Reduced Amylose Effects on Bread and White Salted Noodle Quality

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ABSTRACT

Amylose content in wheat endosperm is controlled by three *Wx* loci, and the proportion of amylose decreases with successive accumulation of *Wx* null alleles at the three loci. The proportion of amylose is believed to influence end-use quality of bread and Asian noodles. The objectives of this study were to determine influence of the allelic difference at *Wx-B1* locus on bread quality, bread firmness, and white salted noodle texture in a spring wheat cross segregating for the *Wx-B1* locus and in a set of advanced spring wheat breeding lines differing in allelic state at the *Wx-B1* locus. In addition, we examined the relationship between amylose content and flour swelling properties on bread and noodle traits. Fifty-four recombinant inbred lines of hard white spring wheat plus parents were grown in replicated trials in two years, and 31 cultivars and breeding lines of hard spring wheat were grown in two locations. Bread and white salted noodles were processed from these trials. The presence of the *Wx-B1* null allele reduced amylose content by 2.4% in a recombinant inbred population and 4.3% in a survey of advanced breeding lines and cultivars compared with the normal. The reduced amylose was accompanied by an average increase in flour swelling power (FSP) for the *Wx-B1* null group of 0.8 g/g for the cross progeny and 2.3 g/g for the cultivar survey group. The *Wx-B1* allelic difference did not affect flour protein in cross progeny where the allelic difference was not confounded with genetic background. Bread from the *Wx-B1* null groups on average had increased loaf volume and was softer than the normal group for the cross progeny and cultivar survey group. The *Wx-B1* allelic difference altered white salted noodle texture, most notably noodle springiness and cohesiveness where the *Wx-B1* null groups was more springy and more cohesive than the normal groups for both sets of genetic materials. Flour protein was more highly related to loaf volume than were FSP or amylose. Both flour protein and FSP were positively related to noodle textural traits, but especially noodle springiness and cohesiveness.

Amylose content in the endosperm of plants is controlled by the enzyme granule bound starch synthase (GBSS) or the Waxy (*Wx*) gene (Tsai 1974; Echt and Schwartz 1981). The Wx protein is the major protein extractable from the interior of starch granules, and in hexaploid wheat (*Triticum aestivum* L.) there are three Wx proteins produced, one each from chromosome 7A (Wx-A1), 4A (Wx-B1), and 7D (Wx-D1) (Chao et al 1989; Nakamura et al 1993). These three proteins can be separated by SDS-PAGE and genotypes missing one or more of the three Wx proteins can be easily identified (Yamamori et al 1994; Graybosch et al 1998). Polymerase chain reaction (PCR) based markers have been developed that can classify alleles at the three *Wx* loci (Nakamura et al 2002).

Wheat starch is composed of both amylose and amylopectin. Normal wheat starch consists of roughly a 3:1 ratio of amylopectin to amylose. A reduction in either amylose or amylopectin results in an altered amylose-amylopectin ratio with profound impacts on the textural qualities of food products. Flours prepared from lines of wheat that contain a null allele for one of the three *Wx* loci, termed partial waxy, contain less amylose (Yamamori et al 1992) . Decreased amylose content is associated with increased hot paste (peak) viscosity of wheat flour or starch (Oda et al 1980) and increased swelling of starch-water suspensions (Crosbie 1991; Crosbie et al 1992). The flour swelling volume (FSV) test is a simple selective procedure for lower amylose that relies on the increased swelling capacity of amylopectin (Crosbie 1991). Because gelatinized amylopectin absorbs more water than amylose, flours from lines with reduced amylose content, and therefore more amylopectin, absorb more water when heated in the presence of water. The flour swelling power (FSP) test, where the weight of the gelatinized starch is calculated, also gives reproducible results (Crosbie et al 1992) in which the environment is a minor component of variation between samples (Morris et al 1997). Surveys of world wheat lines have found that a significant number of Japanese and Australian cultivars tested have null alleles at one or more of the *Wx* loci, and a small percentage of U.S. cultivars contain the null allele at the *Wx B1* locus (*Wx-B1b*) alleles (Yamamori et al 1994; Graybosch et al 1998).

