

Selecting Soft Wheat Genotypes for Whole Grain Cookies

Edward J. Souza,* Mary J. Guttieri, and Clay Sneller

ABSTRACT

Increased consumption of whole grain cereal products has broad health benefits. Using an experimental whole grain flour-milling system, we evaluated soft wheat (*Triticum aestivum* L.) winter wheat genotypes in whole grain flour for use in cookies. Grain from 14 soft winter wheat cultivars grown in two locations within two crop years was milled using a short-flow flour mill to produce white flour, and then the bran was ground and reconstituted with a white flour to produce a whole wheat flour for comparison baking. Flour samples were evaluated with the solvent retention capacity (SRC) test and the wire-cut cookie method. Bran fractions were analyzed for water-extractable nonstarch polysaccharides. Whole grain flour cookie diameter could be estimated from the diameter of cookies made with white flour. The best predictive models for whole grain wire-cut cookie performance were based on milling softness equivalent and the whole grain sucrose SRC test. Greater softness equivalents and smaller whole grain sucrose SRC values were predictive of larger cookie diameters. Variation in whole grain cookie diameter and texture was due to total water extractable arabinoxylan and the arabinose:xylose ratio in the bran. Early generation selection for whole grain characteristics can use softness equivalent and cookie quality information from white flour. Yet identification of the lines with uniquely superior whole grain flour quality may require whole grain flour analysis.

Edward Souza, USDA, Agricultural Research Service, Soft Wheat Quality Lab., Wooster, OH 44691; Mary Guttieri and Clay Sneller, The Ohio State Univ., Ohio Agricultural Research and Development Center, Wooster, OH 44691. Received 12 May 2010. *Corresponding author (Edward.Souza@ars.usda.gov).

Abbreviations: CVD, cardiovascular disease; SRC, solvent retention capacity.

FLOUR-MILLING YIELD AND PARTICLE SIZE are traits that are under genetic control in wheat (*Triticum aestivum* L.) and manipulated through selection. Within United States soft wheat germplasm, flour-milling yield is highly heritable and an important measure of soft wheat quality (Baenziger et al., 1985; Guttieri et al., 2001, 2004; Souza et al., 2008; Knott et al., 2009). Milling yield is quantitatively inherited and influences nearly every other aspect of flour quality measured for soft wheat (Guttieri et al., 2001, 2004; and Knott et al., 2009). The character of the flour also is determined by how it is milled, and this is most evident in whole grain soft wheat flour where adding bran and embryo back to the white flour produces a flour with greater water absorption than traditionally milled white flour alone (Guttieri et al., 2010).

The genetic component of quality and milling characteristics of whole grain soft wheat flour has not been previously investigated. Yet it is necessary for Americans to increase the fraction of their diet devoted to whole grain foods (USDA, 2005). Retrospective studies of the impact of whole grains on cardiovascular disease (CVD) suggest that inclusion of bran and embryo into food products has broad benefits for reducing the incidence of CVD and surrogate indicators for CVD incidence, including blood pressure and total cholesterol concentration (De Moura

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et al., 2009). The Whole Grains Foods Council (2009) reported that the predominant contributors to whole grain intake in the American diet are cold breakfast cereal (42.5% of whole grain intake) and hot breakfast cereal (15%). Most wheat-based breakfast cereals are made with soft wheat, but considerable opportunity exists to expand the consumption of wheat crackers and other snack foods (Maras et al., 2009). To meet this demand, it is necessary to measure the suitability of soft wheats for use in whole grain cookies and crackers.

To develop soft wheat cultivars suited for whole grain products, experimental systems are needed to produce a representative flour and to characterize the basic variation within soft wheat for whole grain flour quality. A short-flow experimental milling system combined with a grinding system for bran can produce whole grain flours from which wire-cut cookies can be evaluated (Guttieri et al., 2010). Nearly all the published studies with whole grain flour have focused on hard-wheat products, primarily bread (Seyer and Gélinas, 2009; Bruckner et al., 2001; Zhang and Moore 1997; Zhang and Moore, 1999), rather than soft wheat products.

Increasing aleurone and bran content in milled white flour typically increases water absorption and decreases soft wheat quality as flour extraction rates increase. The greatest concentrations of minerals are in the aleurone and then the bran layers, the same layers that contribute to increased water absorption within a soft wheat. This is the underlying assumption behind using flour ash as an indicator of quality in soft wheat (Souza et al., 2002). Greater flour water absorption decreases the suitability of a flour for high-sugar products like cookies and cakes (Guttieri et al., 2001). Previous work with whole grain ground-wheat samples indicated that cultivars varied significantly for water absorption in ground meal and that the heritability components of flour water absorption, such as damaged starch content, exceeded 60% (Guttieri et al., 2004, Knott et al., 2009). It is our assumption that there will be genetic variation among cultivars for flour water absorption in a milled whole grain wheat flour.

