Influence of puroindoline genotypes on grain characteristics, physico-chemical properties of flour and end-use quality of Korean wheats

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Puroindoline genotypes, grain characteristics, physico-chemical properties of flour and end-use qualities of Korean wheat cultivars were evaluated to determine the influence of puroindolines genotypes and to provide on those characteristics. Nine Korean wheat cultivars carried *Pina-D1a/Pinb-D1a*, fourteen had *Pina-D1a/Pinb-D1b*, and three had *Pina-D1b/Pinb-D1a*. *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b* genotypes showed significantly higher 1000-kernel weight and hardness index in grain characteristics, higher flour yield, average particle size, ash and protein content, SDS-sedimentation volume, water absorption and mixing time of mixograph, thickness of noodle dough sheet and lower values in lightness of flour and cookie diameter than *Pina-D1a/Pinb-D1a* genotype. The *Pina-D1b/Pinb-D1a* genotype showed significantly higher damaged starch content and water retention capacity than other genotypes. Hardness index of grain was positively correlated with flour yield and average particle size of flour. Those parameters were positively correlated with damaged starch, water retention capacity, SDS-sedimentation volume and water absorption of mixograph, and negatively correlated with lightness of wheat flour. In end-use qualities, thickness and lightness of noodle dough sheet and cookie diameter were correlated with hardness index, milling performances and physical properties. However, bread volume and texture of cooked noodles were not influenced by milling performances and physical properties.

Key Words: wheat, puroindolines, hardness, milling, flour, end-use quality.

Introduction

Grain hardness, either soft or hard, has been often used as a key determinant in differentiating wheat classes because hardness has influences on milling and end-use qualities of wheat (Morris and Rose 1996). Hard wheats generally produce coarser particles of flour and greater number of mechanically damaged starch than soft wheats. Therefore, hard wheat flours are generally used for bread and other yeast-leavened food, whereas soft wheats are preferred for pastries, cakes and cookies.

Symes (1965) reported that grain hardness of wheat is controlled by the hardness locus (*Ha*) located on the short arm of chromosome 5D. Barlow *et al.* (1973) proposed that the major gene must control the production of water-soluble proteins which surround starch granules. Greenwell and Schofield (1986) reported that friabilin, water-soluble 15-kDa protein found in the surface of starch and strongly associated with grain hardness, was identified in soft wheat starch granules. Jolly *et al.* (1993) reported that friabilin was abundant in all soft wheat starch granules, whereas rare on

hard wheat starches and absent in durum wheat.

Two major polypeptides, termed as puroindoline a (*Pina*) and b (*Pinb*), were identified as the major components of friabilin (Blochet *et al.* 1993, Gautier *et al.* 1994, Rahman *et al.* 1994). Genes coding for puroindolines are tightly linked to the *Ha* locus on chromosome 5D and probably function together with *Ha* locus (Sourdille *et al.* 1996, Giroux and Morris 1997, 1998). Soft wheats contain both *Pina-D1a* and *Pinb-D1a* genotypes, which are designated as the wild type of puroindolines. Up to date, 9 allelic variations at *Pina-D1* locus and allelic variations at *Pinb-D1* locus in common wheats were reviewed by Morris and Bhawe (2008).

Hard wheats carrying *Pina-D1b* allele showed different effects on milling and end-use qualities from *Pinb-D1a* genotypes. *Pina-D1b* genotypes showed harder grain texture, higher flour yield, protein content, damaged starch, water absorption, color score of noodles and loaf volume of bread and lower lightness and ash content of flour than hard wheats with *Pinb-D1b* (Giroux *et al.* 2000, Martin *et al.* 2001, Nagamine *et al.* 2003, Cane *et al.* 2004, Chen *et al.* 2007). In Korea, wheat breeding has been focused on increasing grain yield and early maturation and about 30 cultivars have been developed with the pedigree method since 1970s. Recently, quality improvement associated with flour

Communicated by H. Tsujimoto

Received February 3, 2010. Accepted July 20, 2010.

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and end-use has been received more attention by wheat breeders than ever in Korea. However, the information about influences of puroindoline genotypes on milling performance, characteristics of flour and end-use qualities are not available in Korean wheats. This study was conducted to elucidate the relationships among puroindoline genotypes, grain properties and milling performance, as well as to determine the influence of puroindoline genotypes on physicochemical properties of flour and qualities of pan bread, white salted noodles, and sugar-snap cookies made from Korean wheat cultivars in order to provide useful information for improving wheat quality in Korean wheat breeding programs.

