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Structural and physical characteristics of waxy and other wheat starches ☆

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Abstract

Structures and properties of starches isolated from waxy wheat, amylose-reduced wheat (Kanto 107), and normal hard red winter wheat (Centura and a commercial product) grains were examined. Apparent amylose contents of the four starches were < 0.2, 21.5, 26.2, and 26.6%, respectively. Waxy wheat amylopectin (AP) had the largest molecular weight (M_w) and no detectable extra-long branch-chains. The M_w of the AP displayed a negative correlation with the amylose content of the wheat starch, whereas the proportion of extra-long branch-chains of AP displayed a positive correlation with amylose content. Relationships between the M_w and gyration radius (R_z) suggested that the structure of waxy AP was more compact than that of other wheat APs. Branch chain-length distributions of AP analyzed by high-performance anion-exchange chromatography (HPAEC) showed that the peak chain-lengths of all the wheat starches were at DP12, and average chain-lengths varied between DP23.5 and 24.9. Centura AP had the highest proportion of long branch-chains (DP $\geq$ 25). Onset gelatinization temperatures of waxy wheat, Kanto107, Centura, and commercial wheat starches were 55.7, 57.5, 55.6, and 54.9°C, respectively, and enthalpy changes were 13.6, 11.8, 10.7, and 10.6 J/g, respectively. Differences in pasting temperature and peak viscosity between waxy and normal wheat starches were substantially greater than the differences between maize starch counterparts.

Keywords: Waxy wheat starch; Granule-bound starch synthase; Amylopectin; Extra-long chain; Weight-average molecular weight

1. Introduction

Wheat is one of the oldest and most extensively cultivated crops. Commercial cultivars are classified into soft red winter (SRW), hard red winter (HRW), hard red spring (HRS), and durum wheat (Seib, 1994). Starch is the major component of wheat grain and wheat flour. Properties and structures of common and durum wheat starches of different varieties have been reported (Bhattacharya, Jafari-Shabestari, Qualset, & Corke, 1997; Shibanuma, Takeda, & Hizukuri, 1996; Vansteelandt & Delcour, 1999).

Many waxy mutants have been identified in cereals, such as maize, rice, barley, sorghum and amaranth. Natural mutation that leads to amylose-free varieties is considered unlikely in wheat because of its hexaploid genome. Nevertheless, waxy hexaploid wheat has recently been produced by crossing the partial waxy mutants, Kanto 107 and Bai-Huo (Nakamura, Yamamori, Hirano, Hidaka, & Nagamine, 1995). Common wheat (*Triticum aestivum L.*) has three homologous waxy genes, WX-A1, WX-B1 and WX-D1 (Chao, Sharp, Worland, Warham, Koebner, & Gale, 1989). Kanto 107 is an amylose-reduced wheat carrying null alleles at two (WX-A1 and WX-B1) of the three WX loci and Bai-Huo is carrying one null allele at the D1 waxy locus. Waxy wheat mutants lack all three Wx proteins, also known as granule-bound starch synthases (GBSSI; EC 24.1.21). Genetic studies on mutants deficient in GBSSI have demonstrated its role in synthesis of amylose (Hylton, Denyer, Keeling, Chang, & Smith, 1996; Nakamura et al., 1995).

Potential use of wheat starch with reduced amylose content is a current topic of interest among wheat breeders and geneticists (Graybosch, 1998). One of the amylose-reduced wheat varieties is being used for producing Japanese Udon noodle because the starch contributes to overall textures of the cooked noodle. Several studies have reported structures and properties of starch derived from waxy wheat (Fujita, Yamamoto, Sugimoto, Morita, & Yamamori, 1998; Hayakawa, Tanaka, Nakamura, Endo, & Hoshino, 1997; Yasui, Matsuki, Sasaki, & Yamamori, 1996).

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In this study, we investigated the branch structure, molecular weight and gyration radius of amylopectin (AP), amylose content, and thermal and pasting properties of waxy wheat starch and compared them with those of Kanto 107 (amylose-reduced wheat), Centura (HRW wheat), and commercial wheat starch. We also attempted to unravel the relationship between molecular weight, gyration radius, and dispersed molecular density of AP. Pasting properties of waxy and normal wheat starches were compared with those of maize starch counterparts.

2. Materials and methods

2.1. Materials

Waxy wheat, F4 seeds, descended from the cross of Kanto 107 and Bai-Huo, were grown in Southern California in 1998. Kanto 107 is an amylose-reduced wheat carrying null alleles at two (WX-A1 and WX-B1) of the three WX loci. Centura is HRW wheat with three active WX alleles (wild type). A commercial hard red winter wheat starch was obtained from Midwest Grain Products, (Atchison, KS) and used for comparison. Waxy and normal maize starches were gifts of Cerestar, USA (Hammond, IN). Isoamylase (EC 3.2.1.68), from *Pseudomonas amyloderamosa*, was purchased from Hayashibara Biochemical Laboratories, (Okayama, Japan), and amyloglucosidase (EC 3.2.1.3), from *Rhizopus* mold [9032-80-0], was purchased from Sigma Chemical (St. Louis, MO). Other chemicals (reagent grade) were used without further purification.

