

## Effect of dose and modification of viscous properties of oat gum on plasma glucose and insulin following an oral glucose load

BY PETER J. WOOD<sup>1</sup>, JANT T. BRAATEN<sup>2</sup>, FRASER W. SCOTT<sup>3</sup>, K. DOREEN RIEDEL<sup>2</sup>, MARK S. WOLYNETZ<sup>4</sup> AND MAURICE W. COLLINS<sup>3</sup>

<sup>1</sup> Centre for Food and Animal Research, Agriculture and Agri-Food Canada, Ottawa, Ontario K1A 0C6, Canada

<sup>2</sup> Division of Endocrinology and Metabolism, Ottawa Civic Hospital, Ottawa, Ontario K17 4E9, Canada

<sup>3</sup> Nutrition Research Division, Food Directorate, Health Canada, Ottawa, Ontario K1A 0L2, Canada

<sup>4</sup> Research Program Service, Agriculture and Agri-Food Canada, Ottawa, Ontario K1A 0C6, Canada

(Received 6 October 1993 – Revised 24 January 1994 – Accepted 15 February 1994)

An extract from oats known as oat gum (OG) is composed mainly of the polysaccharide (1 → 3)(1 → 4)- $\beta$ -D-glucan, which is highly viscous in aqueous solution. Viscous polysaccharides are known to attenuate postprandial plasma glucose and insulin responses. The purposes of this study were to determine the dose–response to OG and establish quantitatively the effect of viscosity on plasma glucose and insulin levels of healthy humans consuming 50 g glucose. Increasing the dose of OG successively reduced the plasma glucose and insulin responses relative to a control without gum. Reduction of the viscosity of OG by acid hydrolysis reduced or eliminated the capacity to decrease postprandial glucose and insulin levels. The ability of OG to modify glycaemic response was unchanged following agglomeration in the presence of maltodextrin. Agglomerated gum dispersed smoothly in a drink without formation of lumps, and development of maximum viscosity was delayed. These properties improve palatability. There was a highly significant linear relationship between  $\log[\text{viscosity}]$  of the mixtures consumed and the glucose and insulin responses. The relationship shows that 79–96% of the changes in plasma glucose and insulin are attributable to viscosity, and that changes occur at relatively low doses and viscosities.

Oat beta glucan: Dietary fibre: Glucose: Insulin

Dietary fibre has been defined in analytical terms as either soluble or insoluble, each with quite different physiological effects. This sub-division is now generally accepted, but within the two categories effects may be variable (Jenkins, 1980; Eastwood *et al.* 1986; Edwards *et al.* 1987; Roehrig, 1988). Certain soluble fibres, such as guar gum, delay glucose absorption and reduce serum cholesterol levels and these two characteristics may be related (Jenkins *et al.* 1989; Anderson *et al.* 1990).

The reported ability of oat bran to reduce serum cholesterol levels has therefore been attributed to the specific action of its soluble dietary fibre (Anderson *et al.* 1990; Shinnick *et al.* 1991), the major component of which is a (1 → 3)(1 → 4)- $\beta$ -D-glucan (oat  $\beta$ -glucan; Wood, 1986). This viscous polysaccharide is physicochemically similar to guar gum but is not commercially available. A product, oat gum (approximately 80%  $\beta$ -glucan), was therefore extracted from oat bran and purified (Wood *et al.* 1989) in amounts sufficient to evaluate physiological effects. This oat gum was previously shown to inhibit glucose absorption *in vitro* (Lund *et al.* 1989).

In the present study the viscosity of test meals of 50 g glucose in 500 ml water was varied by using three different doses of oat gum and by using oat gum depolymerized by mild acid hydrolysis. The effect of dose and viscosity on postprandial plasma glucose and insulin levels was then evaluated, incorporating earlier data (Braaten *et al.* 1991). In addition, a process of agglomeration or 'instantizing' was used to produce an oat-gum preparation which dispersed smoothly in water without the formation of partly hydrated particles that have an unpleasant texture. Furthermore, hydration of the instantized oat gum was delayed for a few minutes, which allowed consumption before full development of the viscous characteristics that most subjects disliked. The effect of these modified viscosity characteristics on postprandial plasma glucose and insulin levels was also studied.

## MATERIALS AND METHODS

### *General*

Chemicals used were of food or analysis grade and were commercially supplied. Oat gum (OG) was prepared in the POS Pilot Plant (POS Pilot Plant Corp., Saskatoon, Saskatchewan, Canada) as previously described (Wood *et al.* 1989).

Acid-hydrolysed OG was prepared at the POS Pilot Plant as follows. A slurry of 100 g OG in 400 ml ethanol (950 ml/l) was added gradually to 5 litres of water in a blender and mixed. The dispersed gum was transferred to a 20-litre teflon-coated vessel fitted with an overhead stirrer, stirred with a Teflon-coated paddle and heated to 70°. HCl (0.2 M; 5 litres), prepared in a glass vessel and preheated to 70°, was added and the mixture was stirred at 70° for 15 min (OG15) or 60 min (OG60). Each mixture was rapidly cooled in an ice bath to approximately 30° and the pH was adjusted to 6.5–7.0 with 1 M-NaOH followed by 0.1 M-NaOH. An equal volume of ethanol (950 ml/l) was added slowly to the hydrolysed gum solutions with vigorous stirring and the precipitates were recovered after settling by siphoning and centrifugation. The precipitates were washed with ethanol (475 ml/l) in the blender, recovered and re-dispersed in ethanol (950 ml/l), then filtered and dried in an oven at 30°. Yields of OG15 and OG60 were 870 and 830 g/kg respectively.

Instantized OG ('Instagum') was prepared from Pilot Plant OG by Zumbro Inc., Hayfield, MN, USA. In this process (Sander & Cook, 1985) OG (one part by weight) was blended with maize-starch maltodextrin (four parts by weight) of dextrose equivalent (DE) 10. The process produced agglomerated particles containing gum and maltodextrin but otherwise did not modify the ingredients.

Analytical data for the hydrolysed and original OG are reported in Table 1.