Development of U.S. hard wheat cultivars is increasingly focused on selecting lines suitable for production of both high-quality Asian style noodles as well as bread products. Because of its high protein and strong dough mixing properties, hard wheat from the U.S. Great Plains may be suitable for both bread and some types of Asian noodles (Lang et al 1998). Hard wheat breeding programs have focused on Asian noodle types that incorporate hard textured wheat flour rather than Japanese style udon noodles where soft textured wheat is used. Consumers prefer a softer texture for Japanese noodles made from soft grain textured *Wx-B1* null (*Wx-B1b*) genotypes with lower amylose, (Oda et al 1980; Miura and Tanii 1994; Zhao et al 1998). However, consumers prefer a firmer texture for noodles made from hard textured wheat flours, and the softer noodle texture conferred by *Wx-B1b* genotypes may be detrimental to consumer preference (Ross et al 1997).

While the effect of presence or absence of *Wx-B1* null allele and associated lower amylose content on Asian noodles has been described, its effects on bread quality are not well characterized. Amylose and amylopectin have been reported to have large effects on the gelatinization and retrogradation properties of starch-based gels. Increased amylopectin content is associated with increasing firmness of starch-based gels during storage (Ring et al 1987), while increased amylose is largely responsible for the initial firmness of the gels (Miles et al 1985). Based on these observations, differing amounts of amylose and amylopectin may affect the firmness and staling rate of bread. Numerous studies have been conducted to attempt to determine the factors responsible for the staling of bread. Several major components thought to affect bread freshness are moisture content (Platt and Powers 1940), gluten content or quality (Maleki et al 1980), baking temperature (Giovanelli et al 1997), and position of the bread slice in the loaf (Baruch and Atkins 1989). However, crumb structure is partly controlled by starch gelatinization, which occurs more readily in flours with reduced amylose content (Zeng et al 1997). Bhattacharya et al (2002) noted bread made from blends of waxy durum (where Wx proteins are lacking) and normal spring wheat flour was softer and had reduced staling from 0 to 5 days as

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opposed to bread made from 100% normal wheat flour. Bread with increased volume and softer crumb was obtained when starch from waxy wheat was added to starch and gluten from normal wheat (Lee et al 2001). Both the Bhattacharya et al (2002) and Lee et al (2001) studies added waxy flour or starch from a genetic background different from normal flour or starch.

Our objectives were to determine the influence of the allelic difference at *Wx-B1* locus on bread quality, bread firmness, and white salted noodle texture in a spring wheat cross-segregating for the *Wx-B1* locus and in a set of advanced spring wheat breeding lines differing in allelic state at the *Wx-B1* locus, and to examine the relationship between amylose content and flour swelling properties on bread and noodle traits.

MATERIALS AND METHODS

Genetic Materials

Thirty hard white spring wheat genotypes and one hard red spring cultivar (Hi-Line) were grown in a randomized block design with three replicates at Bozeman and Havre, MT, in 1997. The 30 hard white genotypes included Klasic, ID377S and 28 advanced breeding lines. Seed from the three blocks was bulked for quality analyses so that location served as replicates for all quality determinations.

Fifty-four F4-derived recombinant inbred lines were derived from the cross MTHW9420/MTHW9520 through single-seed descent through F4 when single heads were selected from individual plants. Seed of each F4-derived line was increased in a single row. Both MTHW9420 and MTHW9520 are hard white spring wheats. MTHW9420 carries the *Wx-B1b* (null) allele (Lanning et al 2001), while MTHW9520 carries the *Wx-B1a* (normal) allele at the *Wx-B1* locus. The 54 recombinant inbred lines plus parents were grown in a randomized block design with two replicates at Bozeman, MT, in 2000 and 2001. Seed from each plot was harvested for quality analyses.