2.2. Starch isolation

Starches were isolated from wheat grains using a method reported by Badenhuizen (1964) with slight modification (Kasemsuwan, Jane, Schnable, Stinar, & Robertson, 1995). Isolated starch was washed three times with distilled water, rinsed twice with ethanol, and then recovered by filtration using Whatman No. 4 filter paper. Purified starch cake was dried in a convection oven at 35°C for 24 h.

2.3. Starch granule morphology by scanning electron microscopy

Starch granules spread on silver tape and mounted on a brass disk were coated with gold/palladium (60/40). Sample images were observed at 1500× magnification under a scanning electron microscope (JOEL model 1850, Tokyo, Japan) following the method of Jane, Kasemsuwan, Leas, Zobel, and Robyt (1994).

2.4. Crystalline structure by X-ray diffractometry

Crystallinity of starch granules was studied by using X-ray diffractometry. X-ray diffraction pattern was obtained with copper, nickel foil-filtered, Kα radiation using a Siemens D-500 diffractometer (Siemens, Madison, WI). The analysis was conducted by following the procedure of Song and Jane (2000). The degree of crystallinity was calculated based on the method of Hayakawa et al. (1997). The following equation was used to determine percent crystallinity:

$$\text{Crystallinity}(\%) = A_c/(A_c + A_a)100$$

where A_c is the crystalline area on the X-ray diffractogram and A_a is the amorphous area on the X-ray diffractogram.

2.5. Molecular weight distributions of amylopectin and amylose by gel permeation chromatography (GPC) and by high-performance size-exclusion chromatography (HPSEC)

Molecular weight distributions and amylose contents were determined by using GPC following the method of Jane and Chen (1992). An aliquot (5 ml) containing 15 mg starch and 0.75 mg glucose (as a marker) was loaded onto a Sepharose CL-2B gel (Pharmacia, Piscataway, NJ) column (2.6 cm i.d. × 90 cm). The column was run in an ascending mode. The elution profiles were analyzed for total carbohydrate (anthrone–sulfuric acid method) and blue value (iodine staining) at 630 and 640 nm, respectively, by using an Autoanalyzer II (Technicon Instrument Corp., Elmsford, NY) (Jane & Chen, 1992). The AP fractions (Fraction No. 20 to 35) were collected for analyzing their branch structures.

The weight-average molecular weight (M_w) and z-average radius (R_z) of gyration of AP were determined by using high-performance size-exclusion chromatography equipped with multi-angle laser-light scattering and refractive index detectors (HPSEC-MALLS-RI). Starch samples were prepared as described by Yoo and Jane (submitted). The HPSEC system consisted of an HP 1050 series isocratic pump (Hewlett Packard, Valley Forge, PA), a multi-angle laser-light scattering detector (Dawn DSP-F, Wyatt Tech., Santa Babara, CA) and a HP 1047A refractive index detector (Hewlett Packard, Valley Forge, PA). To separate AP from amylose, Shodex OH pak KB-G guard column and KB-806 and KB-804 analytical columns were used. The operating conditions were described in detail by Yoo and Jane (submitted).

2.6. Apparent amylose contents by potentiometric autotitration

Apparent amylose content of starch was determined following the procedure of Lu, Jane, Keeling, and Singletary (1996). Analysis was based on iodine affinities of defatted starches using a potentiometric autotitrator (702 SM Titrino, Brinkmann Instrument, Westbury, NY). Starch samples were defatted using a DMSO (90%) solution (Lim, Kasemsuwan, & Jane, 1994). Determination of amylose content was duplicated for each starch sample.

