyanocobalamin 0.015, vitamin A 0.86, vitamin D 0.025, vitamin E 100, wheat starch 3765.

The dietary fiber residues were corrected for remaining protein (assayed with the Kjeldahl procedure and calculated as N × 6.25) and ash. All analyses were done in triplicate.

Gas-liquid chromatographic characterization of dietary fiber constituents. After acid hydrolysis, gas-liquid chromatography (GLC) of the neutral sugars as their alditol acetates was performed as described by Theander and Åman (1979). The hydrolysis was performed in 12*M* H_2SO_4 for 2 hr. The acid was then diluted to 0.36*M* and the hydrolysis continued by reflux boiling for 6 hr. Dietary fiber constituents were expressed as their polymer weights (0.9 × monomer weight).

Starch determination. Approximately 100 mg of sample was suspended in 1 ml of distilled water and gelatinized in a boiling water bath for 15 min. One-half milliliter of 0.2*M* sodium-acetate buffer, pH 4.75, and 5 μl of amyloglucosidase (Boehringer Mannheim GMBH, suspension of 10 mg/ml) were added. The suspension was incubated at 60°C for 30 min. After centrifugation of the suspension at 4,000 rpm, the released glucose was determined with glucose oxidase peroxidase reagent (5.6 g of GLOX-Novum [Kabi-Diagnostica, Stockholm, Sweden] in 100 ml of 0.5*M* TRIS buffer, pH 7.0). The glucose oxidase incubation was performed at 37°C for 1 hr, and the absorbance was measured at 435 nm. Starch content was expressed as glucose × 0.9.

In some determinations 5 μl Termamyl were added in the gelatinization step.

Paper chromatography. Ten grams of flour (dry matter) or 2 g of feces (dry matter) were extracted overnight in 80% (v/v) ethanol. The extract was filtered, evaporated, and dissolved in 10 ml of distilled water. Paper chromatography was performed on Whatman no. 3 paper. The following solvent system was used: ethylacetate/acetic acid/water, 3:1:1(v/v). Papers were stained with a silver dip reagent (Trevelyan et al 1950). Xylose, glucose, fructose, and maltose (50 μg) were used as standards.

Animal Experiments

Animals and diets. Male, Sprague-Dawley rats weighing approximately 75 g were divided into groups of five and placed individually in metabolic cages. Food intake was restricted to 10 g of dry weight per day. Water was provided ad lib. After a four-day adaption period, feed residues and feces were collected during a five-day balance period (Nyman and Asp 1982). Feces were collected dry, removed every day, and frozen at −20°C. Feces were then lyophilized, weighed, and milled to pass a 0.4-mm screen, and stored at −20°C until analysis.

All diets contained 5% corn oil, 10% sucrose, 4.8% minerals, and 1.0% vitamins, including choline chloride (Table II).

In the case of wheat flour and whole grain wheat flour, the flour was used as protein source, 1.5% N (d.b.). Sucrose was added to adjust dry matter content. In the groups fed wheat starch, the protein source was casein (ANRC reference protein, ICN Nutritional Biochemicals) 1.5% N (d.b.) (Table II).

Dietary-fiber characterization. Dietary-fiber composition in feed and in feces was analyzed by GLC, as described above. The dietary fiber in feed was isolated by using only physiological enzymes. Analysis of dietary fiber constituents in feces was performed directly on pooled samples from five rats. Glucose

TABLE III
Enzymatic Gravimetric Assay of Dietary Fiber in Raw and Extruded Flours: Comparison Between Different Enzyme Systems

	Dietary Fiber (% dry matter)[a]			
	Wheat Flour		Whole-Grain Wheat Flour	
Enzyme System	Raw	Extruded (WF1)	Raw	Extruded (WGF3)
Physiological enzymes only (pepsin, pancreatin)	6.8 ± 0.4	9.1 ± 0.6***	14.5 ± 0.3	20.5 ± 0.8***
Corrected for remaining starch (amyloglucosidase)	4.2 ± 0.4	5.2 ± 0.6*	12.4 ± 0.3	15.1 ± 0.8**
Corrected for remaining starch (Termamyl, amyloglucosidase)	4.0 ± 0.4	3.9 ± 0.6	12.2 ± 0.3	13.5 ± 0.8*

[a] Mean ± standard deviation. Significantly different from raw material (Student's *t*-test). * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$.