We evaluated whole grain wire-cut cookie quality from 14 wheat genotypes grown in four environments, as well as other quality parameters, to identify parameters predictive of whole grain cookie performance in soft wheat.

MATERIALS AND METHODS

Grain Production

Wheat genotypes were grown as part of The Ohio State University wheat-breeding program yield trials at the Northwest Agricultural Research Station near Hoytville, OH, and at the Ohio Agricultural Research and Development Center near Wooster, OH, in 2007 and 2008. Full experimental details of grain production are described in Guttieri et al. (2008). The wheat cultivars and breeding lines included in the study are

listed in Table 1. Plots were harvested with a small plot combine, and grain samples were cleaned with a Carter-Day Dockage Tester (Carter Day Internl., Minneapolis, MN) to remove shriveled seed.

Experimental Milling

Experimental milling used the method described in Guttieri et al. (2010). Grain was tempered and milled on the modified Quadromat Junior Advanced Milling System in the Soft Wheat Quality Laboratory (Finney and Andrews, 1986). Milling yield and softness equivalent were measured for each grain sample as described in detail by Finney and Andrews (1986). Milling yield from the Advanced milling system was measured as the weight of material recovered through a 156 μm mesh screen of mill product from the initial break roll pass combined with the mill product of the reduction milling sifted through a 140 μm mesh screen. The flour weight for milling yield is standardized by dividing by the initial weight of grain milled and expressed on 14 g 100 g⁻¹ moisture basis. Softness equivalent was measured as the weight of material recovered through a 156 μm opening mesh screen of mill product from the initial break roll pass. The fine flour weight was standardized to a percentage by dividing it by the total weight of flour estimated by sifting the mill product over a 471 μm screen and subtracting the course bran (the above screen fraction) from the original weight of milled grain. Softness equivalent is an estimator for break flour yield in a long-flow milling system (Souza et al., 2008).

Bran material and embryo, as well as endosperm adhering to bran and embryo particles (referred to collectively hereafter as bran), were ground with a Quadro Comil conical mill (Quadro Engineering Corporation, Waterloo, ON, Canada) fitted with a grater-style screen. The screen thickness was 0.94 mm, and the hole size was 1.27 mm. The screen had 19% open area. The Comil has an overhead impeller, and material is propelled centrifugally against the grater screen. The Comil was operated at 6000 rpm for these experiments. The impeller on the Comil is driven by a 1 H.P. Baldor Super E motor (Baldor Electric Co., Fort Smith, AR).

Ground bran and flour of each sample were combined in the proportion to which they were milled initially. To form whole grain wheat flour, white flour and processed bran were recombined in the proportion measured during the milling process for each sample. For example, a grain sample that produced a 75% white flour extraction was recombined to form a whole grain flour sample using 25 g of processed bran for every 75 g of white flour.

Flour Quality Evaluation

Wire-cut cookies were prepared from white and whole grain flours using the American Association of Cereal Chemists (AACC) method 10-54, "Baking Quality of Flour—Micro Wire-Cut Formulation" as described previously (Guttieri et al., 2008). The solvent retention capacities of white and whole grain flours were measured in duplicate as described in Guttieri et al. (2008). Whole grain flour solvent retention capacity (SRC) is conducted by the same protocol as white flour SRC. The lower specific gravity of bran material can prevent the formation of a solid pellet during the centrifugation of the sample. In all cases, care was taken to retain the full amount of the flour

Table 1. Description of cultivars and breeding lines evaluated in two Ohio environments in 2007 and 2008, market class, origin, release date, and milling characteristics. SWW, soft white winter; SRW, soft red winter.