### *Meals for dose-response experiment (Expt 1) and hydrolysed gum experiment (Expt 2)*

Meals consisted of 500 ml water, 0.63 g malic acid, 50 g glucose, 0.51 g aspartame (Nutrasweet, Searle Canada Inc., Oakville, Ontario, Canada), 0.54 g raspberry flavour, and colouring (Florasynth Canada Inc., Montreal, Quebec, Canada). Levels of 1.8, 3.6, and 7.2 g OG were used in the dose-response experiment (Expt 1) and 7.2 g OG15 and OG60 were used in the hydrolysed gum experiment (Expt 2). The gum, glucose, aspartame, and flavour were dry-blended before adding to a vigorously stirred solution of water-malic acid in an Osterizer blender (model series 8300) regulated to 70% of the whip setting. Colour was added to attain a desired level. The mixture was then transferred to a Sunbeam Mixmaster (Model MM 1000; Sunbeam Corporation Canada Ltd, Toronto, Ontario), blended for 5 min on setting 10, and allowed to hydrate overnight at 5° before feeding. In both experiments the control meal contained no gum.

Table 1. *Analytical characteristics of oat gum preparations*

Sample	Viscosity* (mPa.s)	Composition (g/kg dry wt)				
		$\beta$ -Glucan	Starch	Pentosan	Protein	Ash
Oat gum	1548	810	20	34	48	18
OG15	50	890	16	tr	34	5
OG60	9.4	890	15	tr	32	7

OG15, oat gum acid-hydrolysed for 15 min; OG60, oat gum acid-hydrolysed for 60 min; tr, trace.

\* Apparent viscosity at 25° and a shear rate of 30 s<sup>-1</sup> of a 10 g/l solution based on  $\beta$ -glucan content.

#### *Meals for the Instagum experiment (Expt 3)*

Instagum (36.2 g; containing 7.2 g OG and 29 g DE 10 maltodextrin) was stirred into a mixture of 250 ml degassed diet soft drink ('7-Up') and 250 ml degassed soda water containing 21 g glucose and consumed immediately. The control drink contained 21 g glucose and 29 g DE 10 maltodextrin; this is equivalent to a total of 53 g glucose.

#### *Subjects and protocol*

Five women (age 31 (SE 3) years, body mass index (BMI) 23 (SE 2) kg/m<sup>2</sup>) and four men (age 32 (SE 1) years, BMI 27 (SE 4) kg/m<sup>2</sup>) participated in the dose-response study; five women (age 38 (SE 5) years; BMI 23 (SE 1) kg/m<sup>2</sup>) and six men (age 37 (SE 4) years, BMI 26 (SE 1) kg/m<sup>2</sup>) in the hydrolysed gum study; and six men (age 37 (SE 6) years, BMI 25 (SE 1) kg/m<sup>2</sup>) and two women (ages 39 and 57, BMI 27 and 28 respectively) in the Instagum study. All were in good health and none was taking medication.

Subjects fasted and refrained from exercise for 12 h before the tests. They were instructed to consume at least 200 g carbohydrate daily for 3 d before the tests. Blood samples were collected from a plastic catheter introduced into the antecubital vein and then distributed into two Vacutainer tubes (Becton Dickinson, Mississauga, Ontario, Canada) containing heparin (for glucose determination) or EDTA (for insulin assay) at -15 and 0 min (baseline), every 10 min subsequently up to 60 min and then at 80, 90, 100, 120, 150 and 180 min. The tests were conducted at least 3 d apart with the control drink being given first to ensure that subjects had normal postprandial glucose profiles. The meals were consumed evenly over a 10 min period, beginning immediately after the time zero blood sample was taken. However, the Instagum meal was mixed in three or four separate portions, each of which was consumed within 2-3 min, before hydration and full viscosity development.

#### *Analytical methods*

Starch and  $\beta$ -glucan were determined as described by Wood *et al.* (1991). Pentosan was determined by acid hydrolysis followed by high-performance anion-exchange chromatography using pulsed amperometric detection (Dionex Corp., Sunnyvale, CA, USA). Protein (Kjeldahl) and ash were determined commercially (Galbraith Laboratories Inc., Knoxville, TN, USA).

Blood samples were kept on ice until processed. Plasma glucose was determined using glucose oxidase in the Beckman Glucose Analyzer II. The plasma was stored at -20° for later determination of insulin by radioimmunoassay (Herbert *et al.* 1965). Postprandial plasma glucose and insulin values for each subject were expressed as change from baseline.

Since the shape of plots of change in glucose and insulin with time varies within and between individuals, the responses were also characterized using the time-independent

variables of each individual's peak and minimum values, the range between these (excursion) and the area under the 2 h curve (AUC); this area was calculated as described for glucose by Wolever *et al.* (1991).

### *Viscosity*

Viscosities were determined on a Carri-Med Controlled Stress Rheometer (Carri-Med Ltd, Dorking, Surrey) using cone and plate (6 cm 2 deg, 4 cm 2 deg and 4 cm 1 deg) at 25°. Viscosities of the gum meals were determined directly on the test meals as served, over a shear rate range of approximately 0–100 s<sup>-1</sup>. Values reported are apparent viscosities at 30 s<sup>-1</sup> and are the average of two or more replicates.

For comparison of viscosities of OG, OG15 and OG60 at 10 g/l, solutions were prepared in duplicate by dissolving with heat (65–75°) and stirring in vessels covered with a double thickness of parafilm for 3–5 h. If undissolved material was evident, stirring was continued overnight at room temperature. Volume was adjusted by weight for losses due to evaporation.

Viscosity development in Instagum was monitored at the concentration (72 g/l) used in the test meal. Instagum was added to the glucose solution, stirred for 1 min and a portion was then transferred to the rheometer, which was operated to reach a peak shear rate of 50 s<sup>-1</sup> in 10 s and held at that shear rate to determine duration to maximum viscosity development. A 6 cm 2 deg cone was used with a solvent trap to prevent evaporation losses, and hence an increase in concentration during measurement. This ensured that viscosity increases observed were solely due to the development of hydration of the gum. Viscosity of the Instagum solutions, hydrated by 45 min stirring, was then determined over a shear rate range of approximately 0–100 s<sup>-1</sup>.

