

Effect of Cooking and Storage on the Amount and Molecular Weight of (1→3)(1→4)-β-D-Glucan Extracted from Oat Products by an In Vitro Digestion System¹

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ABSTRACT

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The extractability and molecular weight of β-glucan in oat bran, oat bran muffins, and oat porridge and the changes taking place during processing and storage were studied. The β-glucan was extracted using hot water and a thermostable α-amylase and by an in vitro system that simulated human digestion. Molecular weight (MW) of the extracted β-glucan was determined using high-performance size-exclusion chromatography. Hot-water treatment extracted 50–70% of total β-glucan in oat bran samples and rolled oats. The chromatographic peak MW of extracted β-glucan was in the 1.4–1.8 × 10⁶ range. Using the in vitro digestion

system, 12–33% of total β-glucan in bran and rolled oats was solubilized, and peak MW was in the same range as β-glucan extracted by hot-water treatment. In muffins, 30–85% of total β-glucan was solubilized by in vitro digestion, with a major difference in extractability among muffins from different recipes. Peak MW of extracted β-glucan was lower in all muffins when compared to original bran. During frozen storage, extractable β-glucan decreased by >50% in all muffins, but no change in peak MW of extracted β-glucan was detected.

There have been over 50 studies on the effect of oat products on serum cholesterol levels in humans (Anderson and Bridges 1993, Anonymous 1996). These generally indicate that oat products may lower serum cholesterol levels. Viscous polysaccharides are known to lower serum cholesterol levels, and in oats (1→3)(1→4)-β-D-glucan (β-glucan) is believed to be the active component (Braaten et al 1994). β-Glucan, the main endospermic cell wall polysaccharide of oats, is enriched in oat bran and is also present in barley and, in lesser amounts, in wheat and rye. Mechanisms by which viscous fibers may lower serum cholesterol levels are uncertain, but increased luminal viscosity in the gastrointestinal tract is believed to be of importance (Story and Kritchevsky 1976, Vahouny et al 1980, Jenkins et al 1987).

Not all oat bran studies have found a significant reduction in serum cholesterol levels, and the magnitude of reported effects varies widely. In a recently accepted health claim proposal for an association between consumption of oat products and reduced risk of heart disease (Anonymous 1996), the U.S. Food and Drug Administration (FDA) reviewed 33 clinical studies on the effect of oat products on serum cholesterol levels. Of these, 21 reported a significant reduction in serum cholesterol, whereas 12 showed no statistically significant reduction. A number of factors could account for variable results. Initial cholesterol level is believed to influence response (Keenan et al 1991, Braaten et al 1994), and the nature of the product is clearly of major importance. For example, in some studies, the oat bran had a low β-glucan content; hence, daily consumption may have been insufficient to achieve an effect. It is also possible that processing and cooking may change the physicochemical properties of oat β-glucan and modify its physiological effects.

If viscosity is as important for cholesterol-lowering effects as it is for glycemic response (Wood et al 1994), then two potential variables of primary importance are solubilization of β-glucan

(hence concentration in the lumen) and molecular weight (MW). Previously we established that ≈70% of whole groat β-glucan could be extracted at 90°C by water containing a heat-stable α-amylase that was free from β-glucanase activity (Beer et al 1997). Molecular weights of 2–2.5 × 10⁶ were observed. Total extraction could be obtained by use of alkali, but this also led to some depolymerization. In this article, hot water solubilization of some commercial oat brans and rolled oats is reported and compared to a technique designed to simulate human digestion. The latter method was then used to evaluate the effect on the β-glucan extracted after incorporating the oat brans into muffins.

MATERIALS AND METHODS

Materials

Commercial samples of rolled oats and oat brans were used. Oat muffins were baked using two different recipes of commercial ingredients, as shown in Table I, and stored at –20°C for up to five months. Termamyl (120 L), a heat-stable α-amylase, was obtained from Novo BioLabs (Danbury, CT). Calcofluor (Calcofluor White M2R New, C.I. 40622, fluorescent brightener 28) was provided by American Cyanamid Co. (Wayne, NJ). β-Glucans of different molecular weight used as standards were provided by Megazyme International Ireland Ltd. (Bray, Ireland) or produced as described by Wood et al (1989).