TABLE IV
Dietary Fiber Content in Raw and Extruded Wheat Flours

Material	Dietary Fiber (% dry matter)[a,b]					
	Total	Total[c]	Insoluble	Insoluble[c]	Soluble	Soluble[c]
Raw wheat flour	4.0 ± 0.2	4.0 ± 0.2	2.3 ± 0.1	2.3 ± 0.1	1.7 ± 0.1	1.7 ± 0.1
Extruded products[d]						
WF1	3.8 ± 0.1	3.7 ± 0.1	1.7 ± 0.1***	1.7 ± 0.1***	2.1 ± 0.1**	2.0 ± 0.1**
WF2	4.2 ± 0.5	3.9 ± 0.5	1.2 ± 0.2***	1.2 ± 0.2***	3.0 ± 0.4**	2.7 ± 0.4***
WF3	4.3 ± 0.1	3.6 ± 0.1*	0.9 ± 0.1***	0.9 ± 0.1***	3.4 ± 0.1***	2.7 ± 0.1***
WF4	4.9 ± 0.2***	3.9 ± 0.2	1.1 ± 0.3***	1.1 ± 0.3***	3.8 ± 0.1***	2.8 ± 0.1***

[a] Dietary fiber content was measured according to Asp et al (1983).
[b] Mean ± standard deviation. Significantly different from raw material (Student's t-test). * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$.
[c] Corrected for remaining starch in the fiber residue (amyloglucosidase).
[d] Process conditions described in Table I.

TABLE V
Composition of Dietary Fiber[a] in Raw and Extruded Wheat Flours

	Dietary Fiber Composition			
	Raw		Extruded (WF4)[b]	
	Insoluble	Soluble	Insoluble	Soluble
Relative composition (%)				
Arabinose	20	13	10	26
Xylose	26	16	9	34
Mannose	3	···	3	···
Galactose	···	3	···	6
Glucose[c]	16	3	6	6
Total	65	35	28	72
Sum of polysaccharides (g/100 g of dry matter)	2.0	1.1	0.9	2.3

[a] Dietary fiber content was measured according to Asp et al (1983).
[b] Process conditions described in Table I.
[c] Corrected for remaining starch in the fiber residue (amyloglucosidase).

values were corrected for the small amounts of free glucose and starch found in feces (approximately 15% of total glucose excretion).

RESULTS

Starch Solubilization and Dietary Fiber Content

In Table III, different enzyme systems for solubilization of starch have been compared for dietary-fiber determination in raw and in extruded wheat samples WF1 and WGF3. When only physiological enzymes were used, the dietary fiber content in extruded products was higher. The increment relative raw material was 2.3% in extruded wheat flour and 6.0% in whole grain wheat flour. After correction for remaining starch with amyloglucosidase, the increase in fiber content due to extrusion was reduced to 1% in wheat flour and to 2.7% in whole grain wheat flour. With Termamyl present in the gelatinization step during starch analysis, corrected dietary fiber values in wheat flour were similar before and after extrusion, about 4%. In extruded whole grain wheat flour, the dietary fiber content (13.5%) was still slightly higher than in the raw material (12.2%).

Dietary Fiber Content After Preincubation with Termamyl

Wheat flour. The content of total, insoluble, and soluble dietary fiber analyzed according to Asp et al (1983) is shown in Table IV. In samples WF1, WF2, and WF3 the total dietary fiber content was not significantly different from that of the raw material. In the most severely processed sample (WF4), total dietary fiber increased from 4.0 to 4.9%. This could be accounted for as starch, analyzed by extensive amyloglucosidase digestion. This altered starch was found in the soluble dietary-fiber fraction.

Extrusion-cooking caused a redistribution of insoluble to soluble dietary fiber. Thus, in raw wheat flour 40% of total fiber was soluble versus 50–75% in the extruded products. Even in the product processed under mild conditions (WF1), the redistribution was statistically significant.