Genotype	Market class	Program of origin	Year of release	Flour-milling yield	Milling softness equivalent		Flour protein
					g 100 g ⁻¹		
Ambassador	SWW	Mich. State Univ.	2009	73.5	56.7	8.2	
Caledonia	SWW	Cornell Univ.	2004	72.9	58.6	8.4	
Caledonia Reselection	SWW	Cornell Univ.	–	71.7	57.7	8.4	
Coral	SWW	Mich. State Univ.	2008	72.2	57.8	8.4	
Cornell 595	SWW	Cornell Univ.	1942	70.2	52.9	9.4	
Frankenmuth	SWW	Mich. State Univ.	1979	70.5	55.0	8.8	
Geneva	SWW	Cornell Univ.	1983	71.9	59.7	9.0	
Hopewell	SRW	Ohio State Univ.	1995	69.8	61.2	8.3	
ID96-16702A	SWW	Univ. of Idaho	–	72.8	62.2	8.2	
Kanqueen	SRW	Kansas	1949	68.8	53.8	11.0	
NY92039-9065	SWW	Cornell Univ.	–	73.1	56.4	8.8	
Pearl	SWW	Virginia Polytech.	2002	71.1	58.0	8.8	
Pioneer 25R26	SRW	Pioneer Brand	1997	71.2	57.3	8.7	
Richland	SWW	Cornell Univ.	2004	70.8	59.6	9.1	
Genotype-F [†]				33.9***	10.1***	16.9***	
Std. Err.				0.3	1.4	0.3	

***Denotes significance at $p < 0.001$.

[†]Genotypes were treated as fixed effects and year (2007, 2008) and location (Northwest Branch, Wooster) as random effects in the analysis of variance.

pellet. For the sucrose SRC, a visually significant fraction of the flour material that appeared to be bran particles failed to pellet and was lost with the supernatant. All SRC values presented are for the actual weighed amount recovered after centrifugation and decanting the supernatant.

Water-Extractable Nonstarch Polysaccharide Composition of Bran

One-gram samples of Comil-ground bran were extracted with 5 mL of water per the water SRC. A 2.5-mL aliquot of the supernatant was hydrolyzed with an equal volume of 4 N trifluoroacetic acid at 105°C for 1 h. The hydrolysate was centrifuged at 3000 × *g*, and a 3-mL aliquot of the supernatant was derivatized to alditol acetates and analyzed as described in Guttieri et al. (2008).

Statistical Analyses

To evaluate the effect of genotype, data were analyzed by mixed effects analysis of variance using PROC MIXED in SAS (Version 9.1.3). Crop year (2007, 2008) and location (Wooster, Northwest Branch) were treated as random effects in the analysis of variance; genotype was treated as a fixed effect in the analyses of variance. Genotype means for whole grain SRC parameters were used to determine intra-SRC correlations in PROC CORR in SAS. The relationship between whole grain and white flour SRC parameters for the 14 genotypes was evaluated by regressing genotype means for SRC parameters on white flour genotype means for the corresponding SRC parameters using PROC REG in SAS. Correlations of milling and SRC parameters with whole grain wire-cut cookie quality were calculated using genotype means in PROC CORR in SAS.

Genotype means for milling and SRC parameters were used to generate regression models to predict genotype means for whole grain wire-cut cookie parameters using the SELECTION option in PROC REG in SAS. The optimal models were selected to

optimize R^2 values and selecting the number of independent variables such that the Mallows' C(P) statistic approaches ($p + 1$), where p is the number of independent variables. The broader validity of optimal models was evaluated by predicting whole grain cookie parameters for 63 soft winter wheat grain samples that were produced from additional genotypes grown among the four trials of this study. The observed whole grain cookie parameters were then plotted against the corresponding predicted whole grain cookie parameters, and the R^2 values of the regressions used as measures of the variation explained by the genotypic models.

RESULTS AND DISCUSSION

Milling Characteristics

The genotypes included in this study represented a range of soft wheat milling characteristics and flour protein (Table 1). The average white flour yield of the 14 genotypes ranged from a low of 68.8 g 100 g⁻¹ for the 1949 Kansas-derived genotype 'Kanqueen' to a high of 73.5 g 100 g⁻¹ for the new Michigan State University genotype 'Ambassador'. Similarly, softness equivalent, an indicator of break flour yield, ranged from a low of 52.9 g 100 g⁻¹ for the 1942 Cornell University cultivar 'Cornell 595' to a high of 62.2 g 100 g⁻¹ for the experimental genotype in testing from the University of Idaho, ID96-16702A. Flour protein ranged from a low of 8.2 g 100 g⁻¹ for Ambassador to 11.0 g 100 g⁻¹ for Kanqueen.

Solvent Retention Capacity

The SRC profile is a multivariate descriptor of the water-holding capacity of flour under a range of conditions, including high sucrose and alkaline dough conditions (Gaines, 2000). Solvent retention capacity is used to assess

Table 2. Correlation among solvent retention capacities of whole grain flours of 14 wheat (*Triticum aestivum* L.) genotypes grown at two Ohio locations in 2007 and 2008.