TABLE I
Recipes for Oat Bran Muffins^a

Ingredient (g)	Recipe 1	Recipe 2
Oat bran	100	105
Milk 1%	95	...
Soy milk 2%	...	120
Sugar	31	25
Honey	42	...
Vegetable oil	10	0.8
Baking powder	5	5
Salt	1.2	0.4
Egg	55	...
White flour	...	21
Gluten	...	23

^a Bake for 20 min at 200°C (400°F); recipe yields six muffins with an average weight of ≈42 g.

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Analytical Methods

Moisture of samples was determined by AOAC (1990) Method 935.36. β -Glucan content in samples and extracts was determined by the method of McCleary and Glennie-Holmes (1985) using, respectively, a β -glucan assay kit (Megazyme International Ireland Ltd.) with an automated glucose oxidase assay (Wood et al 1991) and by flow-injection analysis (FIA) essentially as described by Jørgensen (1988).

High-performance size-exclusion chromatography (HPSEC). The MW of extracts was determined as previously described (Beer et al 1997). Two columns in series (Shodex OHpak KB-806M, Showa Denko K.K., Tokyo, Japan; Ultrahydrogel linear, Waters, Milford, CT), and a Waters model 590 pump were used

for size-exclusion chromatography. The columns were maintained at 40°C, the mobile phase was 0.1M NaNO₃ buffer, and the flow rate was 0.6 mL/min. A Perkin-Elmer ISS 100 autosampler and injector was used with an injection volume of 100 μ L. Samples were filtered (0.45 μ m) before analysis. The MW of eight β -glucan standards was determined using refractive index and viscosity (model 250, Viscotek, Houston, TX), and right-angle laser light-scattering (RALLS, Viscotek) detectors. The β -glucan standards were then used to calibrate the HPSEC columns, and the chromatographic peak MW of extracts was measured using Calcofluor postcolumn detection (Perkin-Elmer LS-5 Spectrofluorimeter, Waters model 510 pump).

Extraction of β -Glucan

Hot water and termamyl and sodium hydroxide extraction. Samples were ground in a cyclone sample mill (Udy Corp., Fort Collins, CO) to pass a 1-mm screen. Before extractions, \approx 5 g of flour was blended with 100 mL of aqueous ethanol (70%) and stirred under reflux for 2 hr at 85°C to inactivate β -glucanases. The supernatant was removed after centrifugation (8,000 \times g, 15 min), and the residue was washed with 20 mL of aqueous ethanol (95%) and dried on a hot plate. The drying step was completed in a vacuum oven at 80°C for 3 hr. A schematic outline of the extraction procedures is presented in Fig. 1. The Termamyl was diluted and preheated before use. Aliquots of extract were analyzed by FIA and HPSEC.

In vitro digestion. To prepare cooked oat bran or rolled oats, a 4-g sample was stirred into 25 mL of boiling water and cooked for 2 min. Samples were allowed to cool for 10 min before digestion. For muffins, four quarter sections from four different muffins were combined and crushed into bite-size pieces by hand.

A sample (\approx 5 g) was mixed in an Erlenmeyer flask with 100 mL (75 mL for cooked oat bran or rolled oats) of 20 mM sodium phosphate buffer (pH 6.9) containing 10 mM NaCl, stirred slowly for 15 min at 37°C, and 250 μ L of human salivary α -amylase solution (5 mg/mL in 3.6 mM CaCl₂; A-1031, Sigma, St. Louis, MO) was added. The mixture was stirred for a further 15 min, pH was adjusted to 2.0 with 6M and 1M HCl, 625 μ L of porcine pepsin solution (0.5 mg/mL in 0.9% NaCl, P7012, Sigma) was added, and the mixture was incubated for 30 min at 37°C. After neutralization (pH 6.9) with 3M NaOH, 1.25 mL of pancreatin solution was added (0.5 mg/mL in 20 mM sodium phosphate buffer containing 10 mM NaCl, P-7545, Sigma) and the incubation was continued for 90 min. An aliquot was centrifuged (7,000 \times g, 10 min) (Fig. 1). The content and peak molecular weight of β -glucan in the extract was determined by FIA and HPSEC. Data presented are the average of at least two replicates.

