Dietary Fibers Affect Viscosity of Solutions and Simulated Human Gastric and Small Intestinal Digesta

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ABSTRACT Two experiments were conducted to determine the viscosities of both soluble and insoluble dietary fibers. In Expt. 1, corn bran, defatted rice bran, guar gum, gum xanthan, oat bran, psyllium, soy hulls, stabilized rice bran, wheat bran, wood cellulose, and 2 methylcellulose controls (Ticacel 42®, Ticacel 43®) were hydrated in water overnight at 0.5, 1, 1.5, or 2% concentrations. In Expt. 2, guar gum, oat bran, psyllium, rice bran, wheat bran, and wood cellulose were subjected to a 2-stage in vitro gastric and small intestinal digestion simulation model. Viscosity was measured every 2 and 3 h during gastric and small intestinal simulation, respectively. Viscosities in both experiments were measured at multiple shear rates. Viscosities of all fiber solutions were concentration- and shear rate–dependent. Rice brans, soy hulls, and wood cellulose had the lowest viscosities, whereas guar gum, psyllium, and xanthan gum had the highest viscosities, regardless of concentration. During gastric simulation, viscosity was higher ($P < 0.05$) at 4 h than at 0 h for guar gum, psyllium, rice bran, and wheat bran. During small intestinal simulation, viscosities were higher ($P < 0.05$) between 3 and 9 h compared with 18 h for guar gum, oat bran, and rice bran. Guar gum, psyllium, and oat bran exhibited viscous characteristics throughout small intestinal simulation, indicating potential for these fibers to elicit blood glucose and lipid attenuation. Wheat and rice brans and wood cellulose did not exhibit viscous characteristics throughout small intestinal digestion; thus, they may be beneficial for laxation. J. Nutr. 136: 913–919, 2006.

KEY WORDS: • *viscosity* • *dietary fiber* • *gastric* • *small intestine* • *digesta*

Dietary fibers possess unique chemical and physical characteristics responsible for eliciting an array of physiological responses. Currently, 2 general classifications of fiber exist, soluble (e.g., gums, pectins) and insoluble (e.g., cellulose, wheat bran, soy hulls) (1). One physicochemical property of fiber, viscosity, is recognized as affecting physiological responses (2). Viscous dietary fibers thicken when mixed with fluids; they include polysaccharides such as gums, pectins, and β-glucans. The degree of thickening when exposed to fluids depends on the chemical composition and concentration of the polysaccharide (2). Viscous fibers have been associated with alterations in blood glucose and cholesterol concentrations, prolonged gastric emptying, and slower transit time through the small intestine (3).

Because of the large variation in physical, chemical, and physiological characteristics of fiber sources, it was suggested that viscosity could serve as an alternative way of classifying soluble fiber (4). Although research has been conducted to address the effects of viscous fibers on physiological responses, few data exist on viscous characteristics of individual fiber sources in relation to one another. For viscosity to serve as a proxy for soluble fiber, it is essential to have an understanding of individual fiber viscosity characteristics.

The objectives of this study were to quantify the viscosities of select dietary fibers (soluble and insoluble) at various concentrations in solution and to determine the effects of altering shear rate on the viscosity of these solutions. A second objective was to determine the effects of fiber source, incubation time, and shear rate on the viscosity of solutions in a two-stage in vitro digestion simulation model.

MATERIALS AND METHODS

Substrates. Twelve fibrous substrates, including corn bran (ADM), defatted rice bran (Riceland Foods), guar gum, gum xanthan (Sigma Chemical), oat bran (IGA), psyllium (Eastern Products), soy hulls (ADM), stabilized rice bran (FoodEx), wheat bran (IGA), wood cellulose (SolkaFloc®; International Fiber), and methylcellulose controls (Ticacel 42 and Ticacel 43; Tic Gums) were tested. Guar gum, gum xanthan, and the methylcellulose controls were already in powdered form; other substrates were ground through a 1-mm screen in a Wiley mill (model 4, Thomas Scientific). Substrates were hydrated in distilled, deionized water for 15 to 18 h before viscosity measurements at concentrations of 0.5, 1, 1.5, and 2% (wt/wt basis).

Experiment 1. All fibrous substrates were analyzed for dry matter (DM),[2] organic matter (OM), and crude protein (CP) (5). Total

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[2] Abbreviations used: AUC, area under the curve; CP, crude protein; DM, dry matter; IDF, insoluble dietary fiber; NSP, nonstarch polysaccharide; OM, organic matter; SDF, soluble dietary fiber; TDF, total dietary fiber.

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dietary fiber (TDF) and insoluble dietary fiber (IDF) were analyzed according to AOAC methodology (5). Soluble dietary fiber (SDF) was calculated as TDF minus IDF (1,6). All chemical analyses were conducted in duplicate, and values were required to be within 5% of each other; otherwise, the analysis was repeated.