Materials and Methods

Plant materials

Twenty six leading cultivars of Korean wheats were harvested at Iksan (Upland Crop Experimental Farm of National Institute of Crop Science, RDA) in 2007. The seeds were sown on October 20 and cultivated following the standard method of wheat in National Institute Crop Science. Mean temperature was higher (9.7°C) than that of average year (8.7°C) and average precipitation was lower (387.6 mm) than that of average year (492.0 mm).

PCR conditions for puroindoline genotypes

Genomic DNA was extracted from 100 mg of young leaf tissue using the Genomic DNA prep kit (Solgent Co., Korea) according to the manufacturer's instructions. The allelic variations for puroindolines were evaluated by the procedure described by Gautier *et al.* (1994).

Grain characteristics

Test weight and 1000-kernel weight were measured by Grain Scale (Seedburo Equipment Co., USA) and Seed Counter (Pfeuffer GmbH, Germany), respectively. Hardness index was measured by the single kernel characterization system (SKCS) 4100 (Perten Instruments AB, Sweden) according to the Approved Method 55-31 (AACC 2000).

Milling performances and flour characteristics

Wheat was milled using a Bühler experimental mill according to AACC Approved Methods 26-10. Two kilograms of wheat were conditioned overnight to reach 15% moisture content and then milled with feed rate of 100 g/min and roll settings of 8 and 5 in break rolls and 4 and 2 in reduction rolls. After milling, flour yield was calculated as the proportion of break and reduction flours to total products and break flour yield was calculated by the proportion of break flours to flour yield.

Distribution of flour particle size was measured by the multi-wavelength laser particle size analyzer LS13320 (Beckman Coulter, Inc., USA). Lightness of flour was measured by Minolta CM-2002 (Minolta Camera Co., Japan) with 11 mm measurement aperture. Moisture, ash content and water retention capacity of wheat flour were determined

according to Approved Methods 44-15A, 08-01 and 56-11. The determination of starch damage content was carried out following the procedure described by Gibson *et al.* (1992) using an enzymatic assay kits (MegaZyme Pty., Ltd., Australia). The SDS-sedimentation test was performed on a constant protein (300 mg) basis according to the procedure of Baik *et al.* (1994). Optimum water absorption and mixing time of wheat flour were determined using 10 g mixograph (National Mfg., USA) according to the approved method, 54-40A (AACC 2000). Dough development was measured by rheofermentometer (Chopin, France) according to the procedure of Czuchajowska and Pomeranz (1993).

Pan bread baking

Pan bread was baked according to the straight-dough methods described by Finney (1984). The ingredients of baking formula consisted of 100 g (14% moisture basis) of flour, 6 g of sugar, 3 g of shortening, 1.5 g of salt, 5.0 g of fresh yeast, 50 mg of ascorbic acid, and 0.25 g of barley malt (about 50 DU/g, 20°C). The dough was fermented in a cabinet at 30°C and 85% relative humidity for 70 minutes with two punches and a proof period of 60 min, and then baked at 210°C for 18 min. Bread loaf volume was measured by rape-seed displacement in a graduated chamber after cooling for two hours at the room temperature.

Preparation of white salted noodles

White salted noodles were prepared with 34% water absorption percent of noodle dough according to the methods described by Park *et al.* (2002). The procedure of noodle making was as follows: 100 g of flour (14.0% moisture basis) was mixed to 34% absorption with 6% sodium chloride solution using a pin mixer (National Mfg., USA) for 4 min with the head speed of 86 rpm. Dough was passed through the rollers of a noodle machine (Ohtake Noodle Machine Mfg., Japan) at 8 rpm and 3 mm gap; dough was folded and put through the sheeting rollers. The folding and sheeting were repeated twice. The dough sheet was rested for 1 hr and then put through the sheeting rollers three times at progressively decreasing gaps of 2.40, 1.85 and 1.30 mm. A piece of noodle sheet was placed in plastic bags for determination of color. Lightness of the dough sheet was measured by Minolta CM-2002 (Minolta Camera Co., Japan) with 11 mm measurement aperture. The rest of the dough sheet was cut through no. 12 cutting rolls into strips about 30 cm in length. The rest of the dough sheet was cut through No. 12 cutting rollers into noodle strands of about 30 cm in length, with cross section of 0.3 × 0.2 cm.