Milling and Bread Quality

All wheat samples were cleaned and processed through a two-stage temper to adjust the wheat to 15.5% moisture. A 1,000-g sample of each experimental unit was milled using a Brabender Automat mill. Flour protein was measured on milled flour by a NIR method using a Technicon InfraAlyzer 400 system calibrated using a LECO FP-528 nitrogen analyzer. Loaves were prepared and baked using 100 g of flour and a 90-min, sugar-based, fermented dough system according to AACC Method 10-10B (AACC 2000). Crumb grain scores were measured after the bread was allowed to cool on racks for 2 hr and were ranked on a scale of 1 to 5, 5 being best, based on subjective measures of the general appearance of cellular structure.

White Salted Noodles

White salted noodles were prepared and tested according to standard methods (AACC 2000). Briefly, 100 g of flour (14% mb) was mixed for 5 min, 45 sec with 29.2 g of a 4.29% (w/v) aqueous solution of NaCl using a 100-g Finney Special mixer (National Manufacturing Co., Lincoln, NE). After compacting, dough was rested for 30 min at room temperature. Dough was sheeted and cut using an Ohtake noodle machine. Dough was compounded by sheeting through a 3-mm gap, then folded once and sheeted three times through a 5-mm gap. Dough was rested in a plastic bag for 30 min at room temperature then sheeted sequentially through gaps of 4, 3, 2, 1.5, and 1 mm. The dough was then slitted through a no. 12 noodle slitter (2.5 mm width). Noodles were stored for 24 hr in plastic bags before cooking and texture evaluation. Noodles (50 g) were cooked for 5 min in 500 mL of boiling water, then drained and rinsed briefly in water at 25–28°C. Noodle textural properties were measured using a texture analyzer (TA.XT2, Texture Technologies Corp., Scarsdale, NY) assembled with a flat Lexan probe 6 mm thick. Textural properties were measured on five noodles cut crosswise 0 and 5 min after cooking. Force versus time was measured with a test speed of 1.0 mm/sec. Noodles were compressed to 70% of their thickness after reaching a 20 g trigger force and then compressed again after resting 1 sec. Noodle chewiness, cohesiveness, hardness, and springiness were as defined previously (Bourne 1982). Hardness was measured as the peak force during the first compression. Noodle cohesiveness was the area of work under the curve of the second compression divided by the area under the curve defining the first compression of the noodles. Springiness was calculated as the distance of the detected height of the product on the second penetration as divided by the original penetration and chewiness was computed as (firmness × cohesiveness) × springiness. Scale of noodle texture measurements changed from the cultivar survey trial to the cross progeny trial due to a change in noodle width from a no. 10 to a no. 12 noodle slitter (noodle width 2.5 mm).

Flour Swelling Power

Flour swelling power (FSP) was measured on samples of flour by a minor modification of a previously described procedure (Crosbie 1991). Briefly, flour samples (30 mg, 14% mb) were added to preweighed 2-mL microfuge tubes. Distilled water (1 mL) was added and tubes were sealed and vortexed till flour was suspended. Tubes were then placed in a 92.5°C water bath and mixed by inverting twice every 20 sec for the first 3 min, then twice every 30 sec for the next 2 min, then twice every min for the next 5 min, and finally by inverting twice every 5 min for the next 20 min. Samples were allowed to cool slightly and then centrifuged at 1,000 × *g* for 10 min at 4°C. Sample supernatants were carefully and completely removed, and the tubes were resealed and weighed. FSP was expressed as ratio of weight of flour-water gel/weight of flour sample.