RESULTS

The total β -glucan content (dwb) in oat bran samples was 7.6–13.4%, in rolled oats it was 4.2%, and in oat bran muffins it was 3.6–6.2% (Tables II and III). Duplicate variation in extracted amount and peak MW of β -glucan was <10% in all samples. Enzyme preparations used in extractions were shown to be β -glucanase free in control treatments of a β -glucan standard.

The β -glucan extractable by hot-water treatment was 50–65% for the oat brans and 70% for rolled oats. The peak MW of the extracted β -glucan was 1.4–1.8 \times 10⁶ (Table II). β -Glucan was quantitatively extracted by NaOH from Bran C (98.1% of total), but the MW decreased (1.2 \times 10⁶). Using the *in vitro* digestion system, 12–33% of total β -glucan was extracted from the bran and rolled oat samples, and the peak MW was in the same range as β -glucan extracted by hot water treatment (Table II). After incorporation into muffins, 55–85% of total β -glucan for recipe 1, and 30% for recipe 2, was extracted by *in vitro* digestion. β -Glucan extracted from either muffin recipe had markedly lower peak MW when compared to the original brans (Table III).

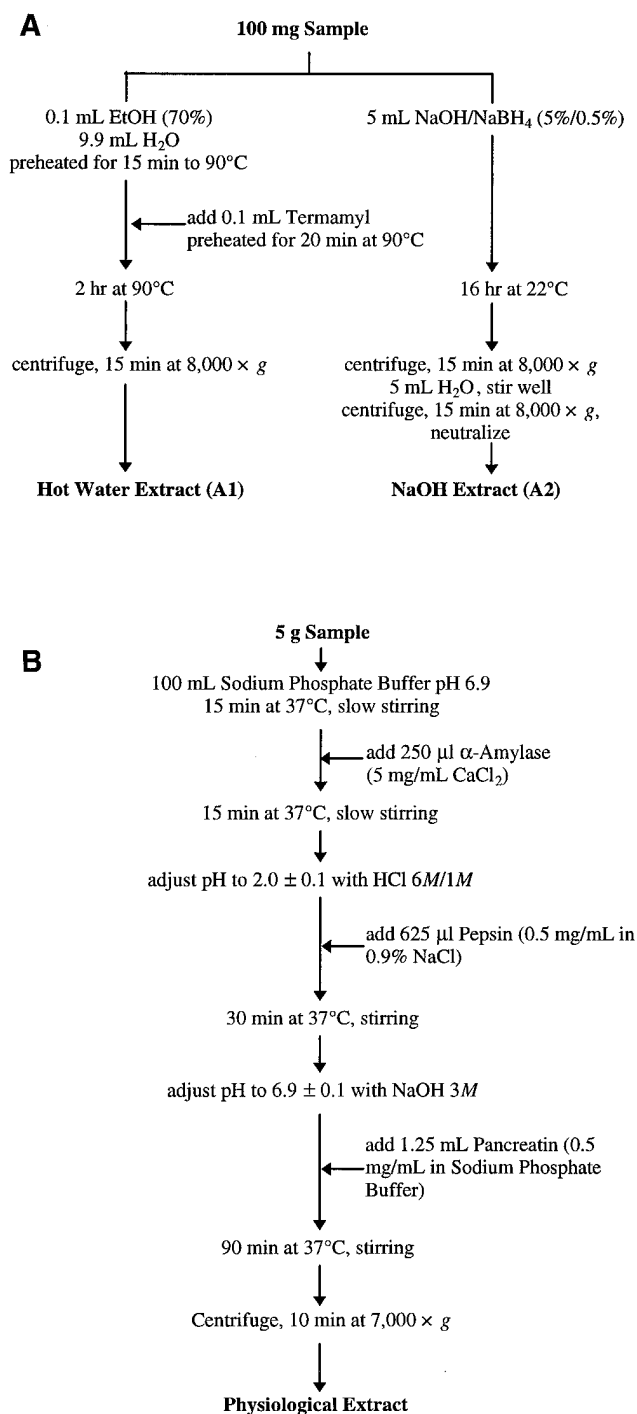


Fig. 1. Procedures for β -glucan extraction from hot water (A1) and sodium hydroxide (A2) and physiological extract (B).