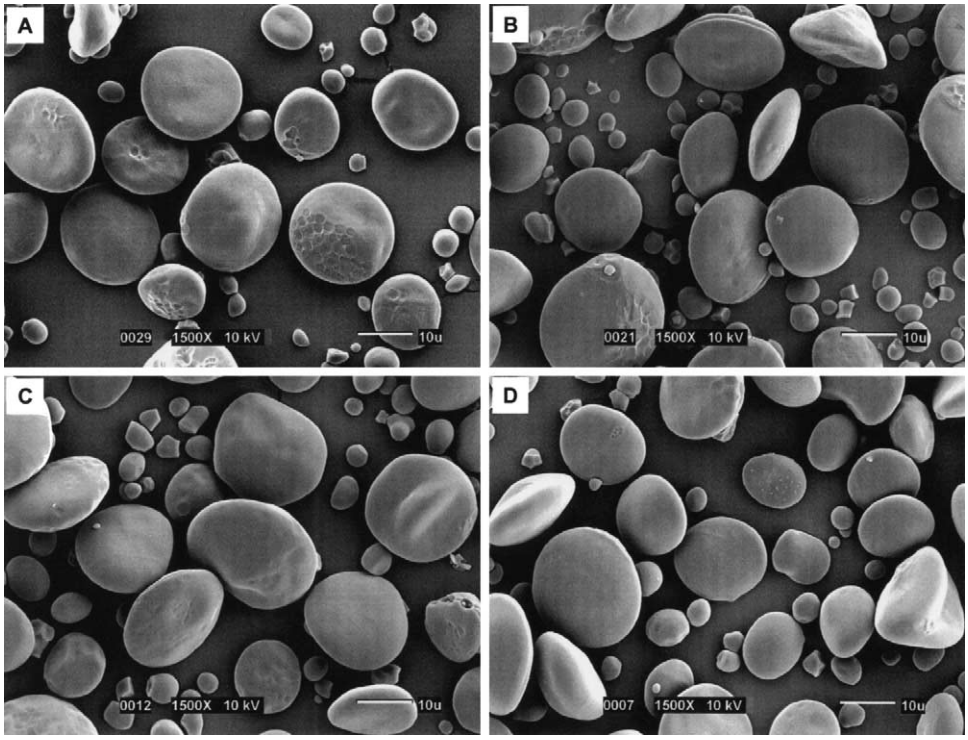

Fig. 1. Scanning electron micrographs of waxy (A), Kanto 107 (B), Centura (C), and commercial (D) wheat starch granules (Scale bar = 10 μm).

2.7. Amylopectin branch chain-length distribution by HPAEC and by HPSEC

The collected AP fractions from the GPC analysis were used for analyzing branch chain-length distribution. AP was debranched by using isoamylase following the method of Jane and Chen (1992). Branch chain-length distribution of AP was determined by using an HPAEC system (Dionex-300, Sunnyvale, CA) equipped with an amyloglucosidase post-column, on-line reactor and a pulsed amperometric detector (HPAEC-ENZ-PAD) (Wong & Jane, 1997). PA-100 anion-exchange analytical column (250 × 4 mm) and a guard column were used for separating debranched starch samples. The gradient profile of eluents and the operating conditions were described previously (McPherson and Jane, 1999). Branch chain-length distribution of AP was also analyzed to determine extra-long branch-chains by using an HPSEC equipped with an RI detector. The operating condition was the same as described earlier (McPherson and Jane, 1999), but the flow rate was 0.6 ml/min; the analytical column used for the analysis was Shodex OH pak SB-803HQ; the sample concentration was 1.0 mg/ml.

2.8. Thermal properties by differential scanning calorimetry (DSC)

Thermal properties of starch samples were determined by using a differential scanning calorimeter (DSC-7, Perkin–Elmer, Norwalk, CT). Approximately 6 mg of starch was weighed in a stainless steel pan, mixed with 18 mg of deionized water and sealed. Sample was allowed to equilibrate for 2 h and scanned at a rate of 10 °C/min over a temperature range of 25–140°C. An empty pan was used as the reference. The rate of starch retrogradation was determined by using the same gelatinized samples, stored at 4°C for 7 days, and analyzed using DSC and the same parameters as described above for starch gelatinization.

2.9. Pasting properties by rapid visco analyzer (RVA)

Starch pasting properties were analyzed by using an RVA (RVA-4, Newport Scientific, Sydney, Australia). A starch suspension (8%, w/w) was prepared by weighing starch (2.4 g, dry starch basis (dsb)) into an RVA canister and making up the total weight to 30 g with distilled water. The sample suspension was equilibrated at 30°C for 1 min, heated at a rate of 6.0 °C/min to 95°C, maintained at that temperature for 5.5 min, and then cooled to 50°C at a rate of 6.0 °C/min. A constant rotating speed of the paddle (160 rpm) was used throughout the analysis.

3. Results and discussion

Scanning electron micrographs of starch granules isolated from four wheat varieties, waxy, Kanto 107, Centura, and a commercial product, are shown in Fig. 1. Distinct bimodal size distributions were observed for all four starch samples. Large (A) granules showed a disk shape and had diameters of 18–33 μm, and small (B) granules, a spherical shape, had diameters of 2–5 μm. The results were in agreement with

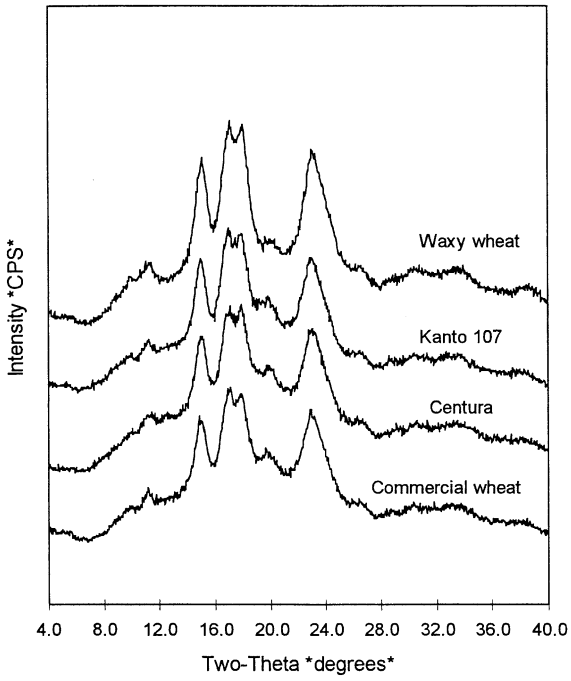

Fig. 2. X-ray diffraction patterns of waxy, Kanto 107, Centura, and commercial wheat starches.