Textural properties of cooked noodles

Raw noodles (20 g) were cooked at the determined cooking time in 500 ml of boiling distilled water for 18 min and then rinsed with cold water. Two replicates of cooked noodles were evaluated by texture profile analysis (TPA) using TA-XT2 Texture Analyser (Stable Micro Systems, England) within 5 min after cooking. One set of five strands of cooked

Table 1. Released year, pedigree, growth habit, heading date, maturing date and yield of 26 Korean wheat cultivars

Cultivar	Released Year	Pedigree	Vernalization (I–VII)	Heading date (M.D)	Maturing date (M.D)	Culm length (Cm)	Yield (MT/ha)
Ol	1976	Norin72/Norin12	III	5.5	6.13	85	3.84
Gereu	1980	Strampelli/69D-3607//Chokwang	III	5.2	6.9	75	3.93
Dahong	1979	Norin72/Wonkwang	III	4.28	6.8	74	4.46
Chungkye	1979	Norin4/Sharbatisonora	IV	4.29	6.8	71	4.51
Eunpa	1982	Chukoku81/3/Tob-CNO//Yuksung3/Suwon185	III	5.1	6.11	76	3.95
Tapdong	1986	Chukoku81//Suwon158/Toropi	IV	5.3	6.11	62	4.70
Namhae	1988	Ol/Calidad	III	5.2	6.11	81	5.41
Uri	1992	Geuru/Ol	III	4.27	6.7	79	5.29
Olgeuru	1994	Geuru/Chokwang//Nishigai143	III	4.26	6.8	80	4.77
Alchan	1995	Suwon210/TapdongAlchan, Anbaek	III	4.30	6.11	68	4.89
Gobun	1996	Eunpa/Tapdong//Eunpa/Shannung6521	III	4.30	6.11	72	4.78
Keumkang	1997	Geuru/Kanto75//Eunpa	III	4.28	6.9	73	4.22
Seodun	1997	Geuru/Genaro81	III	4.29	6.9	71	4.85
Saeol	1997	Sirogane//Norin43/Sonalika	II	4.27	6.8	66	5.32
Jinpoom	1998	Geuru/Genaro81	III	5.1	6.11	75	5.30
Milsung	1998	Sirogane//Norin43/Sonalika	II	4.27	5.28	70	5.24
Joeun	2000	Eunpa/Suwon242	III	4.21	5.29	74	4.14
Anbaek	2001	Sae/Geuru	IV	4.30	6.8	70	5.42
Jopoom	2001	Kanto75//OR8500494P/Bezostaya	III	4.20	6.1	64	4.54
Jonong	2003	Suwon234/SW80199	III	4.17	5.30	67	4.65
Jokyung	2004	Seri82/Keumkang	II	4.19	6.2	81	5.19
Younbaek	2005	Keumkang/Tapdong	III	4.23	6.4	77	6.05
Baekjoong	2007	Keumkang/Olgeuru	II	4.29	6.7	77	5.35
Jeokjoong	2007	Keumkang/Tapdong	II	4.28	6.7	78	5.33
Sukang	2008	Suwon266/Asakaje	III	4.28	6.8	90	4.72
Hanbaek	2008	Shann7859/Keumkang//Guamuehill	IV	4.27	6.8	89	5.05

noodles was placed parallel on a flat metal plate and compressed crosswise twice to 70% of their original height using a 3.175 mm metal blade at the speed of 1.0 mm/sec. From force-time curves of the TPA, hardness, springiness and cohesiveness were determined according to the description of Park *et al.* (2002).

Cookie baking

The cookie formula and baking procedures were followed as described by Finney *et al.* (1950) in micro method III. Baked cookies were rested for two hours at the room temperature and their diameter was measured.

Statistical analysis

Statistical analysis of data was performed by SAS software (SAS Institute, NC, USA) using Fisher's least significant difference procedure (LSD), analysis of variance (ANOVA) and Pearson correlation coefficient. Differences were considered to be significant at $P < 0.05$, unless otherwise specified. All data were determined at least in duplicate and all were averaged.

Results

Grain characteristics and milling performances

Table 1 shows pedigree, growth habit, heading date,

maturing date and yield of 26 Korean wheat cultivars. Based on the pedigree of Korean wheat cultivars, germplasm from Japan and international maize and wheat improvement centre (CIMMYT) has mainly contributed to early maturation and increasing grain yield. Korean wheat cultivars developed in 2000s showed earlier heading and maturation date and higher grain yield than cultivars developed in 1980s and 1990s although there was no differences in growth habit and length. Nine Korean wheat cultivars (Chungkye, Dahong, Jonong, Milseong, Namhae, Ol, Olgeuru, Saeol, Uri and Younbaek) showed *Pina-D1a/Pinb-D1a* genotype (Table 2). Fourteen cultivars had *Pina-D1a/Pina-D1b* allele

