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# The molecular weight, solubility and viscosity of oat beta-glucan affect human glycemic response by modifying starch digestibility

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ABSTRACT

The interaction between oat β-glucan and other food components has the potential to influence starch digestibility and consequently affect its bioactivity in reducing glycemic responses. Blood glucose concentrations were measured before and after ingesting wheat and oat granolas, with 0.6 and 6.2 g of β-glucan, respectively, and two starch doses (40 and 60 g). As the *in vitro* extract viscosity of β-glucan increased, the *in vitro* starch digestibility was reduced and the glucose responses were lowered. The peak blood glucose response (PBGR) and the incremental area under the curve (iAUC) were lower in the 40 g than in the 60 g starch formulation. β-Glucan was significantly more active in reducing PBGR and iAUC when the β-glucan/starch ratio was 1.6:10 rather than 1.1:10. This information is valuable for new product development and for quality assessment of bioactive foods containing oat β-glucan.



## 1. Introduction

Several studies have shown that (1 → 3)(1 → 4)-β-D-glucan is effective in reducing post-prandial glucose and insulin responses (Braaten et al., 1991; Cavallero, Empilli, Brighenti, & Stanca, 2002; Granfeldt, Liljeberg, Drews, Newman, & Bjorck, 1994; Hallfrisch & Behall, 2000; Makelainen et al., 2007; Panahi, Ezatagha, Temelli, Vasanthan, & Vuksan, 2007). This soluble fibre is a major component of oat and barley fibre. Its physiological activity has been attributed to its effect in increasing viscosity in the upper digestive tract (Dikeman & Fahey, 2006; Wood et al., 1994) but the mechanism of action is still not well understood.

It has been suggested that the increase in luminal viscosity impairs the rate of digestion of starch and absorption of glucose due to a reduction of pancreative amylase activity and movement of released sugars to the gut wall (Dunaif & Schneeman, 1981). This mechanism could be important in the physiological functionality of β-glucan *in vivo*, however, other physical mechanisms may also be involved, particularly when the non-starch polysaccharides are part of a food matrix (Brennan, Blake, Ellis, & Schofield, 1996).

The rate and extent of starch digestion is a major determinant in the rate of blood glucose rise. The starch digestion rate is influenced by botanical origin as this determines the amylose:amylopectin ratio and the structural type of the starch granule (Gallant, Bouchet, Buleon, & Perez, 1992). The other important factor is thermal processing, which determines the extent of starch gelatinisation, particle size and the integrity of the plant cell wall (Heaton, Marcus, Emmett, & Bolton, 1988).

The relationship between the rate of digestion and absorption of carbohydrate foods and the glycemic response has been shown in various *in vitro* digestion methods that mimic the *in vivo* situation (Englyst, Veenstra, & Geoffrey, 1996; Englyst, Vinoy, Englyst, & Lang, 2003; Goñi, Garcia-Alonso, & Saura-Calixto, 1997; Granfeldt et al., 1994). Englyst et al. (2003) found a very high correlation between the rate of *in vitro* glucose released from starchy foods and the glycemic index (GI) reported in tables. Rapidly available glucose (RAG) was positively ($r^2 = 0.54$, $P < 0.001$) and slowly available glucose (SAG) was negatively ($r^2 = 0.63$, $P < 0.001$) correlated with

*Abbreviations:* $c_e$, concentration of β-glucan in extract; GI, glycemic index; iAUC, incremental area under the blood glucose curve; HMW, high molecular weight; LMW, low molecular weight; MMW, medium molecular weight; $M_p$, peak molecular weight; MW, molecular weight; PBGR, peak blood glucose rise; RAG, rapidly available glucose = RDS + free glucose; RDS, rapidly digestible starch (g/serving); %RDS, rapidly digestible starch (% of total starch); RS, resistant starch (g/serving); %RS, resistant starch (% of total starch); SDS, slowly digestible starch (g/serving); %SDS, slowly digestible starch (% of total starch); TAC, total available carbohydrate (g/serving).

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the GI of 23 products (five breakfast cereals, six bakery products and crackers, and 12 biscuits).

Soluble fibres may reduce starch digestibility by changing the microstructure of food products (Brennan et al., 1996; Cleary & Brennan, 2006; Tudorica, Kuri, & Brennan, 2002) or by limiting water availability as a consequence of soluble non-starch polysaccharide hydration which, in turn, restricts starch gelatinisation (Banchathanakij & Suphantharika, 2009; Cleary & Brennan, 2006). A wide range of dietary fibres (guar gum, cellulose, pectin, locust bean gum, wheat bran, resistant starch, β-glucan, pea fibre and inulin) have been used in the production of pasta, biscuits and bread (Brennan & Cleary, 2007; Brennan & Samyue, 2004; Brennan et al., 1996; Symons & Brennan, 2004b; Tudorica et al., 2002). Soluble fibres appear to decrease the rate of starch degradation *in vitro* to a larger extent than the insoluble dietary fibres. However, the starch digestibility was reduced to different degrees in food products with the same soluble fibre source indicating that the ability of the fibre to reduce starch digestibility in foods may be process and product dependent (Brennan, 2005). The solubility of the β-glucan also depends on the cereal and tissue source, food formulation, processing and storage conditions (Lan-Pidhainy, Brummer, Tosh, Wolever, & Wood, 2007; Regand, Tosh, Wolever, & Wood, 2009).

β-Glucan depolymerisation has been observed in oat and barley foods. The physical state of the β-glucan in the raw material, β-glucanase activity, processing, and storage conditions affect the molecular weight (MW) of β-glucan (Aman, Rimsten, & Andersson, 2004; Beer, Wood, Weisz, & Fillion, 1997; Tosh et al., 2010). However, little is known about the role of the MW of β-glucan on the reduction of starch digestibility. If the attenuation of reducing sugar release is a function of the increased digest viscosity and reduced motility, then the MW and amount of β-glucan solubilised in the gut should be critical in its capacity to reduce it.