During storage at -20°C , the amount of β -glucan extractable by *in vitro* digestion declined. After eight weeks of storage, the decline in extractable β -glucan for recipe 1 muffins was $>50\%$ (Table IV). The β -glucan of recipe 2 muffins was initially less soluble and declined further in solubility after a seven-day period of frozen storage to 20.4% (Bran B) and 28.1% (Bran C). No change in peak MW of extracted β -glucan was detected during storage.

DISCUSSION

A proposed mechanism for the cholesterol-lowering effect of soluble fiber is an alteration in cholesterol and bile acid absorption and reabsorption, possibly caused by binding to the fiber (Story and Kritchevsky 1976, Vahouny et al 1980, Kritchevsky et al 1984), although recent studies did not detect binding of glycolic acid to β -glucan (Bowles et al 1996). Emulsification characteristics of the luminal fluid could also be modified. Increased viscosity in the gut modifies absorption rates, possibly by slowing mixing and reducing diffusion as measured by an increase in the so-called unstirred layer adjacent to the mucosa (Lund et al 1989). This layer may serve as a physical barrier to nutrient absorption and bile acid reabsorption (Blackburn et al 1984). In clinical studies, Wood et al (1994) demonstrated an inverse linear relationship between $\log(\text{viscosity})$ and postprandial glucose and insulin response. Insulin plays a role in lipid metabolism and may stimulate cholesterol synthesis (Bhathena et al 1974). In a hamster model, Gallaher et al (1993) demonstrated a relationship between viscosity and lowered blood cholesterol levels. Solubility and MW of the β -glucan are, *inter alia*, important factors determining the viscosity in the gastrointestinal tract.

There have been several studies dealing with the extraction of β -glucan from cereals (Anderson et al 1978, Åman et al 1989, Wood et al 1991, Wood 1993, Beer et al 1996), but the extraction procedures used were generally designed to give maximum extraction or maximum MW. The percentage of soluble β -glucan varied over a wide range (24–86%) depending on starting material and extraction conditions used (Wood 1993).

Beer et al (1997) reported that 50–65% of total β -glucan is extractable in oats and barley using hot-water extraction in conjunction with a heat stable α -amylase, which is comparable to the 50–70% of extractable β -glucan in bran and rolled oats in this study. MW of the β -glucan from the commercial products were somewhat lower than noted for the original oat and barley cultivars. This may relate to processing or storage conditions. We have

observed that long-term storage of milled products at ambient temperature may lead to some decrease in MW of extractable β -glucan (*unpublished data*).

Under physiological conditions, 25–30% of total β -glucan was extractable with noticeable differences in different bran samples. Bran A showed a low percentage of extractable β -glucan and a low MW shoulder was evident (Fig. 2). Different processing or storage conditions probably account for these differences. Mälkki et al (1992) reported differences in ease of extraction and changes in MW of β -glucan in oat bran concentrate in relation to the processing technique used.

Cooking Bran C as porridge did not greatly change the amount of extractable β -glucan under physiological conditions compared to uncooked bran and MW remained unchanged. Rolled oats cooked as porridge showed slightly increased extractability relative to brans (Table II). Baking to muffins using recipe 1 increased the physiological extractable amount of β -glucan three- to four-fold but decreased the peak MW by $\approx 50\%$ compared to the original bran (Table II and III). Thus, the baking process led to lower MW but increased solubility of the β -glucan. An association between lower MW and increased solubility has been noted previously (Wood et al 1991). Increased solubility or concentration in solution increases viscosity, whereas a decrease in MW decreases viscosity. Above a critical concentration (where zero shear viscosity is ≈ 10 mPa-sec) small changes in either variable may have profound effects. In the case of oat β -glucan, a doubling in concentration could lead to a 15-fold increase in viscosity (Dublier and Wood 1995). In physiological terms, the increased solubility of β -glucan in the recipe 1 muffins should more than offset the lower MW. However, there was a major difference in extractability between muffins from the two different recipes. In recipe 2, muffins the total extracted β -glucan remained at 30% and the overall potential to develop viscosity was therefore less. Possibly the difference in ingredients in the two recipes led to different accessibilities of solvent to β -glucan, but this requires further evaluation.