that reported by Jane et al. (1994). There were no detectable differences in the granule-size distribution and granule morphology between waxy and other wheat varieties. X-ray diffractograms of wheat starches displayed typical A-type patterns (Fig. 2). A minor peak at $2\theta = 20^\circ$ was found in Kanto 107, Centura, and commercial wheat starches, reflecting the presence of amylose–lipid complex, which was not prominent in waxy wheat starch (Zobel, 1988). Percentage crystallinity of waxy, Kanto 107, Centura, and commercial wheat starches, calculated based on X-ray diffractograms, was 18.0, 14.5, 12.0, and 13.0%, respectively. Waxy wheat starch had significantly greater crystallinity than did others.

Apparent amylose contents of defatted starches are shown in Table 1. Waxy wheat starch contained a negligible amount of amylose (<0.2%). Kanto 107 starch had less amylose content (21.5%) than did other normal varieties (~26%). Total amylose contents determined by GPC (Fig. 3) were greater than those determined by iodine affinity measurements. This was consistent with that reported by Fredriksson (1998). GPC profiles of starch molecular weight distribution showed no detectable amylose in waxy wheat starch (Fig. 3). Molecular weight distributions of amylose of other wheat starches were similar.

Weight-average molecular weight (M_w) and z-average radius of gyration (R_z) of the APs, determined by using an HPSEC-MALLS-RI system, were in the range of 3.10–5.24×10^8 g/mol and 301–328 nm, respectively (Table 2). Among the wheat varieties, AP molecules of waxy wheat starch had the largest M_w and R_z. Molecular weights (M_w) of waxy maize AP (Bello-Perez, Roger, Baud, & Colonna, 1998; Yoo & Jane, submitted) and other cereal and tuber waxy APs (Yoo & Jane, submitted) have been found larger than that of normal starch counterparts. AP molecules of Kanto 107 (amylose-reduced starch) displayed the second largest M_w among the wheat starches (Table 2). However, there were no significant differences in R_z of APs among Kanto 107, Centura, and commercial wheat starches.

From the results, it appeared that the M_w of AP decreased as the amylose content increased. Takeda, Takeda, and Hizukuri, (1993) reported that AP of amylomaize had a smaller M_w than did normal AP. This trend seems related to the absence of GBSSI protein in the waxy wheat mutant. It is plausible that the carbon flux of ADP-Glc (adenosine-5′-diphosphate glucose) exclusively goes into AP biosynthesis in waxy wheat starch. In contrast, ADP-Glc partitions into the biosynthesis of AP and amylose in the normal wheat starch. This could result in larger AP molecular weights of waxy wheat and Kanto 107 than those of normal wheat varieties.

Profiles of branch chain-length distributions of isoamylase-debranched APs of the starches analyzed by HPAEC-ENZ-PAD are shown in Fig. 4. The bimodal chain-length distribution showed peak chain-lengths at DP12 and DP47-51 (Table 3) and an obvious shoulder at DP18–21 for all four varieties of wheat starches. Song and Jane (2000) suggested that fewer branch-chains with DP18–21 (~6.8 nm average chain-length) to develop a crystalline array in the crystalline lamellae (6.6 nm) (Jenkins & Donald, 1995) of AP results in defective crystallites and lower gelatinization temperature. Branch chain-length distributions of the four varieties were similar to each other (Table 3).

It is worthy to note differences in the blue values of AP fractions between different starches as shown on the GPC

Table 1
Iodine affinities and apparent amylose contents of wheat starches

Sample	Iodine affinity (%)	Apparent amylose content (%)[a]	Amylose content by GPC
Waxy wheat	0.04 ± 0.02[b]	< 0.2 ± 0.1	0.0 ± 0.0
Kanto 107	4.29 ± 0.06	21.5 ± 0.3	24.0 ± 1.0
Centura	5.23 ± 0.09	26.2 ± 0.5	31.6 ± 0.6
Commercial wheat	5.32 ± 0.12	26.6 ± 0.6	33.4 ± 0.7

[a] Apparent amylose contents were averaged from at least two analyzes; Values were calculated from dividing iodine affinity by a factor of 0.2.
[b] ± Standard deviation.