The viscosity of solutions was measured at room temperature (23°C). Before measurement, samples were gently mixed for 30 s before removal of a 2-mL aliquot. Viscosity was measured using a Brookfield digital viscometer (LV-DV-II+) with a Wells/Brookfield cone and plate extension. Solutions containing corn bran, both methylcelluloses, oat bran, both rice brans, soy hulls, wheat bran, and wood cellulose were assayed using a CP-41 cone and plate. A Brookfield LV spindle set (LV-2; LV-3) was used for gel-forming substrates (psyllium, guar gum, and xanthan gum). In this case, solutions were placed in 100-mL glass beakers with a 5-cm diameter. Two viscometer geometries were utilized due to differences in solution consistency. Solutions containing soluble gel-forming substrates were too viscous to pipette and utilize the cone and plate extension. Because these substrates were soluble and dissolved into a gel, cylindrical spindles could be immersed into the gels. On the other hand, insoluble fibers fall out of solution, making measurement with spindles difficult and reducing the accuracy of the viscosity measurement. Although 2 viscometer geometries were used, both were assayed using the same rotational viscometer, calibrated for both geometries. The cone and plate geometry assays a viscosity range of 0.6 to 11,000 cP, whereas spindle geometry assays viscosity ranging from 50 to 400,000 cP. Because the solutions were expected to be non-Newtonian and demonstrate shear-thinning behavior, each solution was assayed across a range of shear rates to obtain a minimum of 3 viscosity values for each solution. Viscosity values were assayed in triplicate.

Experiment 2. For the in vitro digestion simulation, cellulose, guar gum, oat bran, psyllium, rice bran, and wheat bran were used. Substrates were weighed (0.5 g) in duplicate in 50-mL plastic centrifuge tubes. Gastric simulation began with the addition of 5 mL of 0.2 mol/L HCl, 0.5 mL of 10% pepsin:HCl (wt:v), and 12.5 mL of 0.1 mol/L phosphate buffer (pH 6). Solutions were adjusted to pH 2 with 0.2 mol/L HCl or 0.6 mol/L NaOH. The tubes were closed with stoppers and incubated for 6 h at 39°C (7,8). One set of substrates was removed from incubation and frozen at −20°C at 0, 2, 4, and 6 h. After the initial 6 h of incubation, small intestinal simulation began in the remaining tubes with the addition of 2.5 mL of 0.6 mol/L NaOH, 5 mL of 0.2 mol/L phosphate buffer (pH 6.8), and 0.5 mL of 5% pancreatin solution (wt:v), with adjustment to pH 6.8 with HCl or NaOH (7,8). Tubes were incubated at 39°C for an additional 18 h. Substrates were removed from incubation and frozen at −20°C at 0, 3, 6, 9, 12, 15, and 18 h from initiation of small intestinal digestion simulation.

During the in vitro digestion simulation, the viscosities of all solutions were measured as in Expt. 1, with the CP-41 geometry, and across speeds of 0.3, 0.6, 1, 1.5, 2, and 3 rpm (shear rates = 0.6, 1, 2, 3, 4, and 6 s^{-1}). Viscosity values across all time points were assayed in triplicate.

Statistical analysis. Viscosity data were analyzed using GraphPad® software (San Diego, CA) and NLREG® software. Area under the curve (AUC) values were calculated using GraphPad software. NLREG was used to develop a working model of the viscosity flow curve data. Pseudoplastic fluids can be adequately represented by the power law equation ($y = a \cdot x^b$) and termed power law fluids (9–12). In the equation, shear stress (y) is a function of the consistency index or constant (a), shear rate (x), and a dimensionless exponent (*b*) that indicates closeness to Newtonian flow. The exponent will equal 1 for Newtonian fluids and will be <1 for shear-thinning fluids. The constant is a parameter proportional to the viscosity of power law fluids and is represented in units of centipoise (cP). Model development allowed for the estimation of the constant and exponent parameters in the above equation.

In vitro data (Expt. 2) did not meet the criteria of normality tested by the univariate procedure of SAS® (SAS Institute); therefore, data were log-transformed before statistical analysis. Data were analyzed using the Mixed models procedure of SAS. The experimental design was a factorial randomized complete block design with fiber substrate serving as block. The statistical model included the fixed effect of substrate and the random effect of replicate. Treatment least-squares means were compared using the Bonferroni method to control for the probability of any type I error. A probability of $P < 0.05$ was accepted as significant.

RESULTS

Chemical analyses. Cellulose contained the highest concentrations of DM, OM, TDF, and IDF (**Table 1**). The 4 brans contained the highest concentrations of CP. Total dietary fiber concentrations ranged from 19.5 (oat bran) to 99.1% (cellulose).

Solution viscosity. All substrates in Expt. 1 exhibited shear-thinning behavior (decreasing viscosity with increasing rpm). Nonlinear regression analysis was utilized to characterize the flow properties of each viscosity curve by calculating exponents based on the power law equation. If the model was not significant, the slope of the line would be 1, indicating a solution that did not exhibit shear-thinning behavior or dependence on shear rate. With the exception of the guar gum solution at 1% concentration, all solutions had negative exponents ranging from −0.26 to −1.69, indicating dependence of viscosity on shear rate. Larger negative exponents indicate more dependence on shear rate. The nonlinear regression model fit the data exceptionally well, indicated by R^2 values ranging from 0.85 to 0.99 (**Table 2**).