### *Statistical analysis*

The data at each time were examined separately. Terms in the analysis of variance (ANOVA) were subject and treatment; all treatment comparisons were on a within-subject basis. The same ANOVA was used to examine the values for peak, minimum, excursion and AUC. In Expt 1 the three degrees of freedom for the treatment effect, arising from the four levels used, were partitioned into a linear component with 1 df and a non-linear component with 2 df. The linear component was used to determine whether there was a linear relationship between the response variables (peak, minimum, excursion, AUC) and log[viscosity].

In addition, the peak, excursion and AUC values from all three experiments and for the 14.5 g doses of guar and OG used in the previous study (Braaten *et al.* 1991) were regressed on log[viscosity]. Results were considered to be significant whenever  $P \leq 0.05$ .

### *Ethical considerations*

The study was approved by the Ethics Committee of the Department of Research, Ottawa Civic Hospital. The objectives of the overall programme were to benefit people with type II diabetes, and to reduce the risk of coronary heart disease in people with elevated serum cholesterol levels.

## RESULTS

### *Expt 1. Dose-response*

Each meal was consumed within 10 min. Fig. 1 shows the mean deviations from baseline for plasma glucose and insulin. Mean values (5.0 (SE 0.1), 5.3 (SE 0.2), 5.2 (SE 0.2) 5.2 (SE 0.2) mmol/l) for glucose before each test (0, 1.8, 3.6 and 7.2 g gum respectively) were not significantly different.

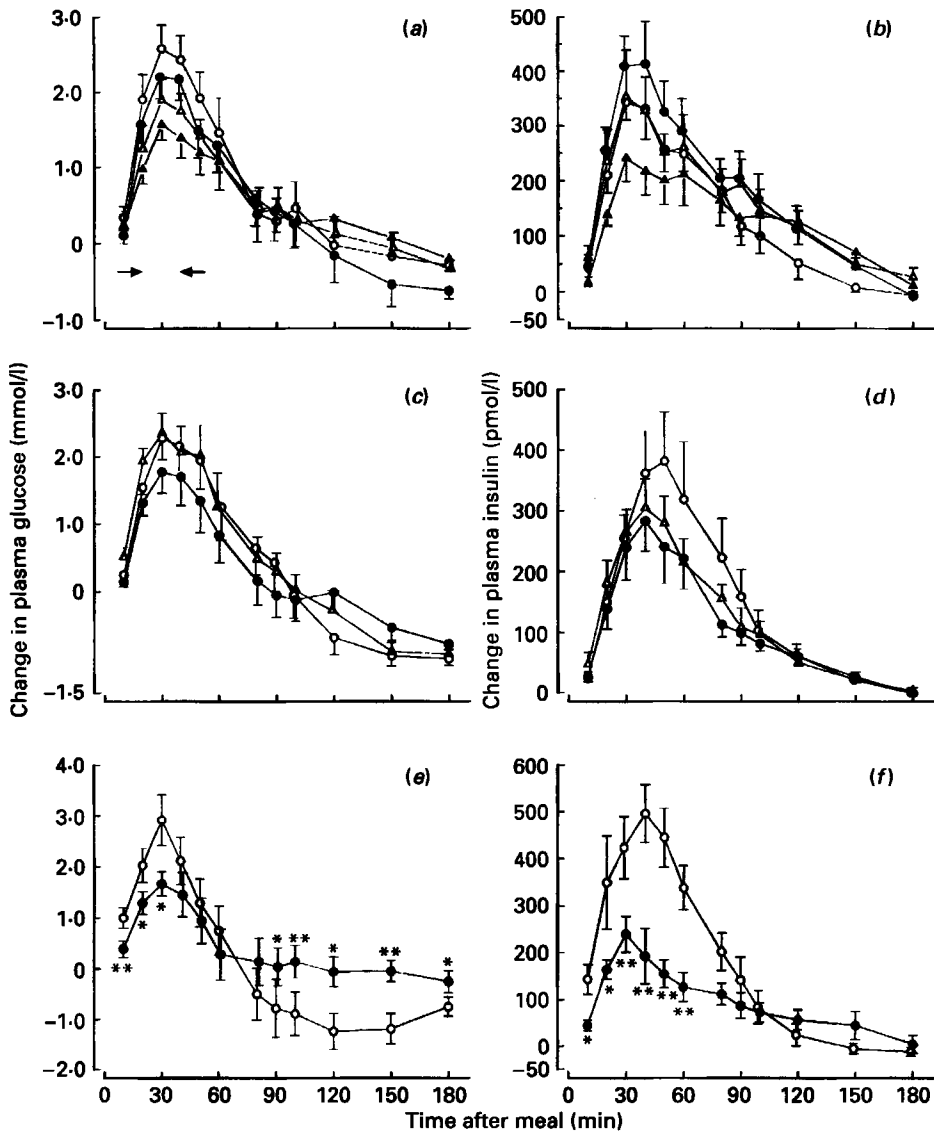


Fig. 1. Postprandial change with time in mean plasma glucose (*a, c, e*) and insulin (*b, d, f*) concentrations after a 50 g glucose or glucose-maltodextrin (*e, f*) load alone (control,  $\circ$ ) or in the presence of oat gum, hydrolysed oat gum or instantized oat gum. Panels (*a*) and (*b*), dose response to oat gum: ( $\bullet$ ), 1.8 g; ( $\Delta$ ), 3.6 g; ( $\blacktriangle$ ) 7.2 g. Panels (*c*) and (*d*), hydrolysed oat gum (7.2 g): ( $\bullet$ ), 15 min acid-hydrolysed gum; ( $\Delta$ ), 60 min acid-hydrolysed gum. Panels (*e*) and (*f*): ( $\bullet$ ), instantized oat gum, 36.2 g. Between-subject standard errors are represented by vertical bars. Mean values were significantly different from control values: \*  $P < 0.05$ , \*\*  $P < 0.01$ . In panel (*a*) there was a significant linear relationship ( $P < 0.05$ ) between levels at times 20–50 min, as marked  $\rightarrow \leftarrow$ .

Plasma glucose rise (Fig. 1(*a*)) decreased with increasing gum dose. By 80 min, glucose levels with control and gum meals were the same, and had returned approximately to baseline values by 120 min. ANOVA of glucose values indicated overall significant treatment differences at times 20, 30, 40 and 180 min. The linear component of the treatment effect was significant from 20 to 50 min.

