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Review article

Viscosity of beta-glucan in oat products

Heli Anttila, Tuula Sontag-Strohm and Hannu Salovaara
Viikki Food Science, Department of Food Technology, PO Box 66 (Viikki EE), FIN-00014 University of Helsinki, Finland, e-mail: heli.anttila@helsinki.fi

Oats contain 3–5% of mixed linked beta-glucan, or (1–3), (1–4) β-D-glucan, referred to hereafter as beta-glucan. Oat beta-glucan is a viscous, and soluble dietary fibre component. Soluble and viscous dietary fibres, including the beta-glucan present in oats are associated with two major health promoting effects, i.e. the attenuation of postprandial plasma glucose and insulin levels and the control of cholesterol. Increased viscosity in the intestine delays absorption of glucose and suppresses absorption of cholesterol and reabsorption of bile acids. In spite of its apparent key role physiologically the viscosity of beta-glucan has been discussed relatively little in terms of analytical procedures. In clinical studies performed with oats, the viscosity of beta-glucan has been properly documented in only a few cases. Viscosity of beta-glucan in foods and in the food digest depends on solubility, concentration and molecular weight. A food manufacturer aiming at health-promoting products must pay attention not only to sufficient concentration of beta-glucan (dose) in the raw material, but also to the processing methods that will ensure sufficient solubility of beta-glucan and minimize enzymatic or mechanical breakdown of the beta-glucan molecule. We have been working both with different food processes utilising oat fractions high in beta-glucan and with the development of a method for viscosity determination of the soluble beta-glucan fibre. This review discusses some of the aspects related to the development with a method that could predict the behaviour of beta-glucan in oat processing with respect to its anticipated physiological functions.

Key words: beta-glucan, viscosity, oat products

Oats and beta-glucan

Dehulled oats, or oat groats contain 3–5% beta-glucan, which is a component of endosperm cell walls. Typical of oats are thick cell walls in subaleurone region of the kernel. Therefore, kernel fractions consisting of the subaleurone layer are especially high in beta-glucan (Wood 1986). Nutritionally beta-glucan is a dietary fibre component, and as such it is resistant to digestion in the human digestive system. However, it may be fermented by colon microflora.

Dietary fibre is classified into two groups, water-soluble and water insoluble fibres. Oat beta-glucan is classified as soluble fibres and it represents most of the water-soluble fibre in oats (Wood 1986). Chemically oat beta-glucan con-

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sists of linear unbranched β-(1→4)-D-glucopyranose units, which are separated every 2–3 units by a single β-(1→3)-linked glucose unit, and these (1→3)-linkages make the molecule flexible, and contribute to its high water binding, solubility and viscosity. Longer blocks of (1→4)-linkages up to five to fifteen glucose units may occur, and such structural differences may affect the physicochemical properties of oat beta-glucan from different sources (Wood et al.1991, Wood 1993, 2002).

Oat beta-glucan is able to form highly viscous solutions at low concentrations. The viscosity depends on the concentration and the molecular weight of beta-glucan. At low concentration (< 0.2%) the beta-glucan solution behaves like a Newtonian solution (Autio et al. 1987, Doublier and Wood 1995), i.e. an increasing shear rate does not affect the viscosity. However, above a specific concentration (> 0.2%) the high molecular weight beta-glucan molecules start to entangle and form viscous and pseudoplastic solutions. The pseudoplastic behavior increases with concentration and molecular weight (Autio et al. 1987, Doublier and Wood 1995). High molecular weight beta-glucan forms viscous and pseudoplastic solutions, whereas lower molecular weight beta-glucans can form soft gels in higher concentrations (Doublier and Wood 1995). Increasing the concentration of a dissolved polymer generally gives rise to increased viscosity, as does increasing the molecular weight of a solute. Processing may affect the physicochemical properties such as solubility and molecular weight, and contribute to viscosity in foods high in beta-glucan.