Overall, solutions containing guar gum, gum xanthan, psyllium, and Ticacel-43 had the highest nonlinear regression constants (Table 2) and AUC values (**Table 3**). Solutions containing cellulose, corn bran, both rice brans, soy hulls, Ticacel-42, and wheat bran all had low viscosity values.

Regardless of the dietary fiber tested, viscosity increased as its concentration in water increased from 0.5 to 2% (Tables 2 and 3). There was a positive, nonlinear relation with the concentration of the fiber in solution and nonlinear regression viscosity constants (Table 2). According to the AUC values (Table 3), the viscosity at 1% concentration was 8.5-fold that of solutions containing gum xanthan at 0.5% concentration. Solutions containing guar gum had lower viscosity AUC values than xanthan gum at 0.5%; however, at 2%, guar gum solutions were ~14% more viscous than the gum xanthan solution. Viscosity AUC values at 2% concentration for psyllium were 60-fold that of the 0.5% concentration, with the greatest increase occurring between 1 and 1.5%.

Solutions containing corn bran were 2-fold greater at 1% concentrations compared with 0.5%; however, there was little change in viscosity AUC among 1, 1.5, and 2% for corn bran

TABLE 1

Chemical analyses of select fibrous substrates[1]

Substrate	DM	OM	CP	TDF	IDF	SDF
	g/100 g dry matter					
Cellulose (Solka floc)	95.4	99.8	0	99.1	98.0	1.1
Corn bran	92.3	99.2	9.1	73.2	70.6	2.6
Defatted rice bran	91.8	87.3	20.2	28.8	26.2	2.2
Guar gum	90.6	99.1	4.3	82.3	14.8	67.5
Gum xanthan	90.3	99.0	1.2	80.4	26.0	54.4
Methylcellulose (Ticacell-42)	95.0	99.4	0	93.0	0.5	92.5
Methylcellulose (Ticacell-43)	94.7	99.6	0	92.0	0	92.0
Oat bran	92.5	97.1	16.7	19.5	10.4	9.1
Psyllium	92.6	97.2	2.5	90.0	82.6	7.4
Soy hulls	92.0	94.7	12.9	79.5	68.6	10.9
Stabilized rice bran	92.1	91.5	15.6	21.4	18.9	2.5
Wheat bran	91.0	93.6	17.0	49.7	46.3	3.4

[1] Values are single measures.

TABLE 2

Nonlinear regression viscosity parameters for dietary fibers at 4 concentrations in water[1–3]

Substrate, *g/100 g*	0.5	1	1.5	2
Cellulose (Solka floc)				
Constant, *cP*	14	29	45	593
Exponent	−0.56	−0.95	−0.84	−0.92
R^2	0.89	0.99	0.99	0.99
Corn bran				
Constant, *cP*	111	233	239	380
Exponent	−1.10	−0.60	−0.96	−1.06
R^2	0.99	0.93	0.99	0.99
Defatted rice bran				
Constant, *cP*	4	23	33	336
Exponent	−0.84	−1.09	−1.14	−1.33
R^2	0.91	0.99	0.99	0.97
Guar gum				
Constant, *cP*	285	24,572	40,979	101,735
Exponent	−1.69	1	−0.23	−0.61
R^2	0.99	NS	0.97	0.88
Gum xanthan				
Constant, *cP*	2,875	48,175	60,110	85,745
Exponent	−0.63	−1.09	−0.76	−0.67
R^2	0.94	0.97	0.99	0.99
Methylcellulose (Ticacel-42)				
Constant, *cP*	78	102	136	407
Exponent	−0.38	−0.76	−0.65	−0.51
R^2	0.85	0.95	0.94	0.87
Methylcellulose (Ticacel-43)				
Constant, *cP*	78	148	2,002	16,245
Exponent	−1.21	−1.43	−0.33	−0.26
R^2	0.95	0.98	0.95	0.99
Oat bran				
Constant, *cP*	100	250	596	598
Exponent	−0.68	−0.93	−1.09	−1.06
R^2	0.99	0.99	0.99	0.99
Psyllium				
Constant, *cP*	501	519	11,173	15,340
Exponent	−1.10	−0.58	−1.28	−0.69
R^2	0.96	0.83	0.98	0.97
Soy hulls				
Constant, *cP*	1	54	25	430
Exponent	1	−1.13	−1.10	−1.07
R^2	NS	0.99	0.92	0.99
Stabilized rice bran				
Constant, *cP*	7	9	49	46
Exponent	−0.89	−1.71	−0.76	−1.08
R^2	0.88	0.99	0.96	0.99
Wheat bran				
Constant, *cP*	4	159	247	240
Exponent	−0.84	−0.74	−1.14	−0.75
R^2	0.91	0.96	0.99	0.99

[1] Values are single measures.