Gas-liquid chromatographic analysis of fiber constituents confirmed the solubilization observed in the gravimetric assay. Results with the most severely processed product (WF4) and the corresponding raw material are shown in Table V. The different fiber constituents were solubilized to approximately the same extent.

Whole grain wheat flour. The content of total dietary fiber analyzed according to Asp et al (1983) was somewhat higher in all the extruded whole grain wheat flours than in the raw material (Table VI). Only minute amounts of remaining starch could be detected in the fiber residues. The increase of about 1% occurred in the soluble-fiber fraction. In two of the samples, there was also a slight increase in insoluble fiber. In raw whole grain wheat flour, 15% of the total fiber was soluble versus about 20% after processing.

Degradation of Dietary Fiber in the Rat Intestinal Tract

Wheat starch. Except for glucose, the excretion of typical fiber constituents in feces of rats given a fiber-free diet with wheat starch was very low, less than 10 mg in five days. The fecal excretion of polyglucose was 51 mg with raw wheat starch, and somewhat higher, 84 mg, with extruded wheat starch. However, calculated on ingested starch, both raw and extruded wheat starch were completely digested, 99.8 and 99.7%, respectively.

Wheat flour. The content of the dietary fiber constituents arabinose, xylose, mannose, and galactose, measured with GLC, was very similar in raw and in extruded wheat flour (Table VII). However, the content of glucans in the fiber fraction, ie, the sum of fiber glucose and starch resistant to enzymatic degradation in vitro was highly dependent on the enzyme system used for solubilization of starch, as shown in Table III. This was particularly evident with extruded materials. When only physiological enzymes were used, the glucan content in extruded wheat flour was 5.3%, compared with only 2.9% in the raw material. When corrected for remaining starch available to amyloglucosidase, the glucan content decreased, but the level in the extruded product was still higher than in the raw material. With Termamyl present in the starch assay, similar glucan values were obtained before and after extrusion.

Dietary fiber in wheat flour was very susceptible to bacterial degradation in the rat intestine (Table VII). When extruded wheat flour was fed to rats, the fecal excretion of dietary fiber constituents was even lower than after raw flour, indicating a higher fermentability due to extrusion. The fecal recovery of the main components, arabinose, xylose, and glucose averaged 22% in raw wheat flour versus 12% after extrusion.

The balance experiment was performed on wheat flour extruded under mild conditions (WF1). The most severely processed flour (WF4) caused diarrhea, making it impossible to collect feces. To study whether the diarrhea was caused by the formation of undigestible oligosaccharides, paper chromatography of ethanol extracts was performed with flour and with feces from rats given raw and extruded wheat flours (WF1 and WF4). In extruded flours, a spot was observed that could not be detected in raw flour. The intensity of the spot was much weaker with the flour processed under mild conditions (WF1). The r_f value was close to that of xylose. Furthermore, an increased content of fructose could be detected in extruded materials. In feces, very similar patterns were

observed with all materials.

Whole grain wheat flour. The dietary-fiber composition measured with GLC was similar in raw and extruded products, except for glucose (Table VIII). As with wheat flour, the content of glucans was dependent on the enzyme system used for solubilization of starch. When Termamyl was present, the glucan content was similar in raw and extruded materials.

The fecal excretion, in milligrams, of dietary-fiber constituents, including glucose, was approximately the same before and after processing. Calculated as percent of intake, the fecal excretion of arabinose was 45% and that of xylose was 33%. If intake was corrected for remaining starch with Termamyl, the excretion of glucans was also similar, 46 and 52%, respectively.

DISCUSSION

Depending on the enzyme system used for solubilization of starch, different dietary fiber values were obtained in both raw and extruded products. The variability in fiber content was most pronounced after extrusion cooking. This was directly related to the glucan content in the fiber residues.