Table 2. *Effects of different doses of oat gum (OG), hydrolysed OG and instantized OG on blood glucose response to a 50 g† oral glucose load‡*

(Mean values with their standard errors for *n* subjects)

Type and dose	Apparent viscosity (mPa.s)§	Δ Plasma glucose (mmol/l)						AUC (mmol.min.l <sup>-1</sup> )	
		Peak		Minimum		Excursion		Mean	SE
		Mean	SE	Mean	SE	Mean	SE		
Expt 1 ( <i>n</i> 9)									
0 (control)	(1)¶	3.0	0.3	-0.7	0.1	3.7	0.3	144	22
OG 1.8 g	23	2.5	0.3	-0.9	0.2	3.4	0.3	125	24
OG 3.6 g	159	2.1	0.2	-0.5	0.1	2.6	0.3	106	14
OG 7.2 g	1940	1.8	0.2	-0.4	0.2	2.2	0.2	102	20
Within-subject SE††		0.2		0.1		0.2		13	
Expt 2 ( <i>n</i> 11)									
0 (control)	(1)¶	2.8	0.4	-1.4	0.1	4.1	0.4	130	30
OG60 7.2 g	18	2.9	0.3	-1.2	0.1	4.1	0.3	131	25
OG15 7.2 g	92	2.3	0.3	-1.0	0.2	3.2*	0.3	101	25
Within-subject SE††		0.2		0.1		0.3		12	
Expt 3 ( <i>n</i> 8)									
0 (control)	(1)¶	3.2	0.4	-1.6	0.3	4.8	0.4	119	26
IG 36.2 g	1910	2.0*	0.3	-0.5***	0.3	2.6**	0.3	86	26
Within-subject SE††		0.2		0.2		0.4		12	

AUC, area under the 2 h glucose curve; OG60, oat gum acid-hydrolysed for 60 min; OG15, oat gum acid-hydrolysed for 15 min; IG, instantized oat gum.

Mean value was significantly different from that of the control: \*  $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*  $P < 0.001$ .

† For instantized gum and control, 21 g glucose plus 29 g maltodextrin.

‡ For details of subjects and procedures, see pp. 732–734.

§ Viscosity of fully hydrated mixture at concentration consumed and a shear rate of 30 s<sup>-1</sup>.

|| The linear component of the treatment effect was significant: peak and excursion,  $P < 0.001$ ; minimum and AUC,  $P < 0.05$ .

¶ Essentially the viscosity of water.

†† Used to compare treatment means.

Mean peak plasma glucose, glucose excursion and AUC were successively reduced with increasing dose (Table 2), with the responses being linearly related to log[viscosity].

For changes in insulin (Fig. 1(b)) the linear component of the treatment effect was not significant at any time, primarily because the values for the 1.8 g dose were greater (though not significantly) than those for the control at 30–80 min. Overall treatment differences at 40 and 50 min arose from the difference between the 1.8 and the 7.2 g treatments.

The treatment differences were significant for mean peak plasma insulin, excursion and AUC (Table 3). These three variables were successively reduced with increasing dose and, as for glucose, were linearly related to log[viscosity].

#### Expt 2. Hydrolysed oat gum

Each meal was consumed within 10 min. Fig. 1(c) and (d) show the mean deviations from baseline for plasma glucose and insulin. Mean values (5.5 (SE 0.2), 5.3 (SE 0.1), 5.4–SE 0.1) mmol/l) for glucose before each meal (control, OG60 and OG15 respectively) were not significantly different.

The plasma glucose values (Fig. 1(c)) for OG15 were somewhat lower relative to the control from 20 to 90 min but the differences were not significant. By 100 min, glucose

Table 3. *Effects of different doses of oat gum (OG), hydrolysed OG and instantized OG on blood insulin response to a 50 g† oral glucose load‡*(Mean values with their standard errors for *n* subjects)

Type and dose	$\Delta$ Plasma insulin (pmol/l)						AUC (pmol.min.l <sup>-1</sup> × 10 <sup>-2</sup> )	
	Peak		Minimum		Excursion		Mean	SE
	Mean	SE	Mean	SE	Mean	SE		
<b>Expt 1 (n 9)§</b>								
0 (control)	535	148	-0.6	9.6	536	140	265	64
OG 1.8 g	446	76	-10.8	4.2	457	78	276	45
OG 3.6 g	388	82	15.6	12.0	373	79	240	50
OG 7.2 g	264	45	1.8	6.6	262	44	184	40
Within-subject SE	56		8.4		56		25	
<b>Expt 2 (n 11)</b>								
0 (control)	509	97	-10.8	9.0	520	104	279	62
OG60 7.2 g	459	66	-16.2	12.6	475	61	250	44
OG15 7.2 g	404	86	-6.6	7.8	410	90	226	43
Within-subject SE	56		10.8		58		32	
<b>Expt 3 (n 8)</b>								
0 (control)	557	59	-18.0	8.4	575	59	301	32
IG 36.2 g	279**	41	-10.8	12.0	290**	47	143***	20
Within-subject SE	37		7.8		40		20	

AUC, area under the 2 h insulin curve; OG60, oat gum acid-hydrolysed for 60 min; OG15, oat gum acid-hydrolysed for 15 min; IG, instantized oat gum.

Mean value was significantly different from that of the control: \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ .

† For instantized gum and control, 21 g glucose plus 29 g maltodextrin.

‡ For details of subjects and procedures, see pp. 732–734.

§ The linear component of the treatment effect was significant: peak and excursion  $P < 0.01$ ; AUC  $P < 0.05$ .

|| Used to compare treatment means.