Physiological effects of oat beta-glucan

The two major health benefits associated with soluble and viscous dietary fibres are attenuation of glycemic response and plasma cholesterol lowering. It is generally recognized today that the physiological value of soluble dietary fibre is based on its ability to increase the viscosity of food digest in the intestine, as first reported by Jenkins et al. (1978). The role of colonic fermentation on the control of cholesterol and glycemic response seems to require further evidence. It is the increased luminal viscosity in the gastrointestinal tract that is believed to be the key mechanism that leads to lower absorption of sugars and cholesterol and bile acid absorption and reabsorption. Soluble viscous fibres contribute to formation of so-called unstirred layer adjacent to the mucosa, which serves as a physical barrier to nutrient absorption and bile acid reabsorption (Würsch and Pi-Sunyer 1997, Schneeman 2001).

The role of viscosity of beta-glucan in reducing the postprandial blood glucose levels is well documented in experimental studies (Braaten et al. 1991, Bourdon et al. 1999, Wood et al. 1990, 1994, 2000). In a study using increasing doses of oat beta-glucan the capability of oat gum to decrease postprandial glucose and insulin response was shown to be lower when the molecular weight or viscosity of the beta-glucan was reduced by acid hydrolysis or by a lower dose (Wood et al. 1994). Increasing doses of pure oat beta-glucan 1.8 g, 3.6 g, and 7.2 g, representing 0.36%, 0.72 or 1.44% in a drink, were used in that study. The effect of dose response on blood glucose and insulin was also shown by Tappy et al. (1996) who used increasing amounts (4.0 g, 6.0 g and 8.4 g) of beta-glucan in extruded breakfast cereals. All three beta-glucan levels gave a significant reduction in glycemic index GI. However, the higher doses, 6.0 and 8.4 grams of beta-glucan, had similar GI's, possibly indicating a 'saturation' level. The meals containing 4–5% beta-glucan reduced postprandial glycemic responses by as much as 50% (Table 1). It was suggested by Wood et al. (1990) that only if the dose and viscosity of beta-glucan are above a critical level an effect on glucose response can be seen. In a recent study by Jenkins et al. (2002) it was estimated that a 3.8 ± 0.5 unit reduction in glycemic index can be seen per gram of beta-

Table 1. The effect of oat gum and oat extract viscosity on the glucose response in human study.

Study	Material	Viscosity measurement		Glucose response study		
		Shear rate (s^{-1})	Beta-glucan (%, w/w) in the extract/oat gum	Viscosity (mPas)	Beta-glucan (%,w/w) in the meal	Glucose response AUC% of the control
Tappy et al. 1996	Breakfast cereals	58	0.84	665	4.9	35
	Breakfast cereals	58	0.60	280	3.7	41
	Breakfast cereals	58	0.40	100	2.6	71
	Control breakfast	58	0	1.2	0	100
Wood et al. 1990	Oat gum	30	1.00	1065	1	41
Wood et al. 1994	Oat gum drink	30	1.44	1940	1.44	71
	Acid hydrolysed (15 minutes) oat gum drink	30	1.44	92	1.44	78
	Acid hydrolysed (60 minutes) oat gum drink	30	1.44	18	1.44	100
	Instant oat gum drink	30	1.44	1910	1.44	72
	Control drink	30	0	1	0	100

AUC = Area under curve (4h)

glucan in a test meal containing 50 g carbohydrate.