Frozen storage of muffins also led to differences in extractability. Over time there was up to a 50% decrease in amount of solubilized β -glucan. In recipe 1 muffins, after eight weeks of frozen storage, only 30–40% of total β -glucan was soluble. In recipe 2 muffins, there was also a decrease in solubility within the first week of storage (33 and 11% for B and C, respectively).

Two clinical studies of oat products (Beer et al 1995, Törrönen et al 1992) failed to detect any significant reduction in serum

TABLE II
Extraction Using Hot Water or a Physiological *in vitro* Digestion Method of Oat Bran and Rolled Oats: Content, Percentage Extracted, and Molecular Weight of β -Glucan

Sample	β -Glucan (g/100g)	β -Glucan Extracted (% of Total)		Molecular Weight ($\times 10^{-3}$)	
		Hot Water	Physiological	Hot Water	Physiological
Bran A	13.4	51.3	12.9	1,400	1,100
Bran B	8.9	56.7	25.1	1,600	1,800
Bran C	7.6	64.1	28.7	1,800	1,900
Bran C ^a	nd ^b	30.2	nd	1,800	
Rolled oats ^a	4.2	69.5	33.4	1,500	1,500

^a Samples cooked before extraction.

^b Not done.

TABLE III
Extraction Using a Physiological *in vitro* Digestion Method of Oat Bran Muffins: Content, Percentage Extracted, and Molecular Weight of β -Glucan

Muffin	β -Glucan (g/100g)		β -Glucan Extracted (% of Total)		Molecular Weight ($\times 10^{-3}$)	
	Recipe 1	Recipe 2	Recipe 1	Recipe 2	Recipe 1	Recipe 2
Bran A	6.7	nd ^a	55.0	nd	597	nd
Bran B	4.3	4.1	77.8	30.3	785	850
Bran C	3.6	3.6	85.3	31.6	950	1,206

^a Not done.

cholesterol levels, and it was suggested that the lack of response might be due to the poor solubility of the β -glucan in the test products used (oat gum instant whip and bread). There are many possible explanations for the variable and sometimes conflicting data in clinical studies of the effect of oat bran on serum cholesterol. Our data show that some forms of delivery may be more effective than others (e.g., recipe 1 vs. recipe 2). Most importantly, long-term frozen storage of cooked products, such as might be used in clinical trials, could lead to a significant reduction in effectiveness on a weight-to-weight basis. The decline in solubility of the β -glucan during frozen storage possibly reflects changes in molecular organization and crystallinity. We have shown (*unpublished data*) that β -glucan solubility may be influenced by drying methods.

In summary, the viscosity development of oat (or barley) products in an aqueous environment depends on the amount and molecular size of β -glucan hydrated or in solution, especially so in the absence of gelatinized starch as after digestion. An *in vitro* digestion system designed to mimic aspects of human digestion was used to evaluate effects of process and cooking on β -glucan. Although the system simulates human digestion, the data cannot be taken to exactly represent what takes place in the human upper gastrointestinal tract but rather should be seen as an indicator of how solubilization and MW of products might differ depending on processing and storage and cooking methods. The data clearly show that major differences in viscosity in the lumen of the intestinal tract might occur with different products consumed. This could translate into significant difference in physiological effect if levels are not in the area of plateau response. For postprandial glucose and insulin response in healthy subjects, in a recently reported model, this plateau became evident at an intake of ≈ 6 g of β -glucan (Wood et al 1994). In the case of serum cholesterol levels, dose response and role of viscosity are not well established. In the meantime, however, it would be worthwhile to

evaluate products used in clinical trials for their relative capacities to increase gastrointestinal viscosity. This can be achieved at the most fundamental level by applying techniques such as described here.