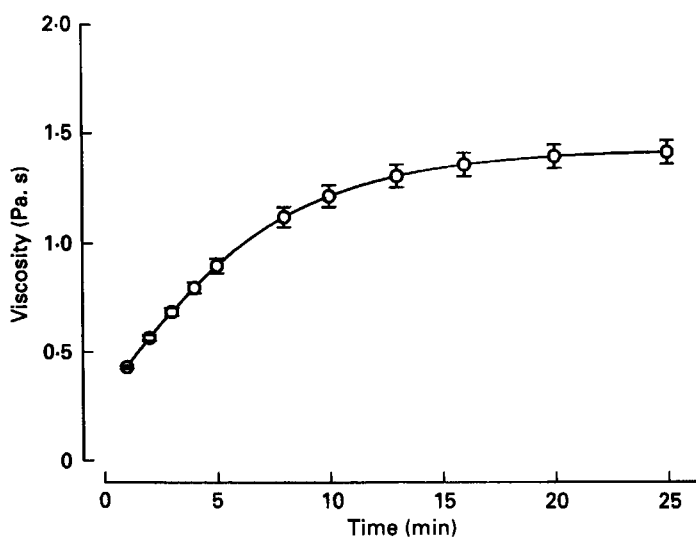


Fig. 2. Development of apparent viscosity (Pa.s at 50 s<sup>-1</sup>) with time in an Instagum meal containing 7.2 g oat gum and 29 g maltodextrin. Values are means for three determinations, with their standard errors represented by vertical bars.

levels with each meal had returned to baseline values, and by 180 min all were below this value.

The mean peak plasma glucose, glucose excursion and AUC for the control and OG60 treatments were similar (Table 2); somewhat lower values were observed following the OG15 treatment but only the excursion was significantly different from the control. Acid hydrolysis of the OG for 15 min and 60 min reduced the apparent viscosity (at  $30 \text{ s}^{-1}$ ) of the resultant meals (7.2 g in 500 ml, 14.5 g/l) 20-fold and 100-fold respectively.

With both hydrolysed gums the plasma insulin rise was somewhat lower than the control (Fig. 1(d)), but the differences were not significant at any time. Similarly peak plasma insulin, insulin excursion and AUC were somewhat lower with the hydrolysed gums than with the control but the differences were not significant (Table 3).

### *Expt 3. Instagum*

The control and Instagum drinks were consumed within 10 min. Fig. 1(e) and (f) show the mean deviations from baseline for plasma glucose and insulin. Mean baseline values for glucose before each meal were the same (5.5 (SE 0.1) mmol/l).

Plasma glucose values (Fig. 1(e)) were lower with the Instagum drink than with the control between 10 and 30 min. At 90 min and beyond, the values for the control were significantly lower than for Instagum and fell below baseline. Plasma glucose peak, minimum, excursion and AUC were all lower following Instagum than following the control (AUC,  $P = 0.08$ ; Table 2).

Plasma insulin values were lower with the Instagum than with the control between 10 and 60 min (Fig. 1(f)); subsequently, values with both Instagum and control declined towards baseline similarly. Insulin AUC, peak and excursion were all significantly lower following Instagum compared with the control (Table 3).

The development of viscosity in the Instagum meal is shown in Fig. 2. Close to full viscosity (recorded at  $50 \text{ s}^{-1}$ ) was reached in 10 min, but within the 3–4 min during which most subjects were able to consume the entire 500 ml, only half the maximum viscosity was attained. The peak viscosity (at  $30 \text{ s}^{-1}$ ) was 1910 mPa.s (Table 2), similar to unmodified gum (1940 mPa.s) at the equivalent gum dose (7.2 g; 14.5 g/l).

### *General observations*

Generally, insulin response followed a similar pattern to the plasma glucose response, but some anomalies were evident, for example the insulin curve following the 1.8 g dose of OG (Fig. 1(b)). The problems with individual variability and analytical error are greater for insulin than for glucose, as reflected in generally larger coefficients of variation.

In addition to the between-subject variability in the peak and minimum values of plasma glucose and insulin, the times to reach the peaks and minima also varied significantly between subjects. The time-independent average peak value or excursion (Tables 2 and 3) more effectively reflected the group physiological response to the test meals than values averaged at a fixed point in time, such as in Fig. 1, or the AUC values. This is illustrated by the insulin response in Expt 1, where AUC (27600 pmol/min.l) with the 1.8 g dose and with the control (26500 pmol/min.l) were similar but the peak value (446 pmol/l) with 1.8 g dose was lower than with the control (535 pmol/l). Furthermore, the between-subject coefficients of variation for peak and excursion were often lower than for AUC.

### *Dose-response and effect of viscosity*

The data from each experiment were examined to determine if the groups used in each experiment had significantly different plasma glucose and insulin characteristics. Generally similar mean baseline plasma glucose, and response to the glucose control meal (peak



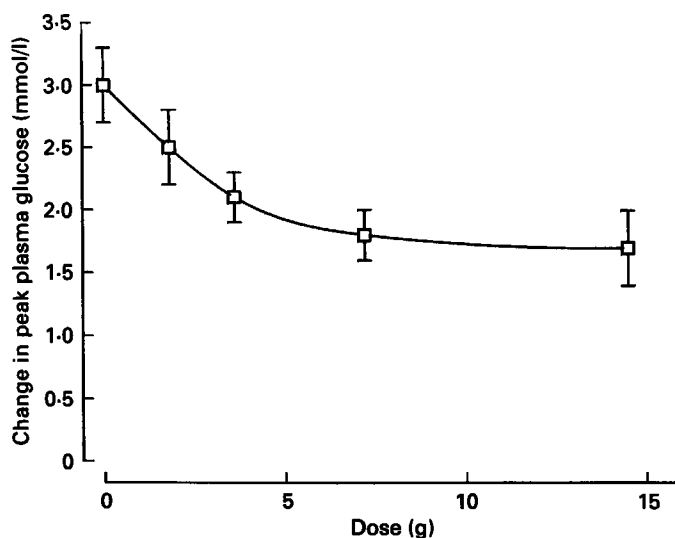


Fig. 3. Effect of dose of oat gum on postprandial change in mean peak plasma glucose increment. Values are means for eight to eleven subjects, with their between-subject standard errors represented by vertical bars.

Table 4. Regression analyses\* of relationships between blood glucose and insulin variables and  $\log_{10}[\text{viscosity}]^{\dagger}$

Variable	<i>a</i>	SEE	<i>b</i>	SEE	$r^2$	$P < \ddagger$
Peak $\Delta$ glucose (mmol/l)	3.00	0.07	-0.31	0.03	0.90	0.0001
Excursion glucose (mmol/l)	4.20	0.17	-0.51	0.07	0.83	0.0001
AUC glucose (mmol/min.l <sup>-1</sup> )	136	4.5	-12.1	2.0	0.79	0.0001
Peak $\Delta$ insulin (pmol/l)	533	11	-71	5	0.96	0.0001
Excursion insulin (pmol/l)	543	11	-75	5	0.96	0.0001
AUC insulin (pmol/min.l <sup>-1</sup> )	29474	1074	-3342	465	0.84	0.0001

SEE, standard error of estimate; AUC, area under curve.