Wx-B1 Protein Status

Each entry in the cultivar survey and cross progeny was genotyped. Samples of starch were purified from flour as described previously (Echt and Schwartz 1981), and amylose content was measured on samples of starch dispersed in dimethylsulfoxide using potato amylose and amylopectin (Sigma) as standards (Bourne 1982). Identification of lines lacking the Wx-B1 protein (*Wx-B1b*) was performed using SDS-PAGE visualized with silver staining (Graybosch et al 1998). Control genotypes for SDS-PAGE were Chinese Spring with normal alleles at all three *Wx* loci, Klasic, null at *Wx-B1* (*Wx-B1b*) locus (Zeng et al 1997), and Ike, null at both *Wx-A1* (*Wx-A1b*) and *Wx-B1* (*Wx-B1b*) loci (Graybosch et al 1998).

In addition plants from each of the 54 cross progeny were genotyped using PCR-based markers (Nakamura et al 2002). Five lines were determined to be mixtures of *Wx-B1a* and *Wx-B1b* types which presumably derived from a heterozygous F4 plant.

Bread Firmness

Bread firmness and staling were measured using a texture analyzer (TA.XT2, Texture Technologies Corp., Scarsdale, NY). After baking and 2 hr of cooling at room temperature, loaves were cut into slices 25 mm thick, placed into polyethylene bags, and sealed. Bread firmness was measured on bread slices at time 0 (2 hr after baking), 24, 72, and 120 hr. Firmness was measured by recording the total force/load (g) in compressing the bread crumb 10 m*M* using a 1 cm^2 round probe that traveled at 1.5 m*M*/sec over the compression/decompression. Force/load reported is that tallied over the 10 m*M* downward and 10 m*M* upward travel of the probe with measurements commencing when probe first contacted bread crumb.

Four readings were taken per slice of bread, two from the top portion and two from the lower portion of the slice, and readings were averaged.

Data Analysis

Data from the cultivar survey were analyzed through mixed effects analysis of variance using PROC MIXED (SAS Institute, Cary, NC), where *Wx-B1* allele classification was treated as fixed and replicate (environment) and entries within *Wx-B1* classes were random effects. Data from the cross progeny were analyzed in similar fashion except combined over the two years. Parents and entries deemed as segregating were dropped from the analysis. Correlations among traits were computed from entry means for both the cultivar survey and the recombinant inbred lines. All recombinant inbred lines including those segregating for *Wx-b1* were included. Two variable regression models were fitted using bread or noodle quality traits as dependent variables and flour protein and either FSP or amylose as independent variables. Regression coefficients were reported as standardized regression coefficients, which were computed by dividing the parameter estimate by the ratio of the standard deviation of the dependent variable to the standard deviation of the independent variable (Steel et al 1997) using PROC REG from SAS. The proportion of variation among entry means accounted for by the *Wx-B1* allelic difference was determined as the sum of squares due to difference between groups divided by the entry sum of squares.

RESULTS AND DISCUSSION

Effects of Amylose Content on Flour Quality

Growing conditions for the two years for the cross progeny at Bozeman were very similar. Flour protein averaged 11.0 and 11.5% for 2000 and 2001, respectively. Interactions of *Wx* locus classification with year were not important for any of the traits measured for the cross progeny trial. Both environments (Bozeman and Havre) for the cultivar survey averaged 12.7% for flour protein. Because seed from replicates was bulked, environments served as replicates. As a consequence, the genotype × environment interactions were confounded with error.

In the cultivar survey, 21 genotypes were classified as having the *Wx-B1b* allele and 10 had *Wx-B1a* The cross progeny had 20 *Wx-B1b*, 29 *Wx-B1a*, and five segregating. The loss of the Wx-B1 protein reduced amylose about 2.4% for the cross progeny and 4.3% for the cultivar survey (Table I). Graybosch et al (1998) found a difference in amylose content between normal and *Wx-B1* null cultivars was ≈3%, and Araki et al (1999) found substitution of a 4A chromosome with *Wx-B1* null allele reduced amylose 2%. Because amylose is expressed as a percentage of starch, a reduction in amylose content is reflected in an increase in amylopectin