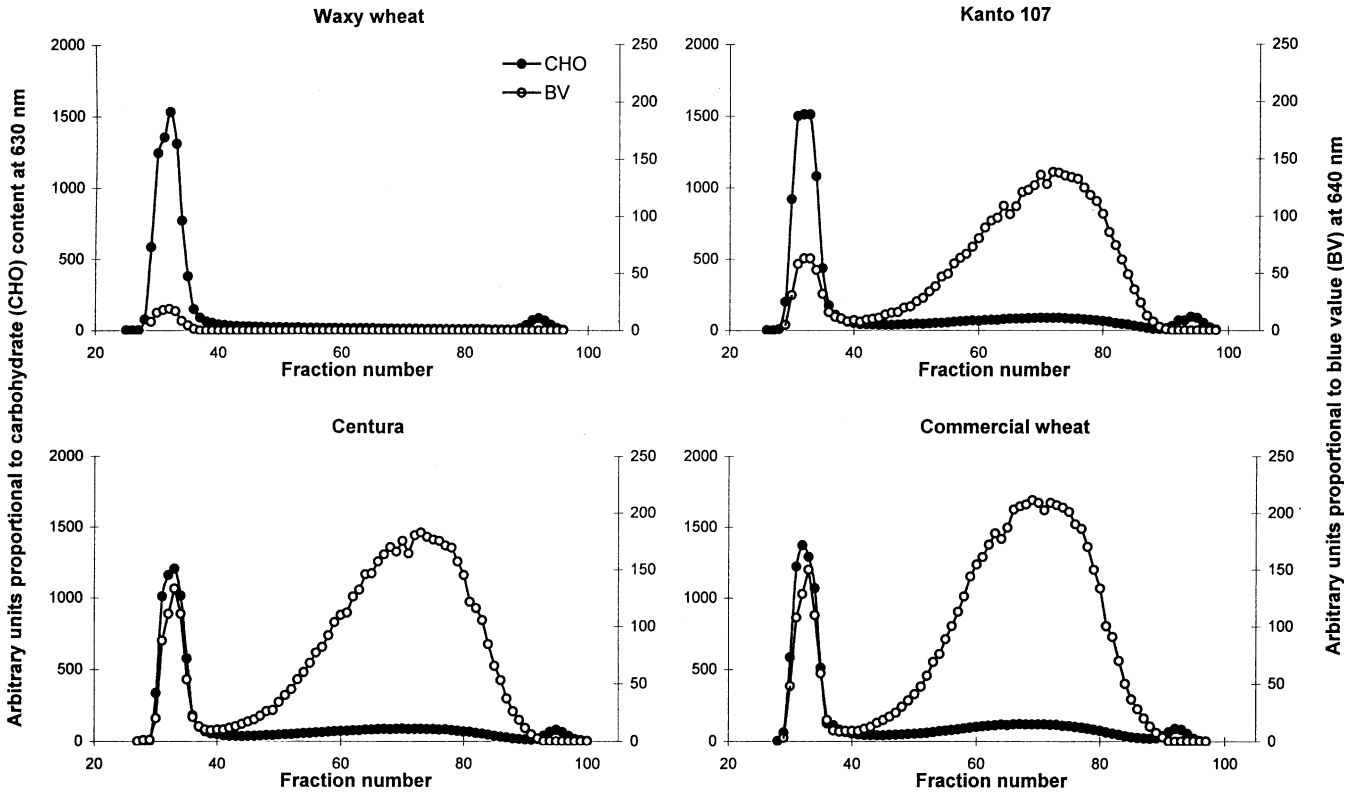

Fig. 3. Sepharose CL-2B GPC profiles of waxy, Kanto 107, Centura, and commercial wheat starches.

profiles (Fig. 3). APs of normal wheat starches displayed greater blue values than did that of waxy wheat starch. These results contradicted the similar branch chain-length distributions of the APs shown in Fig. 4. The greater blue values suggested there were longer branch-chains present in the AP of normal wheat starches, which were beyond the detectable chain-length range of HPAEC-ENZ-PAD. The HPSEC chromatograms of all the four debranched APs are shown in Fig. 5. The chromatograms showed two peaks at DP11 and ~32 and a shoulder at DP14 (Fig. 5). Profiles of normal wheat starches (Centura and commercial) displayed another peak (~DP770), known as extra-long chains (ELC), which was not shown in waxy AP and was less prominent in Kanto 107. The profiles of normal wheat APs were in agreement with that reported by Shibanuma, Takeda, and Hizukuri (1994). Existence of ELC in AP of normal starches has been reported in various botanical sources (Hizukuri, Takeda, Maruta, & Juliano, 1989; Takeda & Hizukuri, 1987; Takeda, Shitaozono, & Hizukuri, 1988) including wheat (Shibanuma et al., 1994). The difference in the amount of ELC between waxy, amylose-reduced, and normal wheat starches suggested that GBSSI was responsible for the biosynthesis of ELC of AP. Denyer, Waite, Motawia, Lindberg-møller, and Smith (1999) reported that GBSSI synthesizes starch by a progressive (or processive) pattern. The dispersed molecular densities

Table 2
Average molecular weight and gyration radius of wheat starches (data were obtained from at least three injections)

Sample[a]	$M_w \times 10^{-8}$ (g/mol)[b]	R_z (nm)[c]	ρ (g/mol/nm^3)[d]	ρ_r[e]
Waxy wheat	5.24 ± 0.37[f]	328 ± 6	14.8	1
Kanto 107	3.98 ± 0.01	303 ± 2	14.3	0.95
Centura	3.50 ± 0.17	301 ± 7	12.8	0.87
Commercial wheat	3.10 ± 0.26	302 ± 3	11.3	0.77

[a] Starch samples were dissolved in 90% DMSO solution and precipitated with 5 vol ethanol; Freshly prepared starch aqueous solution (100 μl; 0.4 mg/ml) was injected to HPSEC system.
[b] Weight-average molecular weight.
[c] z-Average radius of gyration.
[d] Density is equal to M_w/R_z^3.
[e] Relative density based on waxy wheat as 1.
[f] ± Standard deviation.