[2] Nonlinear viscosity parameters are based on the power law equation ($y = a \cdot x^b$) where y is shear stress, a is the viscosity constant, x is the shear rate, and b is a dimensionless exponent indicating deviation from Newtonian flow (exponent < 1 for pseudoplastic fluids); exponents were given as 1 if the nonlinear regression was not significant (NS; $P > 0.05$); R^2 = the proportion of variation explained by the nonlinear regression model.

[3] Constant mean estimates were used in the case of nonsignificant nonlinear regression analysis.

TABLE 3

Viscosity AUC for dietary fibers at 4 concentrations in water[1]

Substrate, *g/100 g*	0.5	1	1.5	2
		cP·rpm		
Cellulose (Solka floc)	6	64	96	1,112
Corn bran	178	542	529	757
Defatted rice bran	6	51	69	804
Guar gum	962	42,918	77,366	141,606
Gum xanthan	6,122	51,845	101,667	124,553
Methylcellulose (Ticacel-42)	169	181	246	1006
Methylcellulose (Ticacel-43)	203	225	3,633	117,103
Oat bran	183	546	1,347	1,358
Psyllium	808	1,078	17,036	48,800
Soy hulls	6	121	41	979
Stabilized rice bran	12	27	103	102
Wheat bran	6	383	574	508

[1] Values are single measures.

solutions. Viscosity AUC for solutions containing wheat bran at 1% concentration were 63-fold that of 0.5% concentrations. Similar to the pattern noted for corn bran, viscosity AUC for solutions containing oat bran at 1% were 3-fold that of solutions at 0.5% concentration. However, similar to the pattern noted for wheat bran, the viscosity of oat bran solutions did not differ at 1.5 and 2%. Viscosity AUC for solutions containing stabilized rice bran at 2% were ~8.5-fold that at 0.5%. Solutions containing defatted rice bran at 2% were 134-fold that of the 0.5% concentrations. Similar increases in viscosity AUC between 0.5 and 2% concentrations were evident with soy hulls and cellulose solutions.

Viscosity of simulated gastric digesta. Overall, during gastric digestion simulation, all substrates differed from one another ($P < 0.05$), with the exception of cellulose and wheat bran, which had similar values for NLREG ($P = 0.74$) and AUC ($P = 0.60$) (**Tables 4** and **5**). Nonlinear regression indicated that at all 4 time points, viscosity was dependent on shear rate, indicated by negative exponent values. Nonsignificant model fit occurred for solutions containing rice bran at 0 and 6 h (Table 4).

At the initiation of gastric digestion simulation (0 h), wheat bran had the lowest viscosity (Tables 4 and 5). After 2 h of gastric simulation, viscosity AUC increased to a high of 1147 cP·rpm ($P < 0.05$) compared with 0 h (Table 5). Nonlinear regression analysis indicated similar statistical differences in AUC for solutions containing wheat bran.

According to nonlinear regression, viscosity constants for solutions containing psyllium were lower at 0 h ($P < 0.05$) than at the other 3 time points (Table 4). The only difference ($P < 0.05$) was detected between 0 and 6 h of gastric simulation for AUC values of solutions containing psyllium (Table 5).

Statistics conducted on nonlinear regression viscosity constants for solutions containing cellulose indicated a lower ($P < 0.05$) constant at 6 than at 4 h (Table 4). The AUC did not differ at any time point during gastric digestion simulation for solutions containing cellulose (Table 5).

Similar to wheat bran, statistical differences were detected with nonlinear regression analysis for solutions containing rice bran (Table 4). At 0 and 6 h, nonlinear regression analysis indicated a nonsignificant model fit; therefore, exponent values were 1. Viscosity AUC increased ($P < 0.05$) after 2 and 4 h of gastric simulation, respectively. Upon completion of gastric simulation (6 h), the viscosity AUC for rice bran solutions fell drastically ($P < 0.05$) compared with all other time points (Table 5).

Guar gum solutions had the highest overall nonlinear regression viscosity constant and AUC values, regardless of time point. Analysis of nonlinear regression data detected an increase ($P < 0.05$) in viscosity between 2 and 4 h of simulation (Table 4). As gastric simulation continued, viscosity AUC for guar gum solutions continued to increase ($P < 0.05$) at 4 and 6 h, respectively.