Without Termamyl, the glucan content in extruded products was considerably higher than in the corresponding raw material. In contrast, with Termamyl, the increase in glucan content due to processing was less pronounced. This could be due to the presence of amylose-lipid complexes in extruded products. Formation of amylose-lipid complexes has been reported during extrusion-

TABLE VI
Dietary Fiber Content in Raw and Extruded Whole-Grain Wheat Flours

Material	Dietary Fiber (% dry matter)[a,b]					
	Total	Total[c]	Insoluble	Insoluble[c]	Soluble	Soluble[c]
Raw whole grain wheat flour	13.1 ± 0.5	13.0 ± 0.5	11.1 ± 0.1	11.1 ± 0.1	2.0 ± 0.4	1.9 ± 0.4
Extruded products[d]						
WGF1	14.4 ± 0.2*	14.1 ± 0.2*	11.6 ± 0.2**	11.6 ± 0.2**	2.8 ± 0.2*	2.5 ± 0.2
WGF2	14.3 ± 0.2*	14.1 ± 0.2*	11.4 ± 0.1*	11.4 ± 0.1*	2.9 ± 0.2*	2.7 ± 0.2*
WGF3	14.2 ± 0.1*	13.9 ± 0.1*	10.9 ± 0.2	10.9 ± 0.2	3.3 ± 0.1**	3.0 ± 0.1*

[a] Dietary fiber content measured according to Asp et al (1983).
[b] Mean ± standard deviation. Significantly different from raw material (Student's *t*-test). * = $P<0.05$, ** = $P<0.01$.
[c] Corrected for remaining starch in the fiber residue (amyloglucosidase).
[d] Process conditions described in Table I.

TABLE VII
Composition and Fecal Recovery of Dietary Fiber in Raw and Extruded Wheat Flour[a]

	Composition of Dietary Fiber[b] (% dry matter)		Intake (mg in five days)		Fecal Excretion (mg in five days)		Fecal Excretion (% of intake)	
	Raw	Extruded[c]	Raw	Extruded[c]	Raw	Extruded[c]	Raw	Extruded[c]
Arabinose	0.9	0.8	310	250	57	29	18	12
Xylose	1.1	1.1	390	320	85	34	22	11
Mannose	0.1	0.2	48	45	15	8	31	18
Galactose	0.2	0.2	75	66	34	17	45	26
Glucose	2.9	5.3	990	1,590	78	52	7	3
	1.1[d]	2.4[d]	360[d]	710[d]	78	52	22	7
	0.9[e]	1.2[e]	310[e]	360[e]	78	52	25	14
Total	3.2[e]	3.5[e]	1,160[e]	1,130[e]	270	140	23	12

[a] Pooled samples from five rats.
[b] Dietary fiber fractions were isolated by using physiological enzymes.
[c] Flour WF1 with process conditions described in Table I.
[d] Corrected for remaining starch in the fiber residue (amyloglucosidase).
[e] Corrected for remaining starch (Termamyl, amyloglucosidase).

TABLE VIII
Composition and Fecal Recovery of Dietary Fiber in Raw and Extruded Whole-Grain Wheat Flour[a]

	Composition of Dietary fiber[b] (% of dry matter)		Intake (mg in five days)		Fecal Excretion (mg in five days)		Fecal Excretion (% of intake)	
	Raw	Extruded[c]	Raw	Extruded[c]	Raw	Extruded[c]	Raw	Extruded[c]
Arabinose	2.9	2.7	1,170	1,060	530	490	45	46
Xylose	4.5	4.2	1,810	1,660	600	540	33	33
Mannose	0.2	0.2	61	80	25	24	41	30
Galactose	0.3	0.4	130	140	135	67	104	48
Glucose	5.6	10.0	2,280	4,000	630	650	28	16
	3.6[d]	6.4[d]	1,460[d]	2,540[d]	630	650	43	26
	3.4[e]	3.1[e]	1,380[e]	1,240[e]	630	650	46	52
Total	11.3[e]	10.6[e]	4,550[e]	4,180[e]	1,920	1,770	42	42

[a] Pooled samples from five rats.
[b] Dietary fiber fractions were isolated by using physiological enzymes.
[c] Flour WFG3 with process conditions described in Table I.
[d] Corrected for remaining starch in the fiber residue (amyloglucosidase).
[e] Corrected for remaining starch in the fiber residue (Termamyl, amyloglucosidase).