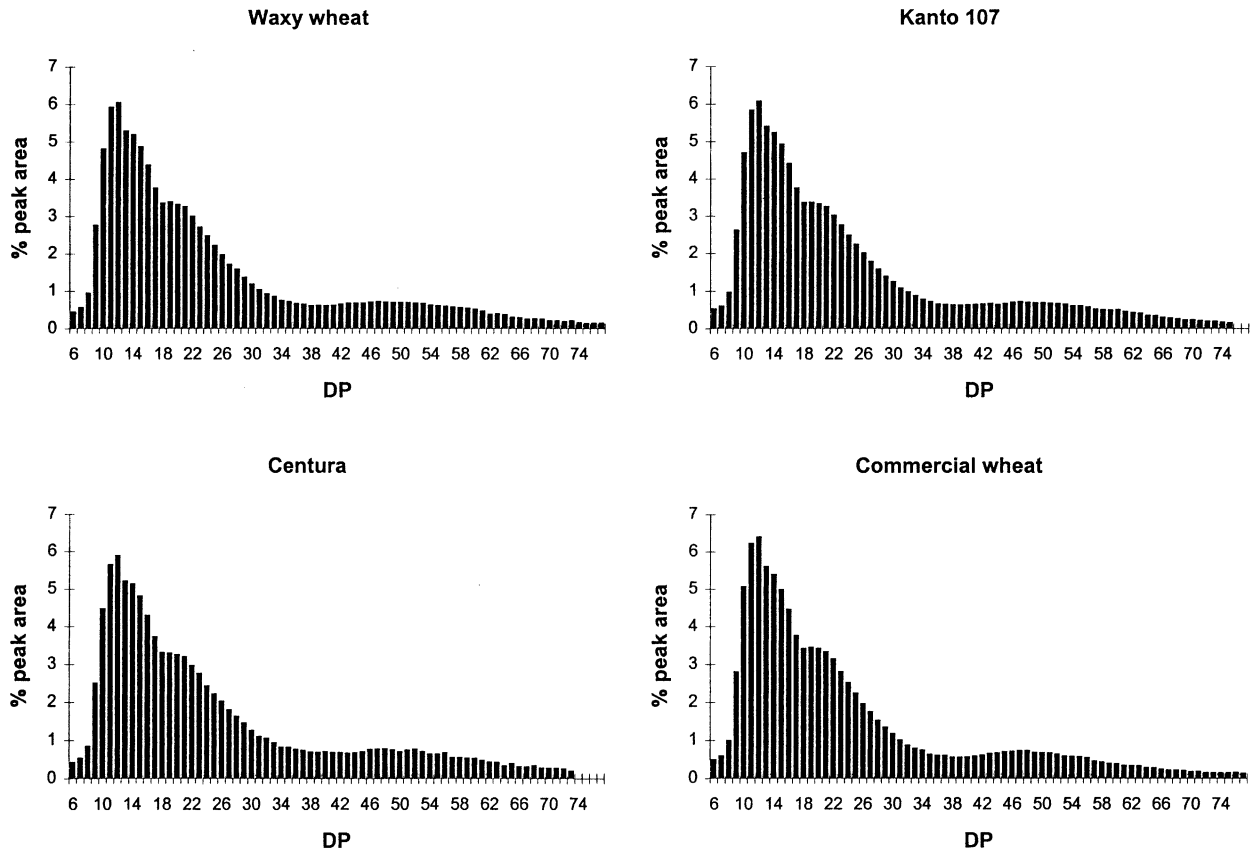

Fig. 4. Relative peak area distributions of wheat starches analyzed by using an HPAEC-ENZ-PAD. DP = Degree of polymerization.

(ρ) of AP in a diluted solution showed that waxy wheat AP was more compact than normal wheat APs (Table 2). The ELCs, synthesized progressively by GBSSI, are expected to have an amylose-like structure, carrying fewer branches, which could result in smaller M_w of normal AP with lower density (Yoo and Jane, submitted).

Thermal analysis of wheat starches showed that onset gelatinization temperatures (T_o) were similar (54.9–57.5°C) and enthalpy changes (ΔH) of the starches were 13.6, 11.8, 10.7, and 10.6 J/g, respectively, for waxy, Kanto 107, Centura, and commercial wheat starches (Table 4), which were consistent with their degrees of crystallinity (18.0, 14.5, 12.0, and 13.0%, respectively). The DSC thermogram of waxy wheat starch showed no melting peak of amylose–lipid complex, whereas other starches showed a peak (91–106°C), corresponding to an amylose–lipid complex melting peak. The ΔH of melting amylose–lipid complex proportionally increased with the increase of the amylose content of wheat starch. These results coincided with the fact that waxy wheat starch had a substantially lower lipid content (0.12 g/100 g starch) than Kanto 107 (1.07 g/100 g starch) reported by Yasui et al. (1996). Lim et al. (1994) reported that there was undetectable or trace amount of phospholipids in waxy starches, whereas normal wheat starch contained a large concentration of phospholipids (0.058%, w/w) (Kasemsuwan & Jane, 1996). Phospholipids are known to form a strong complex with amylose (Morrison, Tester, Snape, Law, & Gidley,