\* From twelve data points.

$\dagger$  Variable =  $a + b \log_{10}[\text{viscosity}]$ ; viscosity units, mPa.s.

$\ddagger$  Significance of regression relationship, or equivalently, correlation coefficient.

plasma glucose increment approximately 3.0 mmol/l), were observed in each experiment. Analysis of the glucose data from the control meals showed statistically significant differences only for the minima between Expt 1 and Expts 2 and 3, and for excursion between Expt 1 and Expt 3. Since there was little difference between the different subject groups, dose and viscosity effects were evaluated using all data points from Expts 1-3, and from Braaten *et al.* (1991). The dose-response curve (Fig. 3) showed that peak plasma glucose responded most in the range of 0-7.2 g OG. There were highly significant ( $P < 0.0001$ ) inverse linear relationships between each plasma glucose and insulin variable

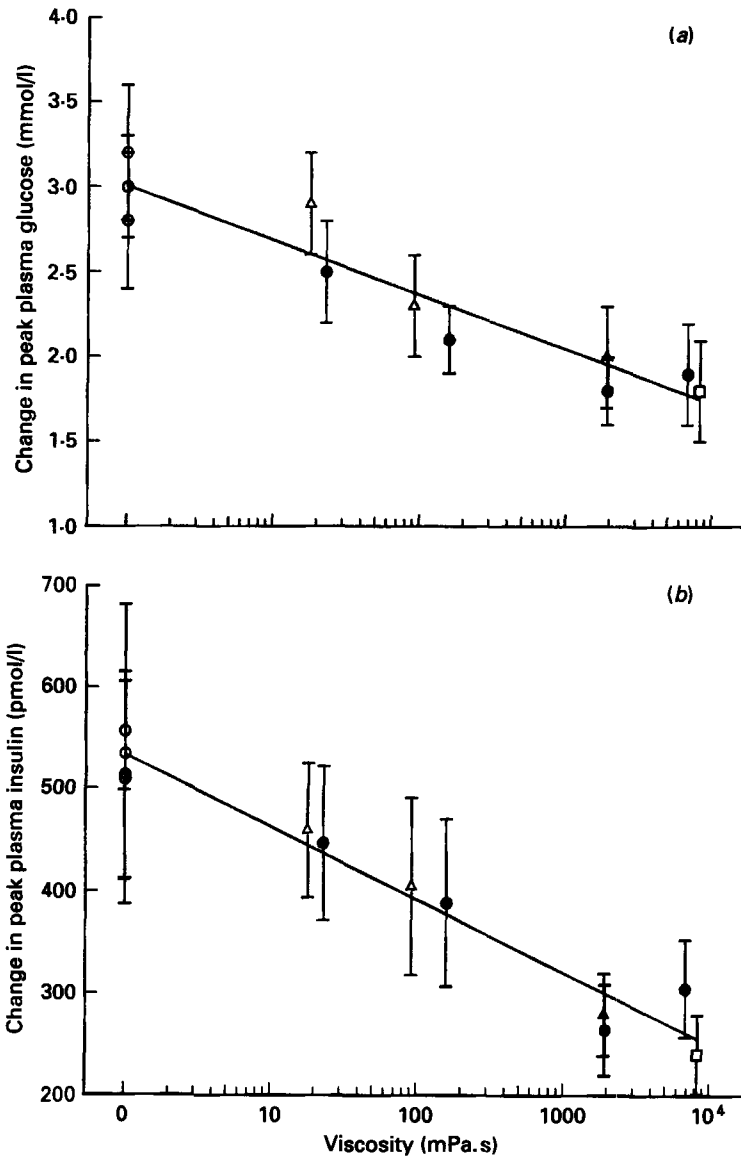


Fig. 4. Relationship of increment in peak plasma glucose (a) and peak plasma insulin (b) to  $\log[\text{viscosity}]$ . (○), controls; (●), dose-response (1.8, 3.6, 7.2 ( $n$  9) and 14.5 ( $n$  10)); (△), hydrolysed oat gum (OG15 and OG60, 7.2 g,  $n$  11); (▲), instantized oat gum (Instagum, 36.2 g,  $n$  8); (□), guar gum (14.5 g,  $n$  9). Viscosity is apparent viscosity in mPa.s at  $30 \text{ s}^{-1}$ . Values are means with between-subject standard errors represented by vertical bars.

and logarithm of the viscosity at  $30 \text{ s}^{-1}$  (Table 4). The plots of peak plasma glucose and insulin increments against  $\log[\text{viscosity}]$  are shown in Fig. 4(a) and (b). In general, individual data points fall close (within the between-subject SE) to the regression line.

The choice of shear rate for viscosity comparisons was arbitrary since the values likely to be experienced in the gastrointestinal tract were not known. Differences between the apparent viscosities of different samples decreased at higher shear rates (Wood *et al.* 1990), and at lower shear rates apparent viscosities became less easily determined with accuracy.

## DISCUSSION

This study extends previous work (Braaten *et al.* 1991) which compared the effect of 14.5 g of oat and guar gum on the postprandial plasma glucose and insulin levels of healthy subjects consuming a 50 g glucose load in 500 ml water. The experimental design and dose of gum used by Braaten *et al.* (1991) were similar to those used by Jenkins *et al.* (1978), with minor modifications to improve palatability. However, despite the relatively pleasing, gel-pudding appearance of the test mixtures, the thick, sticky consistency of this large amount of gum rendered the mixture unpleasant to many participants.

Palatability might be improved by reducing the viscosity of the gum, either by decreasing the dose or by reducing the molecular weight, but this may reduce effectiveness. Ellis *et al.* (1988) reported an inverse relationship between postprandial insulinaemia and dose of guar gum in crispbread biscuits fed to healthy subjects, and depolymerization of guar gum abolished its ability to decrease postprandial plasma glucose levels (Jenkins *et al.* 1978). In general, a correlation between *in vitro* viscosity of gums and attenuation of plasma glucose response has been observed (Jenkins *et al.* 1978; Edwards *et al.* 1987). However, there were no differences in the postprandial plasma glucose and insulin levels of healthy subjects consuming bread containing guar gums of different molecular weights and viscosity (Ellis *et al.* 1991).