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LITERATURE CITED

- Åman, P., Graham, H., and Tilly, A.-C. 1989. Content and solubility of mixed-linked (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan in barley and oats during kernel development and storage. *J. Cereal Sci.* 10:45-50.
- Anderson, M. A., Cook, J. A., and Stone, B. A. 1978. Enzymatic determination of (1 \rightarrow 3)(1 \rightarrow 4)- β -glucans in barley grain and other cereals. *J. Inst. Brew.* 84:233-239.
- Anderson, J. W., and Bridges, S. R. 1993. Hypocholesterolemic effects of oat bran in humans. Pages 139-157 in: *Oat Bran*. P. J. Wood, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Anonymous 1996. Food labeling: Health claims; oats and coronary heart disease. *Fed. Reg.* 61:296-313.
- AOAC. 1990. Official Methods of Analysis, of the Association of Official Analytical Chemists, Vol. II, 15th ed. Method 935.36. The Association: Arlington, VA.
- Beer, M. U., Arrigoni, E., and Amadò, R. 1995. Effects of oat gum on blood cholesterol levels in healthy young men. *Eur. J. Clin. Nutr.* 49:517-522.
- Beer, M. U., Arrigoni, E., and Amadò, R. 1996. Extraction of oat gum from oat bran: Effects of process on yield, molecular weight distribution, viscosity and (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan content of the gum. *Cereal Chem.* 73:58-62.
- Beer, M. U., Wood, P. J., and Weisz, J. 1997. Molecular weight distribution and (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan content of consecutive extracts of various oat and barley cultivars. *Cereal Chem.* 74:476-480.
- Bhathena, S. J., Avigan, J., and Schreiner, M. E. 1974. Effect of insulin on sterol and fatty acid synthesis and hydroxymethylglutaryl CoA reductase activity in mammalian cells grown in culture. *Proc. Natl. Acad. Sci. USA* 71:2174-2178.
- Blackburn, N. A., Redfern, J. S., Jarjis, H., Holgate, A. M., Hanning, I., Scarpello, J. H. B., Johanson, I. T., and Read, N. W. 1984. The mechanism of action of guar gum in improving glucose tolerance in man. *Clin. Sci.* 66:329-336.
- Bowles, K. R., Morgan, K. R., Furneaux, R. H., and Coles, G. D. 1996. ¹³C CP/MAS NMR study of the interaction of bile acids with barley β -D-glucan. *Carbohydr. Polym.* 29:7-10.
- Braaten, J. T., Wood, P. J., Scott, F. W., Wolynetz, M. S., Lowe, M. K., Bradley-White, P., and Collins, M. W. 1994. Oat β -glucan reduces blood cholesterol concentration in hypercholesterolemic subjects. *Eur. J. Clin. Nutr.* 48:465-474.
- Doublier, J. L., and Wood, P. J. 1995. Rheological properties of aqueous solutions of (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan from oats (*Avena sativa* L.). *Cereal Chem.* 72:335-340.
- Gallaher, D. D., Hassel, C. A., Lee, K.-J., and Gallaher, C. M. 1993. Viscosity and fermentability as attributes of dietary fibre responsible for hypocholesterolemic effect in hamsters. *J. Nutr.* 123:244-252.
- Jenkins, D. J. A., Jenkins, A. L., Wolever, T. M. S., Collier, G. R., Rao, A. V., and Thompson, L. U. 1987. Starchy foods and fiber: Reduced rate of digestion improved carbohydrate metabolism. *Scand. J. Gastroenterol.* 22:132-141.
- Jørgensen, K. G. 1988. Quantification of high molecular weight (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan using calcofluor complex formation and flow injection analysis. I. Analytical principle and its standardisation. *Carlsberg Res. Commun.* 53:287-296.
- Keenan, M., Moss, R., Clifton, P. M., and Nestel, P. J. 1991. Comparative effects of three cereal brans on plasma lipids, blood pressure and glucose metabolism in mildly hypercholesterolemic men. *J. Fam. Pract.* 33:600-608.
- Kritchevsky, D., Tepper, S. A., Goodman, G. T., Weber, M. M., and Klurfeld, D. M. 1984. Influence of oat and wheat bran on cholesterolemia in rats. *Nutr. Rep. Int.* 29:1353-1359.