Table 3
Branch chain-length distributions of wheat APs

Sample	Peak DP		Average CL	Percent distribution				
	I	II		DP6–9	DP6–12	DP13–24	DP25–36	DP ≥ 37
Waxy wheat	12	51	24.4 ± 0.2[a]	4.6 ± 0.2	21.5 ± 0.2	45.0 ± 0.2	14.8 ± 0.0	18.7 ± 0.4
Kanto 107	12	47	24.2 ± 0.2	4.6 ± 0.1	21.3 ± 0.0	45.2 ± 0.1	15.2 ± 0.0	18.3 ± 0.3
Centura	12	48	24.9 ± 0.3	4.2 ± 0.2	20.2 ± 0.0	44.2 ± 0.5	15.6 ± 0.1	20.2 ± 0.7
Commercial wheat	12	47	23.5 ± 0.4	4.8 ± 0.0	22.4 ± 0.5	46.1 ± 0.0	14.4 ± 0.0	17.1 ± 0.7

[a] ± Standard deviation.

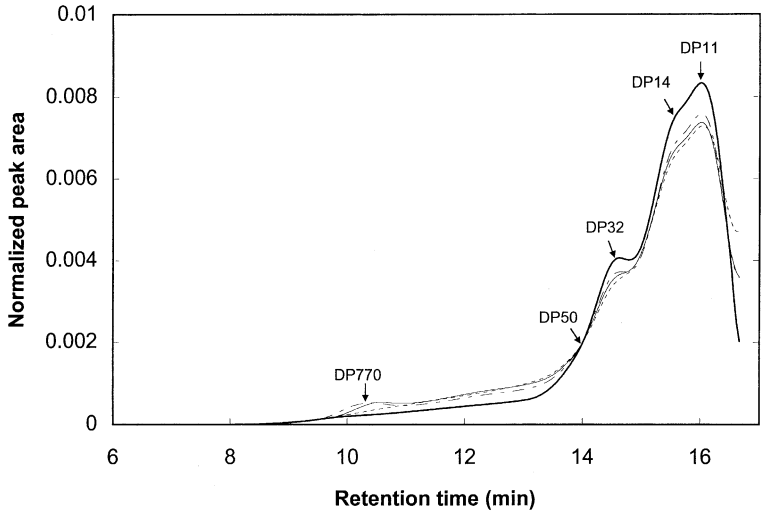

Fig. 5. HPSEC chromatogram of isoamylase-debranched amylopectins. Peak areas of amylopectins of waxy (▬), Kanto 107 (- - -), Centura (—), and commercial wheat (–·–) were normalized.

1993). After storage at 4°C for a week, percentage retrogradation of waxy, Kanto 107, Centura, and commercial wheat starches were 33.7, 39.5, 45.1, and 35.9%, respectively (Table 5). Centura wheat starch showed a greater degree of retrogradation than did other starches, which could be attributed to its larger proportion of branch chains of DP > 25 (Yuan, Thomson, & Boyer, 1993) and smaller proportion of DP6-12 (Shi & Seib, 1992).

Pasting properties of the wheat starches, and normal and waxy maize starches are shown in Fig. 6. Pasting temperatures of waxy, Kanto107, Centura, and commercial wheat starches were 62.5, 88.4, 90.6, and 85.0°C, respectively, and peak viscosities were 230.0, 164.1, 96.2, and 122.0 RVU, respectively. Like other waxy starches, such as waxy barley (Song & Jane, 2000), waxy potato (McPherson & Jane, 1999), and waxy cereals (Jane, Chen, Lee, McPherson, Wong, Radosavljevic, & Kasemsuwan, 1999), waxy wheat starch had the lowest pasting temperature (62.5°C) and the

Table 4
Thermal properties of native wheat starches

Sample[a]	Native starch				
	T_0 (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	Amylose–lipid complex, ΔH
Waxy wheat	55.7 ± 0.1[b]	61.4 ± 0.4	67.6 ± 0.3	13.6 ± 0.4	ND[c]
Kanto 107	57.5 ± 0.2	62.1 ± 0.4	67.0 ± 0.4	11.8 ± 0.2	1.9 ± 0.1
Centura	55.6 ± 0.1	59.1 ± 0.2	63.1 ± 0.2	10.7 ± 0.1	2.7 ± 0.2
Commercial wheat	54.9 ± 0.1	58.9 ± 0.1	63.8 ± 0.2	10.6 ± 0.3	3.1 ± 0.2

[a] Samples (~2.0 mg, dsb) and deionized water (~6.0 mg) were used for the analysis; T_0, T_p, T_c, and ΔH are onset, peak, conclusion temperature, and enthalpy change, respectively.
[b] Values were calculated from three replicates; ±Standard deviation.
[c] Not detectable.