Apparently contradictory observations on the ability of gums to reduce postprandial glucose levels, and the role of viscosity, may arise from the type, quality and amount of gum used, and from experimental design. For example, the viscosity of charged polysaccharides is sensitive to pH and ionic strength (Edwards *et al.* 1987), the effect of gums in solid foods is less than in liquids (Wolever *et al.* 1979), and it is important to ensure that the viscosity enhancement occurs simultaneously with meal consumption and digestion (Ellis *et al.* 1991).

Oat  $\beta$ -glucan, like guar, is a linear, uncharged random-coil polysaccharide and the viscosity of aqueous solutions is not sensitive to pH or ionic strength. In the present study the effects of  $\beta$ -glucan, as OG, were evaluated using liquid meals, or drinks, containing gum and glucose intimately mixed.

The viscosity of the test meals was modified both by altering dose and by using acid-hydrolysed gums. Quantitative relationships were therefore best evaluated in terms of viscosity. The relationship between viscosity and plasma glucose and insulin response (Table 4, Fig. 4) accounted for 79–96% of the changes in the variables tested. This does not necessarily imply a direct causal effect, but the results are consistent with proposed mechanisms for the reduction of postprandial glucose and insulin, such as decreased diffusion rate (as estimated from the unstirred layer thickness) and/or reduced convective movement and mixing (Johnson, 1990). For random-coil polysaccharides, in which viscosity arises from coil entanglement, effective response may be obtained from higher doses of low molecular weight material, or lower doses of high molecular weight material.

The peak plasma glucose response to OG60 appeared anomalous (Fig. 4), but this was not so for the insulin response. Nevertheless, it is worth noting that hydrolysed gums, particularly OG60, are rheologically distinct from unhydrolysed gum, showing weak gel characteristics at low concentration and shear rates (Doublier & Wood, 1993).

The apparent viscosity range covered in these experiments (including data from Braaten *et al.* 1991) was from approximately 20–8000 mPa.s (at 30 s<sup>-1</sup>), with little additional effect achieved beyond 5000 mPa.s, at which point the calculated peak plasma glucose change from baseline is 1.85 mmol/l (Table 4) compared with 1.79 mmol/l at 8000 mPa.s (see also Fig. 3). Choice of viscosity level, or dose, is therefore important if differences in physiological effect of gums (e.g. between grades of guar gum) are to be detected with a

reasonable number of subjects. On this basis, 7.2 g was the level chosen to study the hydrolysed OG and Instagum; above this dose, or equivalent viscosity level, there is decreasing sensitivity of response to sample change, making detection of differences difficult. Even in the more responsive region of the curve (Fig. 3), only large viscosity differences will have an impact that is detectable with a manageably small number of subjects. For example, the regression equation indicates that to reduce the mean peak glucose increment from 2.1 to 2.0 mmol/l, a change that is less than the between-subject SE, requires doubling the viscosity from 1000 to 2000 mPa.s.

Although a threshold level is likely for a physiologically effective response, the regression suggests that even with viscosity as low as 10 mPa.s, an average 12–13% reduction in peak plasma glucose would be observed if the number of subjects was large enough. Both the highly significant linear relationship revealed by the partitioning of the treatment effect in the analysis of Expt 1 alone, and the overall regression analysis, clearly showed that 1.8 g OG is effective in reducing postprandial blood glucose and insulin levels. The equivalent amount of  $\beta$ -glucan, 1.4 g, is present in approximately 35 g commercial rolled oats, or little more than a standard serving (about 30 g). The dose–response to a solid meal might, however, differ from that to a liquid.

It should be recognized that for liquid meals the higher levels of OG that are necessary for maximum effect would have no clinical value for most subjects because regular daily consumption would not be acceptable. Although our study shows that more acceptable, lower, doses would have statistically significant effects, the physiological benefit declines as more palatable levels are reached.

OG, like most viscous polysaccharides, tends to form partly hydrated lumps when first mixed with water. This unpalatable characteristic was eliminated by using Instagum. Furthermore, the 10–15 min delay before maximum viscosity was attained allowed consumption of the gum before the viscosity reached unpalatable levels. Instagum is therefore more acceptable than unmodified gum for regular consumption in a drink, and provided a useful and simple means to deliver OG during the 3–4 weeks required for evaluation of the effect on serum cholesterol (Braaten *et al.* 1993).

A 5 h delay in hydration of guar gum resulted in decreased effectiveness (Ellis & Morris, 1991). By contrast, the delay in hydration of Instagum was brief, and the results demonstrated that the response was similar to an equivalent dose (7.2 g) of unmodified gum. For example, the reduction of peak plasma glucose from 3.2 to 2.0 mmol/l with Instagum was the same as the reduction (3.0 to 1.8 mmol/l) between the control and the 7.2 g dose of unmodified gum. All other glucose and insulin variables and insulin curves (Fig. 1e and 1f; Tables 2 and 3) similarly showed that the process of instantization did not interfere with the physiological effects of OG. Instantization is therefore a potentially useful process for improving palatability of gums without reducing effectiveness.

In conclusion, these results confirm previous observations that the ability of soluble fibre, in this case OG, to reduce postprandial glucose and insulin rise is related to viscosity of the fibre. Reduction in viscosity, either by reducing dose or molecular weight, reduces the effectiveness of OG, but the results indicate an effect, even at low doses and viscosity. Modification of the gum by an agglomeration, or instantizing, process improved dispersability and delayed development of unpalatable viscosity without reducing the effectiveness.

We thank Nicole Fillion, John Weisz and Theresa Vanasse for technical and analytical help. The clinical aspects of the study were funded by the Quaker Oats Co. Ltd, Peterborough, Ontario, Canada. This study was contribution no. 2104 of the Centre for Food and Animal Research, and no. R-148 of Research Program Service.