Viscosity of simulated small intestinal digesta. Overall, during small intestinal digestion simulation, all substrates were

TABLE 4

Nonlinear regression viscosity parameters for solutions containing select dietary fibers during gastric digestion simulation[1–3]

Substrate	Time, *h* 0	2	4	6
Cellulose (Solka floc)				
Constant, *cP*	121[ab]	117[ab]	215[a]	86[b]
Exponent	−0.99	−1.08	−1.04	−1.13
R^2	0.99	0.70	0.99	0.98
Guar gum				
Constant, *cP*	100,927[c]	149,782[bc]	361,217[a]	292,638[ab]
Exponent	−0.60	−0.50	−0.48	−0.43
R^2	0.57	0.90	0.71	0.83
Oat bran				
Constant, *cP*	232	443	306	319
Exponent	−1.19	−1.15	−1.19	−1.40
R^2	0.97	0.99	0.97	0.93
Psyllium				
Constant, *cP*	2,779[b]	6,723[a]	6,635[a]	8,198[a]
Exponent	−0.28	−0.70	−0.81	−0.88
R^2	0.56	0.96	0.96	0.96
Rice bran				
Constant, *cP*	25[b]	158[a]	236[a]	3[c]
Exponent	1	−1.30	−1.03	1
R^2	NS	0.97	0.88	NS
Wheat bran				
Constant, *cP*	6[b]	473[a]	268[a]	274[a]
Exponent	−0.92	−1.03	−0.96	−0.98
R^2	0.85	0.97	0.97	0.73

[1] For all times pooled (0, 2, 4, 6 h), least-squares means ($n = 4$) for NLREG viscosity constants for cellulose and wheat bran did not differ ($P = 0.74$). All other fiber solution viscosity constants differed ($P < 0.05$; all times pooled SEM = 0.0905; log transformed data). Least-squares means (6 fibers, 4 time points; $n = 24$) in a row that do not have common superscript letters differ ($P < 0.05$; pooled SEM = 0.1809; log-transformed data).

[2] Nonlinear viscosity parameters are based on the power law equation ($y = a \cdot x^b$) where y is shear stress, a is the viscosity constant, x is the shear rate, and b is a dimensionless exponent indicating deviation from Newtonian flow (exponent < 1 for pseudoplastic fluids); exponents were given as 1 if nonlinear regression was not significant (NS; $P > 0.05$); R^2 = the proportion of variation explained by the nonlinear regression model.

[3] Constant mean estimates were used in the case of nonsignificant nonlinear regression analysis.

TABLE 5

Viscosity AUC values for solutions containing select dietary fibers during gastric digestion simulation[1]

Substrate	Time, *h* 0	2	4	6
	cP·rpm			
Cellulose (Solka floc)	291	285	313	222
Guar gum	241,886[b]	359,576[ab]	870,266[a]	711,193[a]
Oat bran	588	1,092	739	865
Psyllium	6,479[b]	16,219[ab]	16,150[ab]	19,939[a]
Rice bran	63[b]	415[a]	538[a]	7[c]
Wheat bran	12[b]	1,147[a]	642[a]	658[a]

[1] For all times pooled (0, 2, 4, 6 h), least-squares means ($n = 4$) for AUC viscosity values for cellulose and wheat bran did not differ ($P = 0.60$). All other fiber solution viscosity AUC values differed ($P < 0.05$; all times pooled SEM = 0.0950; log transformed data). Least-squares means (6 fibers, 4 time points; n = 24) in a row that do not have common superscript letters differ ($P < 0.05$; pooled SEM = 0.1901; log-transformed data).

different from one another ($P < 0.05$), with the exception of cellulose and wheat bran where values were similar for NLREG ($P = 0.27$) and AUC ($P = 0.87$) (**Table 6** and **7**).

The viscosity of solutions containing oat bran peaked at 15 h and was higher ($P < 0.05$) compared with the 0-, 12-, and 18-h values when nonlinear regression viscosity constants were analyzed (Table 6). In addition, the viscosity AUC was higher ($P < 0.05$) at 3 h than at 0, 12, and 18 h (Table 7).

During small intestinal digestion simulation, the viscosity AUC at 9 h was 2.8-fold that of 0 h ($P < 0.05$) for solutions containing wheat bran (Table 7). A 52% reduction in viscosity AUC occurred between 9 and 12 h; however, this reduction was not significant ($P = 0.17$). On the other hand, the reduction was detected ($P < 0.05$) when nonlinear regression constants were analyzed (Table 6).

A single difference was detected between 3 and 6 h ($P < 0.05$) when small intestinal simulation viscosity AUC values were analyzed for solutions containing psyllium (Table 7).

Cellulose did not affect viscosity of simulated small intestinal solutions at any time point using either method of analysis.

Nonlinear regression detected a nonsignificant model fit for solutions containing rice bran at 9, 15, and 18 h (Table 6). Viscosity AUC fell ($P < 0.05$) 69, 71, and 82% at 3, 6, and 9 h, respectively, compared with 0 h (Table 7). During the final hours of simulation (15 and 18 h), viscosity AUC was lower ($P < 0.05$) than at other time points.

During small intestinal digestion simulation of solutions containing guar gum, both nonlinear regression and AUC data analysis detected similar differences. Compared with the 9-h peak, viscosity AUC for guar gum solutions was lowest ($P < 0.05$) at the conclusion of small intestinal digestion.

With the exception of wheat bran, all fiber substrates had lower viscosity values (nonlinear regression constants and AUC) at the conclusion of small intestinal digestion than at the initiation of digestion. The largest reduction in viscosity AUC (83%) occurred with solutions containing rice bran. Solutions containing guar gum, oat bran, cellulose, and psyllium were reduced 36, 22, 16, and 15%, respectively, between the initiation and conclusion of digestion.