Table 2. Classification of Korean wheat cultivars with respect to the puroindolines genotypes

Genotype	No. of line	Korean wheat cultivar
<i>Pina-D1a</i> <i>Pinb-D1a</i>	9	Chungkye, Dahong, Jonong, Milseong, Namhae, Ol, Olgeuru, Saeol, Uri
<i>Pina-D1a</i> <i>Pinb-D1b</i>	14	Alchan, Anbaek, Baekjoong, Eunpa, Geuru, Gobun, Hanbaek, Jeokjoong, Jinpoom, Jokyung, Jopoom, Keumkang, Seodun, Tapdong
<i>Pina-D1b</i> <i>Pinb-D1a</i>	3	Joeun, Sukang, Younbaek

Fig. 1. Agarose gel electrophoresis of PCR amplified *Pina-D1* allele (A) and *Pinb-D1* (B) cut with *BsrBI* of Korean wheat cultivars. M, molecular size marker; 1, Jokyeong; 2, Geuru; 3, Keumkang; 4, Uri; 5, Jonong; 6, Tapdong; 7, Joeun; 8, Younbaek.

and three cultivars (Joeun, Sukang and Younbaek) carried *Pina-D1b/Pinb-D1a* allele. *Pina-D1a* allele was 447 bp in agarose gel electrophoresis of PCR, but no product was found in *Pina-D1b* (Fig. 1A). *Pinb-D1a* and *Pinb-D1b* showed 320 bp and 200 bp, respectively after restriction with *BsrBI* of PCR products (447 bp) of *Pinb-D1* allele (Fig. 1B).

Table 3 summarizes grain characteristics, milling performances, physico-chemical properties of wheat flour, dough rheology and end-use quality of Korean wheat flours with different puroindoline genotypes. Korean wheats carrying *Pina-D1a/Pinb-D1a* showed lower thousand kernel weight, hardness index of grain and flour yield (38.83 g, 31.73 and 62.20%, respectively) than wheats with *Pina-D1a/Pinb-D1b* (43.82 g, 64.91 and 69.54%, respectively) and *Pina-D1b/Pinb-D1a* (39.06 g, 67.50 and 71.07%, respectively). However, there were no significant differences in grain characteristics and milling performances between *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b* genotypes. No significant differences in test weight and the proportion of break flour were found among puroindoline genotypes. In Korean wheat cultivars with all different puroindoline genotypes, flour yield was positively correlated with 1000 kernel weight ($r = 0.474$, $P < 0.05$) and hardness index ($r = 0.597$, $P < 0.001$, Fig. 2A). Hardness index of grain was positively correlated with test weight ($r = 0.443$, $P < 0.05$) and negatively correlated with the proportion of break flour ($r = -0.444$, $P < 0.05$). In Korean wheats with *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b*, flour yield was negatively correlated with test weight ($r = -0.528$, $P < 0.05$, Fig. 3A) and positively correlated with the proportion of break flour ($r = 0.575$, $P < 0.05$, Fig. 3B).

Physico-chemical properties and dough rheology

In Korean wheats with *Pina-D1a/Pina-D1b* allele, ash and protein content, SDS-sedimentation volume, optimum water absorption and mixing time of mixograph were higher than those of *Pina-D1a/Pinb-D1a* while average particle size of wheat flour and lightness of flour were lower than those of *Pina-D1a/Pinb-D1a* (Table 3). But there were no significant differences in these properties between *Pina-*

Table 3. Differences in grain characteristics, milling performances, physico-chemical properties of flour, dough rheology and end-use quality in Korean wheat cultivars with all different puroindoline genotypes using pair-wise *t*-test