TABLE I
Mean Values for *Wx-B1a* (Normal) Allele and *Wx-B1b* (Null) Allele for Cross Progeny from Cross of MTHW9420 (*Wx-B1b*) × MTHW9520 (*Wx-B1a*) Spring Wheat and for Survey of Spring Wheat Breeding Lines for Amylose, Flour Swelling Power (FSP), and Bread Quality Traits

Group and Wx-B1 Allele	No. of Lines	Amylose%	FSP (g/g)	Flour Protein(%)	Bake Absorption (%)	Loaf Volume (cm^3)	Crumb Grain[a]
Cross progeny							
Wx-B1a	29	30.5	9.8	11.2	72.4	1,000	3.18
Wx-B1b	20	28.1	10.6	11.3	73.1	1,040	2.99
P value[b]		0.00	0.00	0.20	0.10	0.00	0.09
Parents							
MTHW9420 *Wx-B1b*		26.9	10.3	10.8	70.2	959	3.25
MTHW9520 *Wx-B1a*		31.0	9.2	11.0	73.3	1,031	3.50
LSD[c]		3.6	1.1	0.7	1.9	66	0.87
CV%[d]		8.6	8.0	4.6	1.9	4.6	20.0
Cultivar survey							
Wx-B1a	10	31.7	11.1	12.3	67.7	1,080	3.6
Wx-B1b	21	27.4	13.4	12.9	67.1	1,150	2.9
P value		0.00	0.00	0.03	0.30	0.02	0.00
LSD		3.4	0.98	1.1	3.1	89	1.51
CV%		5.9	3.7	4.5	2.3	3.9	26.2

[a] Scale of 1 to 5 (5 best).
[b] Difference between allelic class means.
[c] Least significant difference ($P < 0.05$); difference between any two entry means.
[d] Coefficient of variation.

TABLE II
Mean Values for *Wx-B1a* (Normal) Allele and *Wx-B1b* (Null) Allele for Cross Progeny from Cross of MTHW9420 (*Wx-B1b*) × MTHW9520 (*Wx-B1a*) Spring Wheat and for Survey of Spring Wheat Breeding Lines for Bread Firmness

		Firmness (g)			
Group and Wx-B1 Allele	No. of Lines	0 hr	24 hr	72 hr	120 hr
Cross progeny					
Wx-B1a	29	108.1	123.5	245.6	363.8
Wx-B1b	20	103.8	114.9	239.7	356.7
P value[a]		0.00	0.00	0.26	0.53
Parents					
MTHW9420 *Wx-B1b*		105.4	114.8	263.3	397.3
MTHW9520 *Wx-B1a*		107.0	132.3	259.7	344.6
LSD[b]		11.8	20.0	45.8	94.6
CV%[c]		7.8	11.8	13.3	18.5
Cultivar survey					
Wx-B1a	10	57.9	91.9	227.9	293.9
Wx-B1b	21	44.9	87.2	210.8	256.4
P value		0.00	0.48	0.24	0.02
LSD		11.7	33.0	68.6	114.4
CV%		11.9	18.7	15.9	21.3

[a] Difference between allelic class means.
[b] Least significant difference ($P < 0.05$); difference between any two entry means.
[c] Coefficient of variation.

by the same amount. Higher amylopectin would lead to increased starch swelling. Flour swelling power was significantly increased in the *Wx-B1b* group compared with *Wx-B1a* group both in the cross progeny (9.8 vs. 10.6 g/g) and the cultivar survey (11.0 vs. 13.4 g/g). No difference in flour protein was detected between allelic classes in the cross progeny, but the *Wx-B1b* (null) group had a significant advantage for loaf volume over normal, and a trend toward lower crumb grain score ($P = 0.09$). In the cultivar survey, the *Wx-B1b* group had significantly higher flour protein compared with *Wx-B1a* class but still had a significant increase in loaf volume and a significant reduction in crumb grain score. The reduction in crumb grain and reduction in amylose associated with the loss of the Wx-B1 protein might be expected if crumb grain structure is partly controlled by amylose content.