## REFERENCES

- Anderson, J. W., Deakins, D. A. & Bridges, S. R. (1990). Soluble fiber. Hypocholesterolemic effects and proposed mechanisms. In *Dietary Fiber. Chemistry, Physiology, and Health Effects*, pp. 339–363 [D. Kritchevsky, C. Bonfield and J. W. Anderson, editors]. Plenum Press: New York and London.
- Braaten, J. T., Wood, P. J., Scott, F. W., Lowe-Braaten, M. K., Bradley-White, P., Wolynetz, M. S., Railton, K. & Collins, M. W. (1993). Cholesterol lowering effect of oat gum in hypercholesterolemic subjects. *Federation of American Societies for Experimental Biology Journal* 7, A721.
- Braaten, J. T., Wood, P. J., Scott, F. W., Riedel, K. D., Poste, L. M. & Collins, M. W. (1991). Oat gum, a soluble fibre which lowers glucose and insulin in normal individuals after an oral glucose load: comparison with guar gum. *American Journal of Clinical Nutrition* 53, 1425–1430.
- Doublier, J.-L. & Wood, P. J. (1993). Structure and rheological properties of hydrolyzed oat gums in aqueous solution. *Cereal Foods World* 38, 623.
- Eastwood, M. A., Brydon, W. G. & Anderson, D. M. W. (1986). The effect of the polysaccharide composition and structure of dietary fibers on cecal fermentation and fecal excretion. *American Journal of Clinical Nutrition* 44, 51–55.
- Edwards, C. A., Blackburn, N. A., Craigen, L., Davison, P., Tomlin, J., Sugden, K., Johnson, I. T. & Read, N. W. (1987). Viscosity of food gums determined in vitro related to their hypoglycemic actions. *American Journal of Clinical Nutrition* 46, 72–77.
- Ellis, P. R., Dawoud, F. M. & Morris, E. R. (1991). Blood glucose, plasma insulin and sensory responses to guar-containing wheat breads: effects of molecular weight and particle size of guar gum. *British Journal of Nutrition* 66, 363–379.
- Ellis, P. R., Kamalanathan, T., Dawoud, F. M., Strange, R. N. & Coultate, T. P. (1988). Evaluation of guar biscuits for use in the management of diabetes: tests of physiological effects and palatability in non-diabetic volunteers. *European Journal of Clinical Nutrition* 42, 425–435.
- Ellis, P. R. & Morris, E. R. (1991). Importance of the rate of hydration of pharmaceutical preparations of guar gum; a new in vitro monitoring method. *Diabetic Medicine* 8, 378–381.
- Herbert, V., Lan, K. S., Gotlieb, C. W. & Bleicher, S. J. (1965). Coated charcoal immunoassay for insulin. *Journal of Clinical Endocrinology* 25, 1375–1384.
- Jenkins, D. J. A. (1980). Dietary fiber and carbohydrate metabolism. In *Medical Aspects of Dietary Fiber*, pp. 175–192 [G. A. Spiller and R. M. Kay, editors]. New York: Plenum Medical Book Company.
- Jenkins, D. J. A., Wolever, T. M. S., Leeds, A. R., Gassull, M. A., Haisman, P., Dilawari, J., Goff, D. V., Metz, G. L. & Alberti, K. G. M. M. (1978). Dietary fibres, fibre analogues, and glucose tolerance: importance of viscosity. *British Medical Journal* 1, 1392–1394.
- Jenkins, D. J. A., Wolever, T. M. S., Vuksan, V., Brighenti, F., Cunnane, S., Rao, A. V., Jenkins, A. L., Buckley, G., Patten, R., Singer, W., Corey, P. & Josse, R. G. (1989). Nibbling versus gorging: metabolic advantages of increased meal frequency. *New England Journal of Medicine* 321, 929–934.
- Johnson, I. T. (1990). The biological effects of dietary fibre in the small intestine. In *Dietary Fibre: Chemical and Biological Aspects*, pp. 151–163 [D. A. T. Southgate, K. Waldron, I. T. Johnson and G. R. Fenwick, editors]. Royal Society of Chemistry Special Publication No. 83.
- Lund, E. K., Gee, J. M., Brown, J. C., Wood, P. J. & Johnson, I. T. (1989). The effect of oat gum on the physical properties of the gastrointestinal contents and on the uptake of D-galactose and cholesterol by rat small intestine in vitro. *British Journal of Nutrition* 62, 91–101.
- Roehrig, K. L. (1988). The physiological effects of dietary fiber – a review. *Food Hydrocolloids* 2, 1–18.
- Sander, E. H. & Cook, D. R. (1985). Product and process for improving the dispersion of a vegetable gum in water. *U.S. Patent 455938*.
- Shinnick, F. L., Mathews, R. & Ink, S. (1991). Serum cholesterol reduction by oats and other fiber sources. *Cereal Foods World* 36, 815–821.
- Wolever, T. M. S., Jenkins, D. J. A., Jenkins, A. L. & Josse, R. G. (1991). The glycemic index. Methodology and clinical implications. *American Journal of Clinical Nutrition* 54, 846–854.
- Wolever, T. M. S., Jenkins, D. J. A., Nineham, R. & Alberti, K. G. M. M. (1979). Guar gum and reduction of post-prandial glycaemia: effect of incorporation into solid food, liquid food, and both. *British Journal of Nutrition* 41, 505–510.
- Wood, P. J. (1986). Oat  $\beta$ -glucan: structure, location and properties. In *Oats: Chemistry and Technology*, pp. 121–152 [F. H. Webster, editor]. St Paul: American Association of Cereal Chemists.
- Wood, P. J., Braaten, J. T., Scott, F. W., Riedel, D. K. & Poste, L. M. (1990). Comparison of viscous properties of oat and guar gum and the effects of these and oat bran on glycemic index. *Journal of Agricultural and Food Chemistry* 38, 753–757.
- Wood, P. J., Weisz, J. & Blackwell, B. A. (1991). Molecular characterization of cereal  $\beta$ -D-glucans. Structural analysis of oat  $\beta$ -D-glucan and rapid structural evaluation of  $\beta$ -D-glucans from different sources by high-performance liquid chromatography of oligosaccharides released by lichenase. *Cereal Chemistry* 68, 31–39.
- Wood, P. J., Weisz, J., Fedec, P. & Burrows, V. D. (1989). Large-scale preparation and properties of oat fractions enriched in (1  $\rightarrow$  3)(1  $\rightarrow$  4)- $\beta$ -D-glucan. *Cereal Chemistry* 66, 97–103.

Printed in Great Britain