Characteristics	Allele		
	<i>Pina-D1a</i> <i>Pinb-D1a</i>	<i>Pina-D1a</i> <i>Pinb-D1b</i>	<i>Pina-D1b</i> <i>Pinb-D1a</i>
Number of cultivar	9	14	3
<i>Grain characteristics</i>			
Test weight (g)	811.67a ^a	822.57a	829.50a
1000-kernel weight (g)	38.83b	43.82a	39.06ab
Hardness index	31.73b	64.91a	67.50a
<i>Milling performances</i>			
Flour yield (%)	62.20b	69.54a	71.07a
Proportion of break flour (%)	29.40a	26.99a	27.98a
<i>Physico-chemical properties of flour</i>			
Average particle size (μm)	64.26b	86.72a	96.62a
Ash (%)	0.46b	0.51a	0.57a
Damaged starch (%)	2.08c	3.50b	3.81a
Water retention capacity (%)	65.18c	70.41b	73.95a
Lightness of flour	90.73a	89.22b	88.99b
Protein (%)	10.36b	11.39ab	12.81a
Amylose (%)	25.42a	25.03a	24.59a
SDS-sedimentation volume (ml)	29.72b	47.14a	45.17a
<i>Dough rheology</i>			
Absorption of mixograph (%)	57.33b	59.43a	59.67a
Mixing time of mixograph (min)	2.99b	3.70a	3.22a
Maximum height of dough (mm)	29.93a	35.00a	32.85a
<i>End-use qualities</i>			
Loaf volume (ml)	793.89a	801.43a	790.83a
Thickness of noodle dough sheet (mm)	1.77b	1.85a	1.91a
Lightness of noodle dough sheet	83.47a	82.14a	81.42a
Hardness of cooked noodles (N)	4.64a	5.13a	4.96a
Springiness of cooked noodles (Ratio)	0.92a	0.93a	0.93a
Cohesiveness of cooked noodles (Ratio)	0.63a	0.63a	0.63a
Cookie diameter (mm)	80.84a	76.56b	76.64b

^a Values followed by same letters within same characteristics are not significantly different at $P < 0.05$.

D1b/Pinb-D1a and *Pina-D1a/Pinb-D1b*. Damaged starch and water retention capacity of *Pina-D1b/Pinb-D1a* were higher than those of other genotypes and *Pina-D1a/Pinb-D1b* showed higher values in these properties than *Pina-D1a/Pinb-D1a*. There were no significant differences in amylose content and maximum height during dough development among puroindoline genotypes.

In Korean wheat cultivars with all different puroindoline genotypes, average particle size of flour was positively correlated with flour yield ($r = 0.663$, $P < 0.001$, Fig. 2B) and damaged starch content ($r = 0.803$, $P < 0.001$, Fig. 2C). Average particle size of flour was also positively correlated with ash and protein content, SDS-sedimentation volume, optimum water absorption of mixograph and negatively correlated with lightness of wheat flour. Damaged starch content was positively correlated with hardness index of grain, flour yield, and water retention capacity. Lightness of wheat flour was negatively correlated with damaged starch ($r = -0.791$, $P < 0.001$, Fig. 2D) and water retention capacity

Fig. 2. The relationships between grain characteristics and physical properties of Korean wheat flours with all different puroindoline genotypes. A, hardness index of grain and flour yield; B, flour yield and average of particle size of flour; C, average particle size of flour and damaged starch; D, damaged starch and water retention capacity; E, damaged starch and lightness of flour; F, water retention capacity and lightness of flour. ○; Korean wheats with *Pina-D1a/Pinb-D1a*, ▲; Korean wheats with *Pina-D1a/Pinb-D1b*, ■; Korean wheats with *Pina-D1b/Pinb-D1a*.

($r = -0.557$, $P < 0.05$, Fig. 2E). SDS-sedimentation volume was positively correlated with mixing time of mixograph and maximum height during dough development. Optimum water absorption of mixograph was negatively correlated with hardness index of grain and the proportion of break flour and positively correlated with average particle size of flour, and protein and damaged starch content ($r = 0.427$, $P < 0.05$, Fig. 2F). There were no significant relationships between mixing time of mixograph and maximum height,

grain characteristics, milling performances and physico-chemical properties of wheat flour.

In Korean wheat cultivars with *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a*, hardness index was positively correlated with damaged starch ($r = 0.637$, $P < 0.01$, Fig. 3C) and water retention capacity ($r = 0.668$, $P < 0.01$, Fig. 3D) and water retention capacity was negatively correlated with 1000 kernel weight ($r = -0.559$, $P < 0.05$, Fig. 3E), flour yield ($r = -0.516$, $P < 0.05$, Fig. 3F) and maximum height during

Fig. 3. The relationships between grain characteristics and physical properties of Korean wheat flours with *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a*. A, test weight and flour yield; B, 1000 kernel weight and water retention capacity; C, hardness index and damaged starch; D, hardness index and water retention capacity; E, flour yield and proportion of break flour; F, flour yield and water retention capacity. ○; Korean wheats with *Pina-D1a/Pina-D1b*, ●; Korean wheats with *Pinb-D1a/Pinb-D1a*.

dough development. There was no significant correlation between rheological properties, grain characteristics, milling performances and physico-chemical properties, although maximum height during dough development was positively correlated with SDS-sedimentation volume and mixing time of mixograph.