	Water	Sodium carbonate	Sucrose	Lactic acid
Water	–	0.88**	0.66**	0.90**
Sodium carbonate	0.88**	–	0.56*	0.92**
Sucrose	0.66**	0.56*	–	0.64**
Lactic acid	0.90**	0.92**	0.64**	–

*Denotes significance at $p < 0.05$.

**Denotes significance at $p < 0.01$.

suitability of a flour for an array of soft wheat products. Cross-correlations among SRC parameters have commonly been observed (Guttieri et al., 2001). Water SRC values of whole grain flours were highly correlated with sodium carbonate, sucrose, and lactic acid SRC values of whole grain flours (Table 2). Sucrose SRC of whole grain flour had the greatest degree of independence from other SRC parameters (Table 2). Sucrose SRC is correlated with water extractable arabinoxylan in white soft wheat flours (Guttieri et al., 2008). The correlation matrix (Table 2) suggests limited value to a complete SRC profile for whole grain flours because of the strong intercorrelation of solvents in the whole grain wheat flour. A two-solvent profile of sucrose plus sodium carbonate SRC may adequately describe the variation in whole grain flours.

To evaluate the extent to which whole grain flour SRC was predicted by white flour SRC, the mean whole grain flour SRC of the 14 genotypes for a given SRC solvent was regressed on the corresponding white flour SRC (Table 3). Whole grain water SRC and whole grain sodium carbonate SRC were well predicted by the white flour SRC; however, whole grain sucrose SRC was poorly predicted, and whole grain lactic acid SRC was not predicted by the white flour SRC. Part of the poor correlation between white flour and whole grain flour SRC is due to difficulties in the method when the bran is present. Whole grain flour forms loose pellets during centrifugation in the 50% sucrose solution, making it difficult to cleanly decant the supernatant from the pellet. Previous work has noted the problems of predicting whole grain lactic acid SRC from white flour measures (Guttieri et al., 2004). The presence of the bran swelling in the lactic acid interferes with the measurement of the glutenin macropolymer.

Table 3. Regression of mean whole grain flour solvent retention capacity (SRC) with the corresponding mean white flour SRC as the independent variable.

Solvent	Slope	Intercept	R^2
Water	0.74 ± 0.10	24.29 ± 5.38	0.79***
Sodium carbonate	1.08 ± 0.11	9.83 ± 7.30	0.88***
Sucrose	0.45 ± 0.13	43.11 ± 12.33	0.43**
Lactic acid	0.15 ± 0.02	55.0 ± 2.32	0.07

**Denotes regression model significance at $p < 0.01$.

***Denotes regression model significance at $p < 0.001$.

Wire-Cut Cookie Geometry

Pioneer Brand '25R.26' produced the smallest mean diameter whole grain wire-cut cookie (15.1 cm per 2 cookies), perhaps because of its strong gluten (Table 4). The two poor-milling, high-protein genotypes, Kanqueen and Cornell 595, also produced small-diameter cookies (15.2 and 15.3 cm per 2 cookies, respectively). The largest diameter whole grain cookies were produced by ID96-16702A (0.3 cm per 2 cookies larger than the next largest entry), the genotype that also had the greatest break flour yield. The whole grain flour of ID96-16702A also produced the smallest stack height cookies; diameter and stack height are typically negatively correlated with each other. Kanqueen, which had the greatest flour protein concentration, produced the largest stack height cookies (21.1 mm per 2 cookies). The spread factor of the whole grain cookies ranged from 0.72 (Kanqueen) to 0.91 (ID96-16702A).

Milling and SRC parameters predicted variation in whole grain wire-cut cookie parameters (Table 5). Softness equivalent was the parameter most correlated with whole grain wire-cut cookie diameter ($r = 0.78$, significant at $p < 0.01$). Whole grain sucrose SRC also was correlated with wire-cut cookie diameter ($r = -0.74$, significant at $p < 0.01$). Whole grain stack height was closely correlated with white flour water SRC ($r = 0.83$, significant at $p < 0.01$) and flour protein ($r = 0.81$, significant at $p < 0.01$). White flour water SRC was most closely correlated with whole grain wire-cut cookie spread factor ($r = -0.79$, significant at $p < 0.01$). Flour yield ($r = -0.79$, significant at $p < 0.01$) and white flour water SRC ($r = 0.78$, significant at $p < 0.01$) were most correlated with whole grain wire-cut cookie moisture. These correlations suggest that breeding can benefit from the favorable correlations of most of the milling and baking traits. Greater flour yield and softness equivalent are desirable milling characteristics and also are positively correlated to cookie diameter and spread factors. It is likely that joint improvement of all the traits is possible through selection.