The increased viscosity in the intestine by beta-glucan is also believed to be the key factor in the lowering of plasma cholesterol, as reviewed by Ripsin et al. (1992) and Brown et al. (1999). According to the meta-analysis 3–4 g of beta-glucan lead to a significant decrease in cholesterol values (Ripsin et al. 1992). On the basis of numerous clinical studies Food and Drug Administration (FDA) permitted the use of a claim that oat soluble fibre has the ability to reduce the risk of coronary heart disease (Federal Register 1997). The FDA concluded that daily consumption of 3g of soluble beta-glucan fibre from oatmeal or oat bran will lead to 5 to 8% reduction in total plasma cholesterol level. The FDA considered this to justify the health claim 'may reduce the risk of heart disease as part of a low-fat low-cholesterol diet'. The required dose of beta-glucan for a single food is 0.75 grams justifying the claim. However, the FDA oatmeal health claim is not a purely a beta-glucan health claim. It is often pointed out that a regular consumption of oat products can also reduce the risk of coronary heart disease through other mechanisms and risk factors, such as weight control and alterations in insulin metabolism (Ripsin et al. 1992, Braaten et al. 1994, Mayer et al. 2000).

However, some results from clinical studies have been inconsistent and some clinical oat studies have not shown any significant effects in serum cholesterol levels (e.g. Törrönen et al. 1992, Beer et al. 1995, Rieckhoff et al. 1999). It may be also worth recognizing that the FDA used the wording beta-glucan soluble fibre when referring to the health effects of the 3 grams per day. No method for the determination of beta-glucan solubility was given.

Solubility as such does not ensure that the beta-glucan is large enough to form entanglements and to be capable to increase the viscosity of intestinal content. Processes involving enzymatic breakdown of beta-glucan may affect the physical state of beta-glucan and reduce its viscosity (Mälkki and Virtanen 2001). Enzymatic breakdown of beta-glucan in processes, including breadmaking were shown in studies where enzyme active ingredients were used (Jaskari et al. 1995, Degutyte-Fomins et al. 2002, Salovaara et al. 2003). However, most of the clinical studies on oats and oat products have paid little attention to describing of the physical state of the beta-glucan. In most studies only the beta-glu-

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can content in the test products has been shown. Those reports showing the physicochemical properties of the fibre components, i.e. solubility, molecular weight and viscosity of the test products in detail are exceptions and include the papers by Tappy et al. (1996), Wood et al. (1990) and Wood et al. (1994). Results from these studies are shown in Table 1.

Kerckhoffs et al. (2003) compared the physiological effects of oat bran baked in bread and cookies with oat bran in a drink. Only the oat bran in the drink gave a significant reduction in cholesterol. The authors concluded that beta-glucan included as oat bran in bread and cookies may lead to lack physiological effects (Kerckhoffs et al. 2003). Earlier studies by Braaten et al. (1994) and Önning et al. (1999) also observed significant reduction in plasma LDL cholesterol when beta-glucan was mixed with a drink.

Effects of processing on the viscosity of beta-glucan

Most of the oats used as food are processed to oat flakes (oatmeal), oat bran and foods made from these. The process involves a heat-treatment called kiln-drying of dehulled oats, or groats, for the inactivation of lipase in a process described in detail by Ganssmann and Vorwerck (1995). In kild-drying and the subsequent steaming at flaking other enzymes are also inactivated. Therefore, kiln-dried oat groats and the oatmeal, oat bran and oat flour are practically free from endogenous enzyme activity.

The milling of oat groat can improve the extractability of beta-glucan, e.g. by reducing the particle size (Wood 1993). Hydrothermal treatments may also change the capability of beta-glucan to form viscous solutions by affecting extractability or solubility (Zhang et al. 1998).

Beta-glucan can be easily depolymerized by enzymatic or chemical hydrolysis. The molecular weight of oat beta-glucan has been reported to be 3×10^6 or higher (Wood et al. 1991, Mälkki et al. 1992). For various processed foods lower molecular weights, such as values between 0.6×10^6 to 2.9×10^6 have been shown (Beer et al. 1997a, Wood et al. 1991). For example, the molecular weight of the beta-glucan in an oat muffins was lower than that in the oat bran used as ingredient (Beer et al. 1997b). During breadmaking the beta-glucan may be hydrolyzed by enzymes from other ingredients, including flour components or accompanying micro-organisms (Degytyte-Fomins et al. 2002).