End-use qualities

Pina-D1a/Pinb-D1a showed lower thickness of noodle

dough sheet and larger cookie diameter than *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a*. There were no significant differences in these properties between *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b*. No significant differences were found in loaf volume of bread, lightness of noodle dough sheet and texture of cooked noodles among puroindoline genotypes.

Table 4 shows the relationships among grain characteristics, milling performances, physico-chemical properties and

Table 4. Correlation coefficients among grain characteristics, milling performances, physico-chemical properties and end-use qualities of Korean wheat cultivars with all different puroindoline genotypes

Parameters	End-use quality						Cookie diameter
	Bread loaf volume	White salted noodles					
		Dough sheet		Texture of cooked noodles			
		Thickness	Lightness	Hardness	Springiness	Cohesiveness	
<i>Grain characteristics</i>							
Test weight	−0.038	0.532** <i>a</i>	−0.381	0.360	−0.144	−0.005	−0.298
1000-kernel weight	0.194	0.199	−0.331	0.120	0.169	0.378	−0.330
Hardness index	0.004	0.640***	−0.395*	0.252	−0.028	0.185	−0.731***
<i>Milling performances</i>							
Flour yield	−0.030	0.507*	−0.042	−0.109	0.225	0.355	−0.517**
Proportion of break flour	−0.249	−0.380	0.389*	−0.495***	0.068	−0.240	0.390*
<i>Physico-chemical properties of flour</i>							
Average particle size	0.091	0.636***	−0.487*	0.293	0.081	0.441*	−0.530**
Ash	0.051	0.480*	−0.640***	0.535**	−0.285	−0.125	−0.305
Damaged starch	0.036	0.706***	−0.404*	0.205	0.074	0.288	−0.747***
Water retention capacity	−0.287	0.322	−0.401*	0.236	−0.201	−0.221	−0.413*
Lightness of flour	0.116	−0.651***	0.528**	−0.197	−0.041	−0.253	0.619***
Protein	0.249	0.725***	−0.879***	0.687***	0.073	0.416*	−0.434*
Amylose	−0.093	−0.363	0.547**	−0.456*	−0.152	−0.362	0.212
SDS-sedimentation volume	0.076	0.469*	−0.126	0.136	0.324	0.210	−0.659***
<i>Dough rheology</i>							
Absorption of mixograph	0.442*	0.571**	−0.727***	0.769***	0.181	0.608***	−0.449*
Mixing time of mixograph	0.493*	0.183	0.017	0.211	0.264	0.198	−0.351
Maximum height of dough	0.589**	0.115	0.072	0.167	0.212	0.286	−0.196

^a* indicates significance at 0.05 level, ** at 0.01 level, and *** at 0.001 level.

end-use qualities of Korean wheat cultivars with all different puroindoline genotypes. Loaf volume of bread was positively correlated with mixograph properties and maximum height of dough. Thickness of noodle dough sheet was positively correlated with hardness index, flour yield, average particle size, damaged starch and protein content, and optimum water absorption of mixograph in all different puroindoline genotypes. Those properties were negatively correlated with lightness of noodle dough sheet and cookie diameter. Flour yield was positively correlated with thickness of noodle dough sheet and negatively correlated with cookie diameter. The proportion of break flour was positively correlated with lightness of noodle dough sheet and cookie diameter. Protein content and optimum water absorption of mixograph were positively correlated with hardness and cohesiveness of cooked noodles. The proportion of break flour and average particle size were also correlated with those parameters of cooked noodles.

Table 5 shows the relationships among grain characteristics, milling performances, physico-chemical properties and end-use qualities of Korean wheat cultivars with *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a*. Loaf volume of bread was negatively correlated with water retention capacity and positively correlated with mixing time of mixograph and maximum height of dough. Properties of noodle dough sheet were significantly correlated with protein content and optimum water absorption of mixograph. Ash content and light-

ness of flour were also correlated with lightness of noodle dough sheet. Hardness of cooked noodles was correlated with flour milling performances, protein content and optimum water absorption of mixograph. Springiness of cooked noodles was positively correlated with flour yield, although springiness showed no significant relationships with grain characteristics, milling performances and physico-chemical properties of wheat flours with all different puroindoline genotypes. Cohesiveness of cooked noodles was correlated with water retention capacity and optimum water absorption of mixograph. Cookie diameter showed no significant relationships with grain characteristics, milling performances and physico-chemical properties of wheat flours.