DISCUSSION

Shear rates in the gastrointestinal tract have not been determined adequately, and they are thought to vary considerably with location and motility within the gastrointestinal tract; therefore, a presentation of viscosity characteristics becomes a difficult task. In the current study, 2 techniques, AUC and nonlinear regression analysis, were utilized to describe and account for the broad viscosity profiles across a range of shear rates for individual solutions to provide more robust explanations of viscosity data.

Pseudoplastic fluids can be described using the power law equation to calculate a consistency index or constant that is proportional to viscosity. Nonlinear regression analysis indicated that all solutions evaluated were non-Newtonian and exhibited shear-thinning behavior as indicated by the negative exponents. This dependency on shear rate was expected and is typical of non-Newtonian fluids exhibiting shear-thinning

TABLE 6

Nonlinear regression viscosity parameters for solutions containing select dietary fibers during small intestinal digestion simulation[1–3]

	Time, *h*						
Substrate	0	3	6	9	12	15	18
Cellulose (Solka floc)							
Constant, *cP*	86	112	65	52	45	184	54
Exponent	−0.78	−0.87	−0.99	−1.23	−0.89	−0.75	1
R^2	0.79	0.66	0.93	0.75	0.76	0.97	NS
Guar gum							
Constant, *cP*	16,820^{ab}	19,148^{ab}	12,907^{ab}	32,006^{a}	14,608^{ab}	14,652^{ab}	10,848^{b}
Exponent	1	−0.38	−0.26	−0.27	−0.37	−0.21	−0.83
R^2	NS	0.87	0.38	0.31	0.96	0.50	0.80
Oat bran							
Constant, *cP*	124^{bc}	325^{a}	257^{abc}	247^{abc}	145^{bc}	291^{ab}	107^{c}
Exponent	−1.12	−1.26	−0.93	−0.89	−0.89	−1.01	−0.73
R^2	0.78	0.78	0.86	0.99	0.98	0.98	0.75
Psyllium							
Constant, *cP*	2,758	3,000	1,502	1,976	3,421	1,969	2,228
Exponent	−1.23	−1.50	−0.78	−0.66	−1.20	−1.04	−1.15
R^2	0.99	0.90	0.98	0.77	0.99	0.93	0.94
Rice bran							
Constant, *cP*	127^{a}	43^{b}	40^{b}	23^{b}	155^{a}	2^{d}	7^{c}
Exponent	−1.27	−0.77	−0.83	1	−0.96	1	1
R^2	0.92	0.48	0.81	NS	0.43	NS	NS
Wheat bran							
Constant, *cP*	55^{b}	53^{b}	55^{b}	176^{a}	84^{b}	167^{a}	103^{ab}
Exponent	−1.19	−0.82	−0.79	−0.87	−0.93	−1.15	−0.92
R^2	0.89	0.79	0.87	0.95	0.72	0.94	0.97

[1] For all times pooled (0, 3, 6, 9, 12, 15, 18 h), least-squares means ($n = 7$) for NLREG viscosity constants for cellulose and wheat bran did not differ ($P = 0.27$). All other fiber solution viscosity constants differed ($P < 0.05$; all times pooled SEM = 0.0751; log transformed data). Least-squares means (6 fibers, 7 time points; $n = 42$) in the same row that do not have common superscript letters differ ($P < 0.05$; pooled SEM = 0.3675; log-transformed data).

[2] Nonlinear viscosity parameters are based on the power law equation ($y = a \cdot x^b$) where y is shear stress, a is the viscosity constant, x is shear rate, and b is a dimensionless exponent indicating deviation from Newtonian flow (exponent < 1 for pseudoplastic fluids); exponents were given as 1 if nonlinear regression was not significant (NS; $P > 0.05$); R^2 = the proportion of variation explained by the nonlinear regression model.

[3] Constant mean estimates were used in the case of nonsignificant nonlinear regression analysis.

(pseudoplastic) behavior, or a reduction in viscosity with increasing shear rate (or) rpm (10–12).

Calculation of AUC and nonlinear regression analysis allowed not only for the interpretation of entire flow profiles or flow curve characteristics of the solutions but also for simplified single-number presentations of data and statistical comparisons of data using both methods. Although both methods tended to detect similar statistical differences, nonlinear regression analysis was slightly more sensitive. In addition, AUC accounts only for the area below the established curve, whereas nonlinear regression analysis provides information about the characteristics of the curve itself based on the exponent values calculated. As the exponent value approaches 1, the solutions become less dependent on shear rate and exhibit a more

TABLE 7

Viscosity AUC of solutions containing select dietary fibers during small intestinal digestion simulation[1]