Bread from *Wx-B1b* lines in the cross progeny was significantly softer than *Wx-b1a* lines at 0 and 24 hr after bake (Table II). Although the difference remained about the same across time, it was not statistically significant beyond 24 hr. This reflects lower precision in measuring firmness with increasing time. A similar pattern with time occurred between the two groups for the cultivar survey, except that the difference expanded at 120 hr, where a significant difference between groups was detected. To determine whether rate of change in bread firmness with time differed between groups, bread firmness was regressed on time for both groups. Regression coefficients for the *Wx-B1b* class (2.2 ± 0.06 for progeny and 1.84 ± 0.08 for cultivar survey) were slightly less than those for the *Wx-B1a* class (2.24 ± 0.05 for progeny and 2.07 ± 0.22 for cultivar survey), but that difference between regression coefficients was not significantly different from zero for the cross progeny ($P < 0.62$) or the cultivar survey ($P < 0.09$).

Lee et al (2001) found bread from starch gluten blends with starch from waxy wheat had increased loaf volume and softer, more porous crumb than bread made from normal starch and gluten. These results were obtained by adding 25–50% waxy starch, whereas our results were obtained by altering amylose content by 2.4 and 4.3% in the cross progeny and cultivar survey, respectively.

Noodle texture was affected by the *Wx-B1* allelic difference 0 and 5 min after cooking. Values for each textural component declined following cooking, but relative difference between allelic groups did not change with time for both groups. Therefore, data after 5 min are reported (Table III). In particular, the *Wx-B1b* group showed significantly increased springiness, cohesiveness, and chewiness over the *Wx-B1a* group, but hardness was not affected in the cross progeny. On the other hand, the cultivar survey showed *Wx-B1b* group averaged significantly higher springiness, cohesiveness, and hardness, but did not affect chewiness.

Previous reports have documented changes in noodle texture from loss of Wx-B1 protein, though most have not measured the specific noodle texture traits as measured here (0da et al 1980; Miura and Tanii 1994; Zhao et al 1998). Epstein et al (2002) found texture of white salted noodles became softer but more cohesive and springy with the successive loss of the three Wx proteins in a set of recombinant inbred lines segregating for the three *Wx* loci. Springiness is a measure of elasticity while cohesiveness measures the ability of the noodle to stick to itself (Epstein et al 2002). Noodle texture preferences vary with noodle type, region, and individual. Generally, consumers prefer white salted noodles made from hard wheat flours that are elastic with a firm bite. It is not known whether the change in noodle textural profile noted here could be discerned by sensory evaluation.

The *Wx-b1* allelic difference affected amylose content and FSP and, subsequently, some key bread and noodle traits. The two allelic classes did not overlap for amylose for the cultivar survey group, but considerable overlap between classes was observed for the cross progeny. Amylose ranges were 29.9–33.1% for *Wx-B1a* and 24.7–29.7% for *Wx-B1b* for the cultivar survey, and 27.5–34.9% for *Wx-B1a* class and 25.5–32.1% for *Wx-B1b* class for the cross progeny. The allelic difference accounted for 72 and 87% of the variation among entry means in the cultivar survey group, 24 and 44% of the variation among entry means in the cross progeny for amylase and FSP, respectively.

Association Between Starch, Bread, and Noodle Texture Quality Traits

A highly negative correlation was observed between amylose content and FSP for the progeny ($r = –0.57$, $P < 0.01$) and the cultivar survey ($r = –0.85$, $P < 0.01$). Amylose was not related to flour protein for the cross progeny ($r = –0.13$), while it was negatively related to flour protein for the cultivar survey ($r = –0.48$, $P < 0.01$). Flour swelling power and flour protein were unrelated for the cross progeny ($r = 0.10$) but showed a positive association for the survey group ($r = 0.47$, $P < 0.01$).