There are also some indications that storage, such as freezing, of the beta-glucan containing products may affect the beta-glucan molecule and its physicochemical properties. Extractability of beta-glucan in oat bran muffins kept frozen for eight weeks was 30% to 50% lower than in fresh oat bran muffins (Beer et al. 1997b). However, freezing did not change molecular weight of beta-glucan (Beer et al. 1997b, Suortti et al. 2000).

It should be noted that although physicochemical properties such as solubility (extractability) and molecular weight (viscosity) are altered, the result of the quantitative analysis of beta-glucan content will be unchanged. This is because of the ethanol precipitation applied in the analytical procedure. The ethanol will precipitate all beta-glucan composed of higher than 10 glucose units, irrespective of the viscosity that this hydrolysed beta-glucan may have. Therefore a complementary method for showing the potential of beta-glucan to raise the viscosity in the intestine is needed.

Viscosity determination of beta-glucan in oat products

Although the role of beta-glucan as a component raising luminal viscosity is the main hypothesis for the role of beta-glucan as a health promoting component, no standard method for de-

termining the viscosity is available. However, Törrönen et al. (1992) and Beer et al. (1996) concluded that the effect of beta-glucan in various foods or preparations cannot be estimated by beta-glucan content alone, but the viscosity of beta-glucan under physiological conditions should be measured.

We have tried to develop a method appropriate for the measurement of viscosity of soluble dietary fibre in oat products. The first problem in such an analysis is the extraction method. In order to measure rheological properties of soluble fibre of the food products an appropriate extraction method of soluble fibre is needed. For their own applications Beer et al. (1997b) and Aura et al. (1999) developed extraction methods that mimic physiological digestion of soluble fibre, including a digestion temperature of 37°C. Such digestion and extractions methods can be applied also for products high in beta-glucan. For a viscosity measurement, the beta-glucan content of the extract must be higher than the critical entanglement concentration. In products of low beta-glucan content or poor solubility the concentration of beta-glucan in the extract might be too low for a viscosity measurement, and concentration is required.

We have applied an extraction method that follows the procedure used in the standard dietary fibre procedure, originally described by Asp et al. (1983). However, we have used smaller liquid volumes and stronger enzyme concentrations in order to ensure starch and protein removal but to avoid excessive dilution. In spite of these changes the extract needs to be concentrated (in vacuum) before viscosity measurement in a rotational rheometer (Anttila et al. 2002, 2003).

Useful curves are obtained when the apparent viscosities of oat extracts are plotted against increasing concentration of the soluble fibre (beta-glucan). Figure 1 shows the viscosity plot of a soluble fibre extract from an oat bran ingredient with that from oat bran bread baked with wheat flour. The deviating shapes of curves in extracts indicate that processing has caused changes in the soluble fibre because the relationship between extractable beta-glucan and viscosity had changed.

In conclusion, increased viscosity in the gastrointestinal tract is considered to be the main mechanism for the beneficial effects of oat beta-glucan on blood sugar and cholesterol attenuation. For the physiological effects a high content (dose) of beta-glucan in the oat products is