	Time, *h*						
Substrate	0	3	6	9	12	15	18
	cP·rpm						
Cellulose (Solka floc)	202	275	161	137	113	245	170
Guar gum	42,266^{ab}	46,863^{ab}	32,490^{ab}	80,204^{a}	35,916^{ab}	37,266^{ab}	26,928^{b}
Oat bran	326^{b}	858^{a}	610^{ab}	586^{ab}	338^{b}	693^{a}	255^{b}
Psyllium	7,033^{ab}	8,795^{a}	3,606^{b}	4,754^{ab}	8,655^{a}	4,966^{ab}	5,984^{ab}
Rice bran	328^{a}	101^{b}	95^{b}	60^{b}	372^{a}	13^{d}	54^{c}
Wheat bran	151^{b}	128^{b}	131^{b}	418^{a}	202^{ab}	413^{a}	246^{ab}

[1] For all times pooled (0, 3, 6, 9, 12, 15, 18 h), least squares means ($n = 7$) for AUC viscosity values for cellulose and wheat bran did not differ ($P = 0.87$). All other fiber solution viscosity values were different ($P < 0.05$) (all times pooled SEM = 0.0742; log transformed data). Least-squares means (6 fibers, 7 time points; $n = 42$) in a row that do not have common superscript letters differ ($P < 0.05$; pooled SEM = 0.1962; log-transformed data).

Newtonian characteristic. The larger negative numbers indicate a significant dependence on shear rate, as noted for the majority of solutions in the current study.

At a constant temperature, there is typically a nonlinear increase in viscosity as the concentration of polysaccharide in solution increases; therefore, it was expected that viscosity of all substrate solutions would increase with increasing concentration. Ellis et al. (13) fed growing pigs semipurified diets containing 0, 20, or 40 g guar gum/kg diet and observed an increase in jejunal digesta viscosity, strongly dependent on guar gum concentration in the diet. Compared with controls, the pigs fed 20 and 40 g guar gum/kg diet had 28- and 93-fold increases ($P < 0.05$), respectively, in viscosity of digesta 60 min after feeding. In addition, Danielson et al. (14) fed rats barley milled fraction shorts (barley tempered to 10% moisture for 12 h followed by milling in an 8-roller dry mill) containing 8.4% β-glucan at concentrations of 0 (control), 30, 60, or 90% of the diet for 21 d. Digesta viscosity increased ($P < 0.05$) from 0.2 (control) to 1.9 cP (90% shorts), and was associated with a reduction ($P < 0.05$) in liver cholesterol (from 12.4 to 3.8 mol/g for control and 90% shorts treatments, respectively). The viscosity of polysaccharides in aqueous solutions will develop as a result of interpenetration of individual chains or coils to form entangled networks. The extent of entanglement and resultant viscosity is determined by the concentration of polysaccharide in solution or the number of chains or coils present (15).

The largest increase in viscosity AUC occurred with Ticacel-43, a high-molecular-weight methylcellulose containing a very high concentration of SDF (92%). It was expected that this substrate would hydrate rapidly and form a gel. Although Ticacel-42 also contained high concentrations of SDF (92.5%), a lower viscosity was attained in a 2% solution. These 2 substrates are low-viscosity (Ticacel-42) and high-viscosity (Ticacel-43) methylcelluloses used as additives in food preparations to control viscosity of products during processing stages. Molecular weight differences likely contributed to the variation in viscosity AUC between Ticacel-42 and Ticacel-43.

An increase in the consumption of dietary fiber will likely contribute to an increase in the viscosity of gastrointestinal contents. Although substrates containing high concentrations of SDF (methylcellulose, guar gum, and gum xanthan) resulted in very high viscosities, other fibers such as psyllium, oat bran, and soy hulls also were effective in achieving higher viscosity values in 2% solutions. It is unclear, however, whether physiological responses such as reduced blood glucose and blood lipids associated with ingestion of viscous fibers are dependent on dietary concentration of viscous fiber.

The initial increase in viscosity during simulated gastric digestion may have been a response to hydration of the fibrous substrates and their interaction with the acidic medium that could release bound nonstarch polysaccharides (NSP). The reductions in simulated gastric viscosity may have resulted from the breakdown of polysaccharide structure with prolonged exposure to acidic conditions. Nonstarch polysaccharide fractions of fiber sources may be released and broken down upon acidification. There may be an optimal pH, dependent on the chemical composition of the fiber source, at which NSP are released, resulting in increased viscosity. Beyond that pH, viscosity may be lost due to the breakdown of NSP (16). The reduction in viscosity was not expected for solutions containing guar gum. Guar gum is a neutral β 1–4 linked linear polymer of mannose with single D-galactopyranosyl units attached to alternate D-mannopyranosyl units by α 1–6 linkages. This chemical composition is responsible for the neutral characteristic of guar gum and its lack of interaction with the acidic medium (17).

During simulated small intestinal digestion, viscosity increased and peaked between 3 and 12 h, and then dropped by 18 h. During simulated small intestinal digestion, substrates were exposed to solutions that digest proteins and digestible carbohydrates, including starch. The interaction with digestive solutions likely would contribute to structural interactions with fluid that would result in increased viscosity as noted during the early and middle stages of digestion. As digestion proceeded, polysaccharide structural interactions may have been modified, resulting in lower viscosity values observed at the end of simulated small intestinal digestion.