The two-parameter regression model for whole grain wire-cut cookie diameter as a function of softness equivalent (SE) and whole grain sucrose SRC (WGSucr) was significantly better than either single-parameter regression model.

$$\text{Diameter} = 15.29 + (0.078 \times \text{SE}) - (0.048 \times \text{WGSucr}); R^2 = 0.81$$

Similarly, the two-parameter regression model for whole grain stack height as a function of white flour water SRC and flour protein concentration (FLPRC) was superior to either single-parameter regression model.

$$\text{Stack height} = 3.19 + (0.454 \times \text{FLPRC}) + (0.239 \times \text{Water SRC}); R^2 = 0.76$$

Table 4. Whole wheat (*Triticum aestivum* L.) wire-cut cookie quality of 14 soft wheat genotypes grown at two Ohio locations in 2007 and 2008.

Genotype	Whole grain wire-cut cookie				
	Diameter	Stack height	Spread factor	Moisture	Punch force
	cm per 2 cookies	mm per 2 cookies	cm/mm	g 100 g ⁻¹	kg
Ambassador	15.9	18.4	0.87	3.21	1.39
Caledonia	15.8	19.4	0.82	3.42	1.40
Caledonia Resel.	15.8	19.0	0.84	3.56	1.52
Coral	16.1	18.6	0.86	3.41	1.45
Cornell 595	15.3	20.4	0.75	3.81	1.84
Frankenmuth	15.5	19.7	0.79	3.61	1.48
Geneva	16.1	19.0	0.85	3.36	1.57
Hopwell	16.0	19.5	0.82	3.74	1.61
ID96-16702A	16.4	18.1	0.91	3.56	1.50
Kanqueen	15.2	21.1	0.72	3.89	2.11
NY92039-9065	15.7	19.6	0.80	3.63	1.47
Pioneer 25R26	15.1	20.2	0.75	3.72	1.79
Pearl	15.7	19.6	0.80	3.56	1.59
Richland	15.9	19.7	0.81	3.77	1.67
Genotype-F [†]	20.2***	7.5***	10.6***	2.0*	3.22**
Std. Err.	0.2	0.4	0.02	0.19	0.59

*Denotes significance at $p < 0.05$.

**Denotes significance at $p < 0.01$.

***Denotes significance at $p < 0.001$.

[†]Genotypes were treated as fixed effects and year (2007, 2008) and location (Northwest Branch, Wooster) as random effects in the analysis of variance.

Few predictive studies of wire-cut cookies have been published. However, predictive studies with the other standard soft wheat test, the sugar-snap cookie (AACC Approved Method 10-52), identified softness equivalent, sucrose SRC, and flour protein as the best predictors of cookie diameter in single- and multiple-regression models (Gaines, 2004). In a different set of environments, Guttieri et al. (2001) found that flour protein in combination with sucrose SRC was the best predictive model for sugar-snap cookie diameter. The factors identified in the literature—flour protein, softness equivalent, and sucrose SRC—also were predictive of whole grain flour cookie performance, which suggests that the underlying predictive factors for white flour and whole grain flour in cookie performance are similar.

Because spread factor is a calculated parameter (the ratio of diameter to stack height) we evaluated the ratios of the parameters that predicted diameter and stack height as independent variables to predict spread factor. The ratio of softness equivalent to white flour water SRC was most highly predictive of whole grain wire-cut cookie spread factor:

$$\text{Spread factor} = 0.101 + (0.634 \times \frac{\text{SE}}{\text{Water SRC}});$$

$$R^2 = 0.81$$

The ratio of SE to flour protein also produced a good regression model, which explained 68% of the variation in spread factor:

$$\text{Spread factor} = 0.413 + (0.0607 \times \frac{\text{SE}}{\text{Flour Protein}});$$

$$R^2 = 0.68$$

Table 5. Genotypic correlation of whole grain wire-cut cookie parameters with milling and solvent retention capacity parameters.

Parameter	Cookie diameter	Stack height	Spread factor	Moisture
Flour protein	-0.58*	0.81**	-0.73**	0.61*
Softness equivalent	0.78**	-0.65**	0.71**	ns [†]
Flour yield	0.53*	-0.79**	0.71*	-0.79**
<u>Solvent retention capacity</u>				
Water	-0.70**	0.83**	-0.80**	0.78**
Sodium carbonate	ns	ns	ns	0.63*
Sucrose	-0.61*	0.72**	-0.68**	0.67**
Lactic acid	ns	ns	ns	ns
Whole grain water	-0.60*	0.68**	-0.67**	0.70**
Whole grain sodium carbonate	ns	0.54*	ns	0.71**
Whole grain sucrose	-0.74**	0.54*	-0.63*	ns
Whole grain lactic acid	ns	0.60*	-0.58*	0.77**

*Denotes significance at $p < 0.05$.