Discussion

Most Korean wheat cultivars were shown to have *Pina-D1a/Pinb-D1b*, which was similar to the genetic variations of CIMMYT lines, North American, Europe, China and Australia (Lillemo and Morris 2000, Morris *et al.* 2001, Cane *et al.* 2004, Xia *et al.* 2005, Chen *et al.* 2006, Lillemo *et al.* 2006, Pickering and Bhavé 2007). There were no significant differences in grain characteristics and milling performances of Korean wheats with *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b* genotypes, although these genotypes showed higher 1000 kernel weight, hardness index and flour yield than Korean wheats with *Pina-D1a/Pinb-D1a*

Table 5. Correlation coefficients among grain characteristics, milling performances, physico-chemical properties and end-use qualities of Korean wheat cultivars with *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b*

Parameters	End-use quality						Cookie diameter
	Bread loaf volume	White salted noodles					
		Dough sheet		Texture of cooked noodles			
		Thickness	Lightness	Hardness	Springiness	Cohesiveness	
<i>Grain characteristics</i>							
Test weight	0.056	0.349	−0.236	0.366	−0.127	−0.068	−0.149
1000-kernel weight	0.088	−0.209	0.003	−0.181	0.077	0.270	0.060
Hardness index	−0.292	0.223	−0.110	0.013	−0.152	−0.364	−0.433
<i>Milling performances</i>							
Flour yield	−0.094	0.024	0.448	−0.512*	0.496*	0.145	−0.008
Proportion of break flour	−0.177	−0.371	0.412	−0.573*	0.283	−0.119	0.362
<i>Physico-chemical properties of flour</i>							
Average of particle size	−0.065	0.135	−0.028	−0.146	0.121	0.404	0.134
Ash	−0.033	0.326	−0.557*	0.440	−0.533*	−0.308	−0.132
Damaged starch	−0.052	0.423	−0.100	−0.140	0.210	0.051	−0.470
Water retention capacity	−0.542 ^{*a}	−0.023	−0.246	0.081	−0.412	−0.581*	0.034
Lightness of flour	0.264	−0.368	0.517*	0.010	−0.199	−0.125	0.210
Protein	0.157	0.712**	−0.854***	0.592*	0.074	0.413	−0.191
Amylose	−0.131	−0.271	0.562*	−0.467	−0.161	−0.382	−0.172
SDS-sedimentation volume	0.081	0.012	0.500*	−0.164	0.414	−0.050	−0.293
<i>Dough rheology</i>							
Absorption of mixograph	0.272	0.519*	−0.626**	0.762***	−0.008	0.568*	−0.014
Mixing time of mixograph	0.605**	−0.067	0.409	0.125	0.073	0.048	−0.149
Maximum height of dough	0.721***	−0.135	0.408	0.019	0.135	0.205	0.061

^a* indicates significance at 0.05 level, ** at 0.01 level, and *** at 0.001 level.

genotypes. Nagamine *et al.* (2003) reported that *Pina-D1a/Pinb-Db* had higher flour yield than *Pina-D1a/Pinb-Da* in 110 doubled haploid lines, although there was no significant difference in 1000 kernel weight. Hard wheats with *Pina-D1a/Pinb-D1b* had significantly higher flour yield, break flour yield and milling score than wheats with *Pina-D1b/Pinb-D1a* in recombinant inbred lines of hard red spring wheats (Martin *et al.* 2001) and Australian wheats (Eagles *et al.* 2006). However, there was no significant difference in flour yield and proportion of break flour between *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a* genotypes in Korean wheats.

Hardness index of SKCS is widely accepted as the standard method to determine the single wheat kernel texture and is the most discriminating measure of the material properties of the wheat endosperm manifested by the action of the *Ha* locus (Moris *et al.* 1999, Osborne and Anderssen 2003). Hardness index was significantly correlated with flour yield and the proportion of break flour in Korean wheats with all puroindoline genotypes, but no significant relationships were found in Korean hard wheats. However, hardness index was negatively correlated with flour yield in hard wheats (Ohm *et al.* 1998, Martin *et al.* 2001) and Chinese winter wheats (Zhang *et al.* 2005) and also negatively correlated with break flour yield in US wheats with various puroindoline genotypes (Bettge and Morris 2000).