Therefore, the major objective of this study was to investigate whether the physicochemical properties of β-glucan were related to its capacity to retard starch digestibility and therefore reduce glycemic responses. The secondary objective was to examine the importance of the starch/β-glucan ratio in the efficacy of β-glucan by testing two different starch doses with the same content of β-glucan.

## 2. Materials and methods

### 2.1. Materials

The ingredients used to prepare the test foods were: large flake rolled oats (Quaker Oats, ON, Canada, 4.3% β-glucan), OatWell® 22 oat bran (CreaNutrition, Switzerland, 22% β-glucan), white wheat flour (Five Roses, ON, Canada), rolled wheat flakes (Grain Process Enterprises LTD, ON, Canada), egg white powder (El Peto Pts, ON, Canada), vegetable oil shortening (Crisco®, The J.M. Smucker Company, ON, Canada), baking powder (Nabisco, ON, Canada) and vanilla extract (McCormick, ON, Canada). SEBflo, a food-grade β-glucanase enzyme was used to vary the MW of β-glucan (Specialty Enzymes and Biochemicals Co., Chino, CA, USA).

Alpha-amylase (EC 3.2.1.1, from human saliva), pepsin (EC 3.4.23.1, from porcine stomach) and pancreatin (EC 232.468.9, from porcine pancreas) used for the β-glucan *in vitro* digestion were from Sigma–Aldrich (Oakville, ON, Canada). Pancreatin from porcine pancreas (Sigma P7545, activity 8 × USP/g) was purchased from Sigma Chemical Company (St Louis, MO, USA), amyloglucosidase (EC 3.2.1.3., 3300 U/ml) and glucose oxidase–peroxidase assay kit were purchased from Megazyme International Ireland Ltd. (Bray, Ireland).

### 2.2. Experimental foods

Product formulations, energy and nutrient composition for oat and wheat control products are shown in Table 1. Oat products were formulated to contain 6.2 g of β-glucan with two different levels of total available carbohydrates (TAC): approximately 40 and 60 g. The amount of free sugars was kept to a minimum (0.3 g per serving). The sources of β-glucan in the oat products were oat bran and whole oat flakes. Wheat control products with similar TAC and minimal amounts of β-glucan (0.6 g/serving) were made with whole wheat flakes and white wheat flour. Oat and wheat control products were analysed for fat (AOAC 960.39), protein (AOAC 990.03), free sugars and total starch (AOAC 996.11). Dry matter content was determined according to a standard method (AACC method 44-15A, 2000). Dry egg white powder and vegetable shortening were added in varying amounts to equalise fat and protein content. For each test food formulation, three different MW distributions of β-glucan, designated as low (L), medium (M) and high (H), were produced after incubating the dough for 30 min with different concentrations of β-glucanase: for L and M, 2.5 and 16 μl per serving, respectively, and by no added enzyme in the HMW product.

For the preparation of the products, the ingredients required for 18 servings (plus 5% to allow for wastage) were mixed using an industrial mixer (Hobart, Corp., Troy, OH, USA) and the resulting batter was kept at room temperature for 30 min to allow β-glucan hydrolysis to occur. After this time, the batter was poured in a large baking tray and baked at 350 °C in an oven (LC Bakery Equipment Services LTD, Brantford, ON) for approximately 3 h until it reached 40% moisture content. After cooling, the food was cut into 5 × 5 cm pieces and packaged in plastic bags in individual servings. Throughout the clinical trial, the products were stored at 4 °C for no more than 10 days. Microbiological analysis, performed by MAXXAM Analytics (Mississauga, ON, Canada), demonstrated that, under these storage conditions, the shelf life of the products was more than 1 month.

**Table 1**
Formulations (g/serving), energy (kcal/serving) and nutrient composition (g/serving) of oat and wheat control products with 40 g and 60 g starch contents.

| | 40 Oat | 40 Wheat | 60 Oat | 60 Wheat |
|---|---|---|---|---|
| *Formulations* | | | | |
| Oat bran | 15 | 0 | 8 | 0 |
| Whole oat flakes | 72 | 0 | 108 | 0 |
| Wheat flakes | 0 | 52 | 0 | 49 |
| White wheat flour | 0 | 20 | 0 | 50 |
| Egg white powder | 4 | 7 | 0 | 3 |
| Shortening | 2 | 7 | 0 | 7 |
| Vanilla extract | 2 | 2 | 2 | 2 |
| Baking powder | 1 | 1 | 1 | 1 |
| Water | 145 | 145 | 175 | 175 |
| Total | | | | |
| Before baking | 241 | 234 | 294 | 287 |
| After baking | 141 | 146 | 169 | 146 |
| *Energy and nutritional composition* | | | | |
| Energy | 362 | 360 | 440 | 406 |
| Fat | 8 | 8 | 8 | 7 |
| Carbohydrate | 57 | 58 | 76 | 73 |
| Total dietary fibre | 20 | 18 | 16 | 15 |
| β-Glucan | 6.2 | 0.6 | 6.3 | 0.6 |
| TAC[a] | 38 | 40 | 60 | 58 |
| Free glucose | 0.2 | 0.4 | 0.2 | 0.4 |
| Starch | 37 | 39 | 60 | 57 |
| Protein | 17 | 15 | 16 | 14 |
| Ash | 2 | 1 | 2 | 1 |
| Moisture | 57 | 64 | 67 | 51 |

[a] Total available carbohydrates calculated as glucose + starch.