**Denotes significance at $p < 0.01$.

[†]ns, nonsignificant.

Flour protein is conveniently and rapidly measured by near infrared technology following experimental milling and is data that is readily accessible to end users.

Cookie moisture after baking is an indicator of quality, with lower values typically preferred. The two-parameter regression model for whole grain wire-cut cookie moisture that included both white flour water SRC and flour yield was not significantly better than the model that included only water SRC. The variation in water SRC and flour

yield are tightly correlated. Therefore a single-parameter regression model for moisture is most appropriate:

$$\text{Cookie moisture} = (0.0865 \times \text{Water SRC}) - 0.853;$$
$$R^2 = 0.61$$

Model Validation

The 14 genotypes that were the focus of this study were a subset of all the cultivars grown in the breeding trials described within the materials and methods. Most of the lines were not replicated across years as is common in breeding nurseries. We used the wire-cut cookies from the broader set of germplasm to test the predictive power of our models in a broader data set. The model for whole grain cookie diameter explained 47% of the variation in whole grain wire-cut cookies in a set of 63 samples from wheat genotypes grown in the four trials. And the model for stack height explained 46% of the variation observed. The model for spread factor as a function of softness equivalent and white flour water SRC explained only 38% of the observed variation. However, the alternative model for spread factor based on softness equivalent and flour protein explained 60% of the observed variation in the validation dataset, which suggests that this simple measurement may provide better general utility than the ratio of softness equivalent and water SRC. The model for whole grain cookie moisture as a function of white flour water SRC was not predictive in the validation dataset, explaining only 5% of the variation in the final moisture of the whole grain wire-cut cookies.

The Role of Bran in Baking

Some of the important predictors of whole grain wire-cut cookie quality are white flour parameters: white flour water SRC, flour protein, and the softness equivalent during flour milling, a measure of flour particle size distribution through the break rolls. The whole grain parameter that was an important predictor of whole grain wire-cut cookie quality was whole grain sucrose SRC, which is a measure of water-extractable arabinoxylan concentration. The whole grain sucrose SRC had greater correlation with whole grain wire-cut cookie diameter than did white flour sucrose SRC, despite the difficulty in conducting whole grain sucrose SRCs. The correlation of sucrose SRC to whole grain cookie quality suggests that there are important differences in water-extractable arabinoxylan concentration in the bran fractions. Plotting the whole grain wire-cut cookie diameter versus the corresponding white flour wire-cut cookie diameter (Fig. 1) reveals that, for 12 of the 14 genotypes, the whole grain cookie diameter would be consistently predicted by the white flour performance. Yet two of the genotypes in the study, ID96-16702A and Coral, baked substantially larger diameter whole grain wire-cut cookies than would be expected, based on their white flour cookies. This

suggests that factors in the bran of these genotypes distinguish them from the other 12 genotypes in the study.

The concentrations of monosaccharides derived from hydrolysis of the water-extractable nonstarch polysaccharides in the bran offer an indication of factors that may distinguish ID96-16702A and Coral from the other 12 genotypes. Genotype effects for monosaccharides of nonstarch polysaccharides were highly significant among the 14 genotypes included in this study (Table 6). Coral had the lowest arabinose and xylose concentrations among the 14 genotypes. Yet arabinose and xylose concentrations of ID96-16702A were similar to many other wheat genotypes in the trial. ID96-16702A had a notably low galactose concentration, suggesting low arabinogalactan peptide concentration. Second lowest was Coral. This is consistent with the cookie quality data and with previous results in white wheat flours (Guttieri et al., 2008) indicating a role for arabinogalactans in cookie quality. Yet the Caledonia Reselection had a relatively similar concentration of galactose to Coral. The relationships among the nonstarch polysaccharides and whole grain flour quality are clearly complex.

Galactose concentration was not correlated with xylose concentration in this set of 14 genotypes, suggesting that the genetics that regulate water-extractable arabinoxylan concentration in bran may be independent of the genetics that regulate arabinogalactan concentration in bran (Table 7). Galactose also was independent of glucose concentration. However, xylose concentration was negatively correlated with glucose concentration. As xylose concentration in bran increased, glucose concentration decreased. Water-extractable glucose concentration likely is a measurement of the extent to which damaged starch is present in the bran sample. The broken starch granules are not pelleted in centrifugation and are included in the hydrolysate, increasing the glucose concentration. Xylose and arabinose concentration were closely correlated in this study.