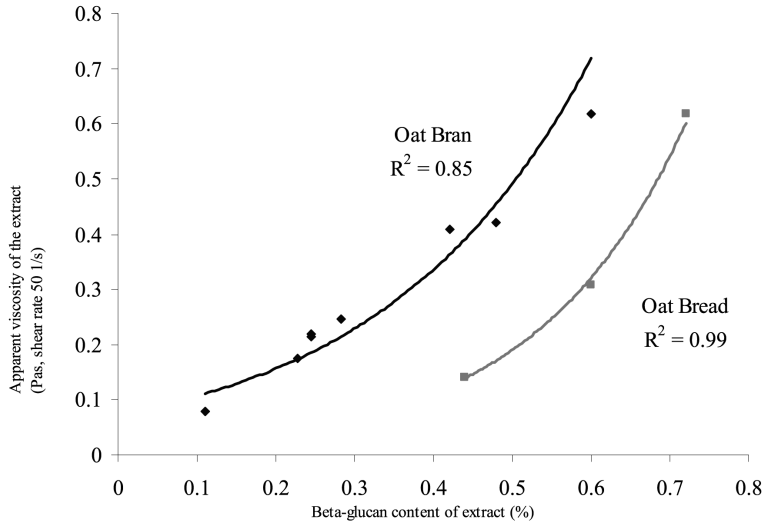

Fig. 1. Apparent viscosities of extracts from oat bran and oat bran pala bread at different beta-glucan concentrations (Salovaara et al. 2003).

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required. As it comes to such complex compounds as dietary fibre it is very difficult to predict physiological properties on the basis of structure alone. In terms of beta-glucan, a quantitative measurement is not sufficient, since this procedure pays no attention to viscosity of beta-glucan which might be affected by processing. It is important for a food manufacturer to minimize factors that can reduce solubility and molecular weight of beta-glucan, and hence physiological luminal viscosity. A standardised method for viscosity measurement of beta-glucan is required for consideration of the potential of oat-based foods and food processes with respect to health benefits based on beta-glucan.

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SELOSTUS

Kauran beetaglukaanin viskositeetti kauratuotteissa

Heli Anttila, Tuula Sontag-Strohm ja Hannu Salovaara
Helsingin yliopisto

Kauran jyvä, kauran ydin sisältää 3–4 % ns. vaihtuvasidoksellista beetaglukaania, jossa glukoosiyksiköt liittyvät haaroittumattomaksi ketjuksi β(1→4)- ja β(1→3)-sidoksin. Ravitsemuksellisesti kauran beetaglukaani luetaan liukoiseen, suolensisällön viskositeettia lisäävään ravintokuituun, jolla on kahdenlaisia terveyttä edistäviä vaikutuksia, nimittäin verensokerin glukoosi- ja insuliinitasoja tasaava vaikutus ja kolesterolitasoa alentava vaikutus. Suolensisällön viskositeetin kasvu hidastaa glukoosin imeytymistä ja heikentää kolesterolin ja sen rakennusaineiden, sappihappojen, imeytymistä. Vaikka beetaglukaanin viskositeetilla on siten ilmeisen tärkeä merkitys sen fysiologisten vaikutusten kannalta, sen mittaamisen analytiikkaan on kiinnitetty suhteellisen vähän huomiota. Vain muutamissa kauratuotteiden kliinisissä kokeissa on kunnolla kuvattu beetaglukaanin viskositeetti. Elintarvikkeessa ja sen ruokasulassa beetaglukaanista johtuva viskositeetti riippuu beetaglukaanin liukenevuudesta, konsentraatiosta ja molekyylipainosta. Kun pyritään valmistamaan kauran beetaglukaaniin perustuvia terveysvaikutuksia omaavia elintarvikkeita, valmistuksessa on kiinnitettävä huomiota raaka-aineen beetaglukaanin määrän ja pitoisuuden (annoksen) lisäksi myös prosessointimenetelmään. Menetelmän tulee taata beetaglukaanin riittävä liukoisuus ja minimoida sen hajoaminen esimerkiksi entsymaattisesti. Tutkimustemme kohteena ovat olleet eri elintarvikeprosessit ja niissä käytetyt suuren beetaglukaanipitoisuuden omaavat kaurafraktiot sekä toisaalta beetaglukaanin viskositeetin määritysmenetelmän kehittäminen. Tässä katsauksessa pohditaan eri näkökohtia kehitettäessä sellaista beetaglukaanin viskositeetin määritysmenetelmää, joka pystyisi kuvaamaan ja ennakoimaan beetaglukaanin käyttäytymistä prosesseissa ja fysiologisesti.