It was expected that fibrous substrates containing high concentrations of IDF would exhibit the lowest viscosity values during simulated gastric and small intestinal digestion and would not affect viscosity over time. Insoluble dietary fibers typically have lower water-holding capacity than SDF; however, many fibers such as wheat bran contain water-soluble arabinoxylans that contribute to water-holding capacity and increased viscosity in solutions (18). Maziya-Dixon and Klopfenstein (19) measured the viscosity of diet slurries containing oat bran, wheat brans (2), wheat flours (4), and cellulose. Diet slurry viscosity was highest for oat bran (240 cP) followed by the 2 wheat brans (120 cP) and wheat flours (70–100 cP). Diet slurries containing cellulose had the lowest viscosity (60 cP). In the current study, oat bran also resulted in higher solution viscosity compared with wheat bran or cellulose. Oat bran has been studied extensively because of its effects on physiological responses such as the attenuation of blood glucose. The major component that contributes to the viscosity characteristics of oat bran solutions is the concentration of β-glucan. This highly viscous polysaccharide is present in rolled oats but reaches a concentration of ~15% in oat bran (20).

Although psyllium contains a very high concentration of IDF (82.6%), viscosity values for gastric and small intestinal solutions were very high during digestion simulations. Even with a high concentration of IDF present, psyllium has an extraordinary gel-forming characteristic that results in a very viscous solution upon hydration. Psyllium has been studied extensively for its physiological responses such as blood lipid profile attenuation and laxation. Three fiber fractions are associated with the unique properties of psyllium. According to Marlett and Fischer (21), fraction A is alkali insoluble and not fermented by microbiota in the colon, whereas fraction B, constituting ~55% of the psyllium, is poorly fermented and is associated with increased stool moisture and fecal bile acid excretion. Fraction C is highly viscous and rapidly fermented by colonic microbiota. The gel-forming polysaccharide in psyllium is a highly branched arabinoxylan consisting of a xylose backbone and arabinose- and xylose-containing side chains. The arabinoxylans in psyllium are not fermented as they are in many cereal grains (21).

Viscosity values for solutions containing guar gum were very high during gastric digestion simulation. Guar gum is a very soluble galactomannan derived from the Indian cluster bean. Once guar gum is fully hydrated, thick solutions and gels are formed rapidly. Guar gum is a neutral polysaccharide; therefore, no differences were expected due to exposure to acidic conditions during gastric simulation (17). The viscosity of solutions containing guar gum has been studied extensively, particularly for physiological responses. Jarjis et al. (22) indicated a dependence of concentration on viscosity of guar gum inclusion at 2.5 and 14.5 g, added to a 50-g glucose solution consumed by healthy adult humans. In addition, Gallaher and Schaubert (23) fed rats diets containing 8% guar gum. After diet acclimation, rats were injected with streptozotocin (40 mg/kg body weight) to induce a diabetic response. The rats were killed after 28 d of

treatment. The viscosity of the small intestinal contents increased from 2 to 1147 cP in rats fed control (cellulose) and guar gum diets, respectively. The percentage of glycated hemoglobin was reduced ($P < 0.05$) from 19.5 (basal) to 16% in rats fed guar gum diets. Consumption of viscous gums such as guar gum and gum xanthan may elicit beneficial physiological responses (attenuation of post-prandial blood glucose, reduction in plasma cholesterol).

The drawback to in vitro investigations is the inability to account for absorption of digested molecules and water, or secretion of fluid/mucous in the stomach and small intestine. A large proportion of water absorption occurs in the small intestine, as does the majority of macronutrient absorption (24). It is unclear how the removal of digested nutrients and water would affect the resultant viscosity of fluid within the gastrointestinal tract. Further research is warranted to elucidate the effect these processes might have on in vivo viscosity to compare in vitro data with that obtained using in vivo animal models.

In summary, because of the dependence of viscosity on shear rate, it is necessary to assay non-Newtonian solutions at multiple shear rates to establish the entire viscosity profile of such solutions. In the current study, the presentation of viscosity data as AUC values or as parameters calculated through nonlinear regression analysis resulted in similar representations of the viscous characteristics of the solutions. Although similarities in the 2 methods were noted, presentation of parameters from nonlinear regression analysis provides additional information regarding flow properties of solutions that had previously been overlooked in studies presenting only 1 viscosity value.

Cellulose, rice bran, and wheat bran did not increase the viscosity of simulated stomach and small intestinal contents. These insoluble dietary fibers do not appear to play a significant role in the production of viscosity in the gastrointestinal tract. Therefore, their inclusion in diets may be most beneficial for laxation, rather than physiological responses associated with viscosity such as blood glucose attenuation. On the other hand, solutions containing guar gum and psyllium were very viscous during gastric and small intestinal simulations. Oat bran was intermediate in viscosity characteristics. Consumption of oat bran, psyllium, and guar gum may affect physiological responses such as postprandial blood glucose and blood lipid concentrations.

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