TABLE IV
Physiological *in vitro* Extraction of β -Glucan in Recipe 1 Muffins: Fresh and After Four, Six, and Eight Weeks of Storage at -20°C

Muffin	β -Glucan Extracted (% of Total)			
	Fresh	4 Weeks	6 Weeks	8 Weeks
Bran A	55.0	46.4	46.0	27.0
Bran B	77.8	60.1	57.3	39.8
Bran C	85.3	64.9	51.9	36.1

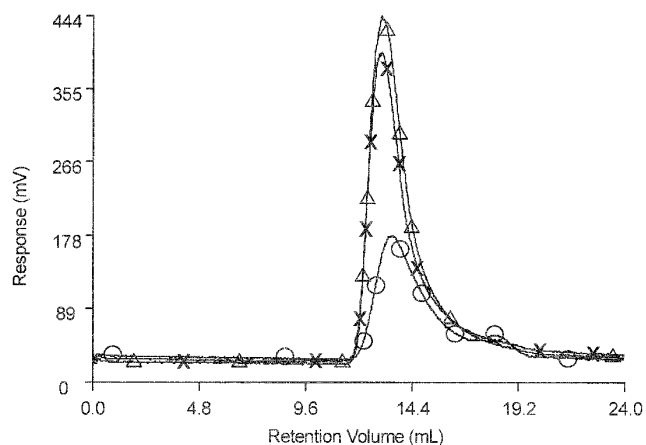


Fig. 2. High-performance size-exclusion chromatography (HPSEC) of β -glucan extracted from oat bran samples (\circ = Bran A; \times = Bran B; Δ = Bran C) using an *in vitro* digestion system. HPSEC conditions: two columns in series (Shodex OHpak KB-806M; Ultrahydrogel linear) maintained at 40°C and eluted with 0.1M NaNO_3 buffer at 0.6 mL/min ; peak detection used Calcofluor binding and fluorescence.

- Lund, E. K., Gee, J. M., Brown, J. C., Wood, P. J., and Johnson, I. T. 1989. The effect of oat gum on the physical properties of the gastrointestinal contents and the uptake of D-galactose and cholesterol by rat small intestine *in vitro*. *Brit. J. Nutr.* 62:91-101.
- Mälkki, Y., Autio, K., Hänninen, O., Myllmäki, O., Pelkonen, K., Suortti, T., and Törrönen, R. 1992. Oat bran concentrates: Physical properties of β -glucan and hypocholesterolemic effects in rats. *Cereal Chem.* 69:647-653.
- McCleary, B. V., and Glennie-Holmes, M. 1985. Enzymatic quantification of (1 \rightarrow 3)(1 \rightarrow 4) β -D-glucan in barley and malt. *J. Inst. Brew.* 91:285-295.
- Story, J. A., and Kritchevsky, D. 1976. Comparison of the binding of various bile acids and bile salts *in vitro* by several types of fiber. *J. Nutr.* 106:1292-1294.
- Törrönen, R., Kansanen, L., Uusitupa, M., Hänninen, O., Myllymäki, O., Härkönen, H., and Mälkki, Y. 1992. Effects of oat bran concentrate on serum lipids in free-living men with mild to moderate hypercholesterolaemia. *Eur. J. Clin. Nutr.* 46:621-627.
- Vahouny, G. V., Tombes, R., Cassady, M. M., Kritchevsky, D., and Gallo, L. 1980. Dietary fibers: V. Binding of bile salts, phospholipids and cholesterol from mixed micelles by bile acid sequestrants and dietary fibers. *Lipids* 15:1012-1018.
- Wood, P. J., Weisz, J., Fedec, P., and Burrows, V. D. 1989. Large-scale preparation and properties of oat fractions enriched in (1 \rightarrow 3)(1 \rightarrow 4)- β -D-glucan. *Cereal Chem.* 66:97-103.
- Wood, P. J., Weisz, J., and Mahn, W. 1991. Molecular characterisation of cereal β -glucans. II. Size-exclusion chromatography for comparison of molecular weight. *Cereal Chem.* 68:530-536.
- Wood, P. J. 1993. Physicochemical characteristics and physiological properties of oat (1 \rightarrow 3),(1 \rightarrow 4)- β -D-glucan. Pages 83-112 in: *Oat Bran*, P. J. Wood, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.
- Wood, P. J., Braaten, J. T., Scott, F. W., Riedel, K. D., Wolynetz, M. S., and Collins, M. W. 1994. Effect of dose and modification of viscous properties of oat gum on plasma glucose and insulin following an oral glucose load. *Brit. J. Nutr.* 72:731-743.

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