Korean wheats with *Pina-D1a/Pinb-D1a* genotypes

showed different physico-chemical properties including particle size of wheat flours, flour color, ash, protein and damaged starch content, water retention capacity, SDS-sedimentation volume and mixograph properties from Korean wheats with *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b* genotypes. Soft wheats showed lower average particle size of flour, ash and damaged starch content, and higher lightness of flour than hard wheats in doubled haploid lines from Japan and US wheats with different puroindoline genotypes (Bettege and Morris 2000, Nagamine *et al.* 2003). Korean wheats with *Pina-D1b/Pinb-D1a* had greater starch damage in milling processing than *Pina-D1a/Pinb-D1b* genotypes and the damage could have an effect on water absorption of rheological properties, which are in agreement with previous results (Cane *et al.* 2004, Eagles *et al.* 2006, Chen *et al.* 2007). There were no significant differences in any other physico-chemical properties and mixing properties between those Korean wheat cultivars. In hard red spring wheats and cultivated wheats in China, *Pina-D1a/Pinb-D1b* had lower ash content and brighter flour color than *Pina-D1b/Pinb-D1a* but there was no difference in mixing time of mixograph (Martin *et al.* 2001, Chen *et al.* 2007). In near-isogenic lines of puroindolines, no difference was found in ash content and water retention capacity between *Pina-D1a/Pinb-D1b* and *Pina-D1b/Pinb-D1a*, however, the former had lower damaged starch content and brighter color than the latter (Ma *et al.* 2009).

In Korean wheats, physical properties of flour including average particle size of flour, ash and damaged starch content, water retention capacity and lightness of flour showed significant relationships with hardness index or flour yield. There were also significant relationships between these physical properties in Korean wheats. Those results are in good agreement with previous results (Bettege and Morris 2000, Morgan *et al.* 2000, Martin *et al.* 2001, Nagamine *et al.* 2003, Zhang *et al.* 2005, Chen *et al.* 2007). Therefore, grain characteristics, especially hardness index of grain, could have influence on the milling performance and physical properties of Korean wheat flours.

Pina-D1b/Pinb-D1a genotypes had better bread quality in pan bread and Chinese steam bread than *Pina-D1a/Pinb-D1b* (Martin *et al.* 2001, Chen *et al.* 2007). However, there were no significant differences in bread volume among Korean wheats, although bread volume showed significant relationships with dough rheological properties. It should be considered to increase the frequency of *Pina-D1b/Pinb-D1a* genotypes in Korean wheat cultivars with strong gluten strength to improve bread-baking quality. In noodle making properties and texture of cooked noodles from Korean wheats, no significant differences were found among puroindoline genotypes except for thickness of noodle dough sheet. Ma *et al.* (2009) reported that there were no significant differences in qualities for Chinese raw white noodles between *Pina-D1b/Pinb-D1a* and *Pina-D1a/Pinb-D1b*. They also proposed that *Pina-D1a/Pinb-D1e* and *Pina-D1a/Pinb-D1g* had slightly superior noodle qualities in comparison with other genotypes. However, Chen *et al.* (2007) reported that *Pina-D1b/Pinb-D1a* also had higher noodle score for dry white Chinese noodles than *Pina-D1a/Pinb-D1b* and *Pina-D1a/Pinb-D1a*. Therefore, it should be considered to introduce various puroindoline genotypes such as *Pina-D1a/Pinb-D1e* and *Pina-D1a/Pinb-D1g* to improve noodle quality. Cookie diameter was influenced by hardness index, milling performances and physico-chemical properties, and especially by the particle size of flour, damaged starch content and SDS-sedimentation volume. *Pina-D1a/Pinb-D1a* had larger cookie diameter than other genotypes, which is in agreement with the report of Bettge and Morris (2000).

Grain hardness, flour yield and physical properties of flour were mainly associated with the genetic variations of puroindolines in Korean wheat cultivars. Most of the Korean wheat cultivars developed in the 2000s showed hard wheat type in puroindoline alleles because of higher flour yield than soft wheat types. Korean wheat cultivars carrying *Pina-D1b* or *Pinb-D1b* alleles showed higher grain weight, flour yield, average of particle size of flour, damaged starch content and water absorption than Korean wheats with *Pina-D1a* and *Pinb-D1a* alleles. However, end-use qualities have not been affected by the allelic variations in puroindolines, albeit significant differences were found in dough rheological properties. Therefore, it is necessary to introduce various puroindoline genotypes, like *Pinb-D1e* and *Pinb-D1g* alleles and increase the frequency of *Pina-D1b* allele of Korean

wheats to improve flour yield and qualities of bread and noodles to overcome the narrow genetic background in glutenin and puroindolines. In addition to puroindolines, factors related to starch pasting properties and discolorations, such as *Wx-1*, *Ppo-2* and *Psy-1* alleles, should be investigated to improve noodle processing and textural properties of cooked noodles. It is necessary to introduce diverse *Glu-3* alleles in Korean wheat cultivars with *Glu-D1d* alleles to improve dough strength for better bread-baking qualities.

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