Perhaps the combined effect of low water-extractable arabinoxylan with the relatively low galactan concentration in Coral produces an effect similar to the very low arabinogalactan in ID96-16702A. The two genotypes that produced the smallest diameter whole grain wire-cut cookies (Pioneer Brand 25R26 and Kanqueen) had substantially greater concentration of galactose (Pioneer Brand 25R26) and xylose (Kanqueen) than other genotypes in the trial.

One of the more challenging cookie parameters to predict is texture. All combinations of all parameters were evaluated as potential predictors of cookie texture, as measured by the 5-punch test. The best regression model was a two-parameter regression model using parameters from the analysis of the water extractable carbohydrates.

$$\text{Force} = 1.399 + (0.105 \times [\text{AXG}])$$
$$- (0.834 \times \frac{[\text{Ara}]_{\text{AX}}}{[\text{Xyl}]}); R^2 = 0.77$$

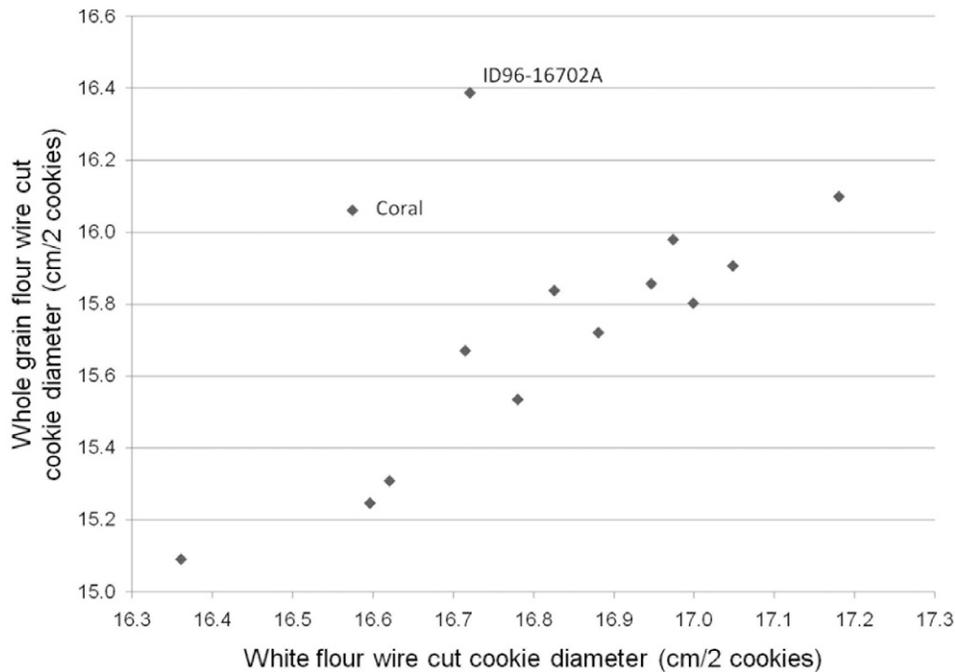


Figure 1. Wire-cut cookie diameters from whole grain soft wheat (*Triticum aestivum* L.) flour plotted as a function of wire-cut cookie diameters from white flour of the same grain samples for 14 soft winter wheat cultivars; data averaged for samples across two locations in Ohio, 2007 to 2008.

Table 6. Analysis of carbohydrate composition of water extracts of bran fractions of 14 wheat (*Triticum aestivum* L.) genotypes grown in two Ohio locations in 2007 and 2008.

Genotype	Monosaccharides from hydrolysates of water extracts of bran				
	Arabinose	Xylose	Mannose	Galactose	Glucose
	mg g ⁻¹ bran				
Ambassador	2.83	2.19	10.56	5.15	40.2
Caledonia	2.80	2.45	9.59	5.59	38.5
Caledonia Resel.	2.86	2.51	10.02	4.89	39.2
Coral	2.57	2.04	9.78	4.80	37.2
Cornell 595	2.90	2.69	9.20	5.13	34.0
Frankenmuth	2.60	2.20	9.70	5.89	36.6
Geneva	2.95	2.53	9.35	5.56	35.5
Hopwell	2.70	2.57	8.12	5.33	30.9
ID96-16702A	2.85	2.57	9.54	4.54	35.3
Kanqueen	3.47	4.03	7.41	5.71	29.9
NY92039-9065	2.84	2.32	9.57	5.45	37.0
Pioneer 25R26	3.27	3.24	9.62	6.77	36.3
Pearl	3.07	2.58	9.29	5.31	39.1
Richland	2.95	2.68	8.47	5.30	33.1
Genotype-F†	18.5***	81.4***	6.8***	14.4***	19.8***
Std. Err.	0.14	0.09	0.52	1.13	2.3

***Denotes significance at $p < 0.001$.

†Genotypes were treated as fixed effects and year (2007, 2008) and location (Northwest Branch, Wooster) as random effects in the analysis of variance.