Similar trends were observed for associations between flour protein, FSP, and amylose content with bread quality traits water absorption, loaf volume, and crumb grain score for the cross progeny and the cultivar survey groups (Table IV). The relationships were usually weaker for the cross progeny group and were not always statistically significant. Bake absorption increased with increasing flour protein but was not statistically related with

TABLE III
Mean Values for *Wx-B1a* (Normal) Allele and *Wx-B1b* (Null) Allele for Cross Progeny from Cross of MTHW9420 (*Wx-B1b*) × MTHW9520 (*Wx-B1a*) Spring Wheat and for Survey of Spring Wheat Breeding Lines (31 advanced breeding lines and cultivars) for White Salted Noodle Texture 5 min After Cooking

Group and Wx-B1 Allele	No. of Lines	Springiness	Cohesiveness	Hardness (g)	Chewiness (g)
Cross progeny					
Wx-B1a	29	0.85	0.51	1,097	478.6
Wx-B1b	20	0.88	0.54	1,080	513.2
P value[a]		0.00	0.00	0.39	0.01
Parents					
MTHW9420 *Wx-B1b*		0.84	0.52	926	408.8
MTHW9520 *Wx-B1a*		0.87	0.52	1,109	506.8
LSD[b]		0.04	0.02	82	56.6
CV%[c]		3.2	2.1	5.3	8.1
Cultivar survey					
Wx-B1a	10	0.77	0.53	641.3	260.8
Wx-B1b	21	0.81	0.56	586.9	267.0
P value		0.00	0.01	0.00	0.62
LSD		0.05	0.03	76	47.1
CV%		3.4	2.9	6.3	8.9

[a] Difference between allelic class means.
[b] Least significant difference ($P < 0.05$); difference between any two entry means.
[c] Coefficient of variation.

FSP or amylose. Increasing loaf volume was associated with increasing FSP and decreasing amylose. Increased crumb grain was associated with decreasing FSP and increasing amylose. Increased bread firmness was associated with decreasing flour protein and FSP but with increasing amylose.

TABLE IV
Correlations for Flour Protein, Flour Swelling Power (FSP), and Amylose with Bread and Noodle Traits

Trait	Flour Protein	FSP	Amylose
Bake absorption			
Cross progeny[a]	0.55**[c]	0.13	–0.08
Survey[b]	0.66**	–0.15	0.15
Loaf volume			
Cross progeny	0.75**	0.28*	–0.21
Survey	0.84**	0.57**	–0.49**
Crumb grain			
Cross progeny	–0.26	–0.13	0.26
Survey	–0.70**	–0.54**	0.56**
Bread firmness 0 hr			
Cross progeny	–0.28*	–0.50**	0.26
Survey	–0.73**	–0.74**	0.69**
Bread firmness 24 hr			
Cross progeny	–0.57**	–0.45**	0.32*
Survey	–0.62**	–0.19	0.13
Noodle springiness			
Cross progeny	0.42**	0.51**	–0.24
Survey	0.66**	0.60**	–0.53**
Noodle cohesiveness			
Cross progeny	0.41**	0.57**	–0.34*
Survey	0.67**	0.69**	–0.54**
Noodle hardness			
Cross progeny	0.20	–0.37**	0.26
Survey	0.12	–0.50**	0.60**
Noodle chewiness			
Cross progeny	0.44**	0.14	–0.03
Survey	0.63**	0.20	–0.04

[a] 54 recombinant inbred lines from MTHW9420 × MTHW9520.
[b] 31 advanced breeding lines and cultivars.
[c] *,** Significant at the 0.05 and 0 01 level, respectively.

Noodle textural traits were highly positively related at 0 and 5 min following cooking for both groups. Correlations between 0 and 5 min ranged from 0.74 ($P < 0.01$) for springiness to 0.95 ($P < 0.01$) for hardness for cross progeny, and from 0.46 ($P < 0.01$) for springiness to 0.75 for hardness for the survey group. Since 5 min after cooking represents the point where noodle structure has been set and the two time points were highly related, the noodle textural values at 5 min were used in subsequent analyses. Except for noodle hardness, flour protein was related to noodle textural traits for both groups, where increased flour protein was associated with increased springiness, cohesiveness, and chewiness. Both FSP and amylose were related to noodle textural traits, except neither was associated with noodle chewiness. As amylose decreased and FSP increased, noodle springiness and cohesiveness increased while noodle hardness decreased for both groups, but correlations were not always statistically significant.