cooking. According to Mercier (1980), these complexes are resistant to α-amylase during in vitro incubation at 37°C. However, Holm et al (1983) recently showed that amylose-lysolecithin complexes were completely digested and absorbed in the rat small intestine. Physiologically, these complexes should therefore be looked upon as starch rather than dietary fiber. It was further demonstrated that amylose-lipid complexes were efficiently hydrolyzed by Termamyl. The complexes were also available to pancreatic α-amylase, but high enzyme levels and a long incubation time were needed to obtain complete digestion. The high efficiency of the thermostable α-amylase Termamyl is probably due to dissociation of the amylose-lipid complexes at high temperature (Ghiasi et al 1982), thus increasing the susceptibility for enzymatic attack. When using Termamyl in the analytical procedure for determination of dietary fiber (Asp et al 1983, Theander and Åman 1979), artifacts due to insufficient digestion of starch in vitro are therefore minimized. This point is particularly important when analyzing processed products.

The rat balance experiments indicated that the starch digestion was very efficient in vivo. The glucan content in feces of rats given extruded products was similar to that obtained with the corresponding raw materials. However, the technique used in the balance experiments does not allow us to distinguish between digestion and absorption in the small intestine and bacterial fermentation. It is interesting that the fecal excretion of glucans with wheat flour was only slightly higher than that obtained with raw wheat starch.

In the present study, a solubilization of dietary fiber was observed during extrusion cooking of wheat flour. The solubilization appears to be dependent on process conditions. In the wheat product (WF1) processed at a high feed rate, ie, at a shorter residence time, the solubilization was less pronounced. Varo et al (1983) compared different methods for the determination of dietary fiber in processed materials. With some of these methods, soluble and insoluble dietary fiber was redistributed in extruded wheat flour and in whole grain wheat flour. However, when results from all methods were combined, the redistribution was not significant. Thus, the solubilization effect was method dependent.

The digestibility of both raw and extrusion-cooked wheat starch was almost 100%. Only minute amounts of starch could be detected in rat feces with amyloglucosidase. Thus, extrusion-cooking of pure wheat starch did not affect its digestibility. The excretion of polyglucose on a fiber-free wheat starch diet was 51 mg in five days. This is in good agreement with the basal excretion obtained with maize starch by Nyman and Asp (1982).

The balance experiments indicated that the dietary fiber in raw wheat flour was fermented to a high degree. However, extrusion-cooking of wheat flour further increased the fermentability. No such effect was obtained with extruded whole grain wheat flour. Our data thus indicate that extrusion cooking primarily affects the fermentability of the smaller fiber fraction connected with the endosperm.

Food processes that lead to an increase in the surface area of the product could be expected to increase the availability of fiber to fermentation. In extruded wheat flour, the solubilization of fiber might be a factor in increasing the availability to microorganisms. In general, soluble fiber is more easily fermented than insoluble fiber (Cummings et al 1979, Nyman and Asp 1982). The significant increase in soluble dietary fiber in extruded wheat flour products could be interpreted as the breaking of chemical bonds. Degradation of fiber has been reported with other processes that involve shear at low moisture content. Thus, according to Assarsson et al (1959), glycosidic bonds in cellulose may be broken during dry ball milling.

With whole grain wheat flour, the content of dietary fiber constituents in feces was very similar before and after extrusion. This indicates that certain chemical structures resist bacterial degradation in the large intestine in spite of the prominent homogenization during extrusion. These results are in agreement with a recent study[3] in which the particle size, per se, did not affect the fermentation of purified wheat bran in the rat.

Paper chromatography on raw and on extruded wheat flour (WF1, WF4) indicated an increase in fructose content due to processing. This is in agreement with earlier results with extrusion-cooked wheat flour (Chiang and Johnson 1977). The diarrhea observed in rats given severely processed wheat flour cannot be explained at present. Maillard-reaction products formed during heat treatment by a reaction between proteins and reducing sugars have not been reported to cause diarrhea.

[3]M. Nyman and N.-G. Asp. Unpublished results. Department of Food Chemistry, University of Lund, Sweden.

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