Where [AXG] is the sum of arabinose, xylose, and galactose concentration; [Ara]_{AX} is the arabinose concentration in water-extractable arabinoxylan; and [Xyl] is the water-extractable xylose concentration. This regression equation considers both total water extractable arabinoxylan and arabinogalactan concentration as well as the ratio of arabinose to xylose in arabinoxylan. Flour quality also is affected by small differences in the ratio, which are

indicative of the degree of branching in the arabinoxylan polymer (Martinant et al., 1999) and remodeling of the polymer that occurs during seed development (Toole et al., 2009). In this study and previous white flour studies (Guttieri et al., 2008) greater concentrations of highly branched arabinoxylans, as measured by the ratio of arabinose to xylose, tend to reduce water absorption in whole grain flour and more tender cookies.

Table 7. Correlation of genotypic means for monosaccharide concentration of hydrolysates of water extracts of bran of 14 soft wheat (*Triticum aestivum* L.) genotypes grown at two Ohio locations in 2007 and 2008.

	Xylose	Galactose	Mannose	Glucose
Arabinose	0.91**	ns [†]	ns	ns
Xylose		ns	-0.70**	-0.62*
Galactose			ns	ns
Mannose				0.91**

*Denotes significance at $p < 0.05$.

**Denotes significance at $p < 0.01$.

[†]ns, nonsignificant.

CONCLUSIONS

Whole wheat snack products in the United States are commonly presented to the public in novel, ready-to-eat products such as snack bars or breakfast cereals reformulated in a ready-to-eat snack form. A second way of presenting whole wheat products to the consumer is to prepare a whole grain wheat flour and manufacture a whole grain flour version of a traditional cookie or cracker. Challenges of increased water absorption and particle size in whole grain wheat flour routinely limit the percentage of the flour formula represented by a whole grain flour product. Few cookies and crackers are able to be manufactured from a whole grain wheat flour because of product quality concerns. We chose to use a standard test of soft wheat flour quality, the wire-cut cookie. Improvements in the flour quality for manufacture of a cookie with whole grain wheat should lead directly to increasing the percentage of the flour fraction contributed by whole grain wheat flour. Selection for traits that improve whole grain wheat flour should, in turn, lead directly to increased consumption of whole grain flour.

For the purposes of early selection of soft wheat breeding lines, the attributes of whole grain wire-cut cookie quality can be predicted based on the flour particle size distribution from experimental milling and flour protein. The whole grain sucrose SRC test also is predictive of whole grain wire-cut cookie quality. The origins of the value of the whole grain sucrose SRC test may be in detecting water extractable nonstarch polysaccharides. Differences in water-extractable, nonstarch polysaccharides in bran fractions of wheat genotypes may contribute to particularly desirable functionality for whole grain wire-cut cookies. On the basis of this work, the target soft wheat genotype produces bran with low water-extractable arabinoxylan and arabinogalactan concentration and a high degree of arabinose substitution on the xylan backbone in the water-extractable arabinoxylan. Whole wheat flour with this profile produces more tender wire-cut cookies with larger spread factors than those with high water-soluble arabinoxylan concentrations and low substitution.

The excellent end-use quality of ID96-16702A in Ohio trials was a surprising result. Wheat genotypes from

the western United States generally are poorly adapted to Ohio growing conditions and therefore produce grain under biotic and abiotic stress. Thus the grain quality of western U.S. genotypes grown in Ohio trials tends to be poor. However, the pedigree of ID96-16702A is 86-09015/'Houser'/'Brundage'. Houser is a wheat variety from the Cornell program in New York. Brundage is an Idaho cultivar derived from the cross of Stephens/Geneva, and Geneva is a wheat variety from the Cornell program as well. Therefore, the parentage of ID96-16702A is at least 50% from the eastern United States. This example illustrates the potential for positive outcomes from germplasm exchange between the eastern and western U.S. soft winter wheat germplasm pools.

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