Two variable models with flour protein and either FSP or amylose accounted for the highest proportion of variation for loaf volume (highest R^2) (Table V). Because standardized regression coefficients are dimensionless, it is possible to examine the relative contribution of each variable after accounting for variation in the other. Although both variables often accounted for significant variation in the response variable, they did not yield much additional information beyond single variable models shown in Table IV.

The flour protein contribution was larger than either amylase or FSP, except the coefficient for FSP was larger in absolute value than that for flour protein for bread firmness at 0 hr and noodle hardness for both groups and for noodle springiness and cohesiveness for the cross progeny group. Two variable models showed that flour protein and either FSP or amylose contributed independently to the bread or noodle traits as the interaction between flour protein and the other variable was never significant (data not shown).

TABLE V
Standard Partial Regression Coefficients from Regressing Bread and Noodle Quality Traits on Flour Protein with Either Flour Swelling Power (FSP) or Amylose

	Flour Protein + FSP			Flour Protein + Amylose		
Trait	Flour Protein	FSP	R^2	Flour Protein	Amylose	R^2
Bake absorption						
Cross progeny[a]	0.54**[c]	0.08	0.31	0.55**	–0.01	0.30
Survey[b]	0.93**	–0.58**	0.69	0.95**	0.61**	0.72
Loaf volume						
Cross progeny	0.73**	0.22*	0.61	0.73**	–0.11	0.57
Survey	0.73**	0.23*	0.74	0.78**	–0.11	0.71
Crumb grain						
Cross progeny	–0.25	–0.10	0.08	–0.23	0.22	0.11
Survey	–0.45**	–0.32*	0.44	–0.44*	0.32*	0.44
Bread firmness 0 hr						
Cross progeny	–0.23*	–0.48**	0.30	–0.25	0.23	0.13
Survey	–0.49**	–0.51**	0.74	–0.52**	0.45**	0.67
Bread firmness 24 hr						
Cross progeny	–0.53**	–0.40**	0.48	–0.54**	0.25	0.40
Survey	–0.68**	0.13	0.40	–0.72**	–0.21	0.42
Noodle springiness						
Cross progeny	0.38**	0.47**	0.40	0.39**	–0.19	0.21
Survey	0.49**	0.37*	0.55	0.53**	–0.27	0.49
Noodle cohesiveness						
Cross progeny	0.35**	0.54**	0.45	0.37**	–0.29*	0.25
Survey	0.49**	0.44**	0.63	0.52**	–0.29	0.51
Noodle hardness						
Cross progeny	0.24	–0.39*	0.19	0.24	0.30*	0.13
Survey	0.46*	–0.72*	0.41	0.54*	0.86**	0.58
Noodle chewiness						
Cross progeny	0.43**	0.10	0.20	0.49**	0.01	0.19
Survey	0.68**	–0.11	0.41	0.78**	0.32*	0.47

[a] 54 recombinant inbred lines from MTHW9420 × MTHW9520.
[b] 31 advanced breeding lines and cultivars.
[c] *,** Significant at the 0.05 and 0 01 level, respectively.

The average effect of the *Wx-B1b* over the *Wx-b1a* allele was toward enhanced bread quality with increased loaf volume and softer texture. On the other hand, the changes in certain textural characteristics for white salted noodles may be detrimental to consumer preference. The cross progeny provided a means to examine the effect of the *Wx-B1* allelic difference averaged over other genetic factors. The cultivar survey suffers from the disadvantage that the allelic difference observed may be confounded with genetic background. However, it is interesting to note that results from the two sets of genetic materials were very similar.

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