Table 5
Thermal properties of retrograded wheat starches

Sample	Retrograded starch[a]				Retrogradation (%)[b]
	T_0 (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	
Waxy wheat	41.0 ± 0.2[c]	50.2 ± 0.5	56.5 ± 0.3	4.6 ± 0.2	33.7
Kanto 107	41.6 ± 0.5	50.4 ± 0.2	57.2 ± 0.2	4.7 ± 0.2	39.5
Centura	40.6 ± 0.5	49.4 ± 0.5	55.8 ± 0.4	4.8 ± 0.3	45.1
Commercial wheat	41.2 ± 0.3	49.4 ± 0.2	56.2 ± 0.5	3.8 ± 0.5	35.9

[a] After storage at 4°C for 7 days.
[b] Retrogradation (%) = $\Delta H_{retro}/\Delta H_{native} \times 100$.
[c] Values were calculated from three replicates; ±Standard deviation.

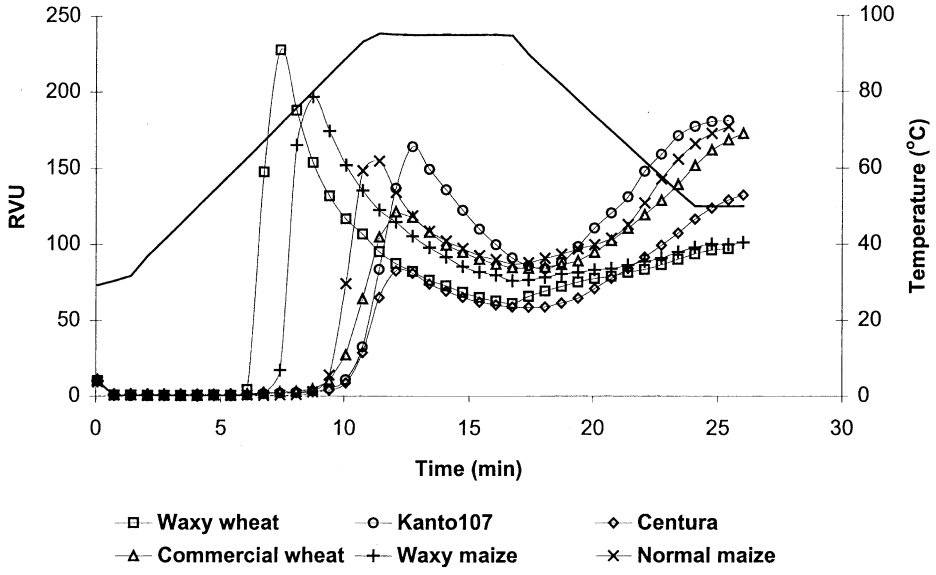

Fig. 6. Rapid ViscoAnalyzer pasting profiles of wheat starch varieties compared with that of normal and waxy maize starches (8.0% dsb, w/w).

largest peak viscosity among all wheat starch varieties, which was consistent with that reported by Kiribuchi-Otobe, Nagamine, Yanagisawa, Ohnishi, and Yamaguchi (1997). Amylose content had strong negative correlation with the peak viscosity of the wheat starches analyzed ($r = -0.94$, $P < 0.05$). This agreed with that reported for sweet potato starches ($r = -0.89$, $P < 0.001$). (Collado, Mabesa, & Corke, 1999).

Comparing the pasting properties of wheat starches with that of maize counterparts, normal wheat varieties (Centura and commercial wheat) showed higher pasting temperatures (90.6 and 85.0°C, respectively) and lower peak viscosity (96 and 122 RVU, respectively) than did normal maize starch, 81.5 and 159.1 RVU, respectively, for pasting temperature and peak viscosity (Fig. 6). Waxy wheat, however, displayed a lower pasting temperature (62.5°C) but a higher peak viscosity (230 RVU) than did waxy maize starch (69.8°C and 200 RVU, respectively) (Fig. 6). The absence of amylose and lipids in waxy wheat starch had more profound effects on the pasting properties than did those of maize starch counterparts. The difference in pasting temperature between waxy wheat starch and normal wheat starches (Centura) (28.1°C) was much larger than the difference between maize starch counterparts (11.7°C), and the difference in peak viscosity between waxy and normal wheat starch (Centura) (134 RVU) was also much larger than that of maize starch counterparts (41 RVU). A lower gelatinization temperature (T_0) of waxy wheat starch (55.7°C) than waxy maize starch (64.1°C) (Jane et al., 1999) facilitated the lower pasting temperature of waxy wheat starch. The drastic differences in the pasting properties between waxy and normal wheat starches are attributed to the large phospholipid concentration in normal wheat starch (Kasamsuwan & Jane, 1996; Lim et al., 1994). Amylose–phospholipid complex (Table 4) restricted swelling of wheat starch granules (Tester & Morrison, 1990). Without the restriction on granule swelling caused by the amylose–lipid complex, waxy wheat starch could swell and develop viscosity at a much lower temperature.

4. Conclusion

The absence of amylose in waxy wheat starch did not affect crystalline polymorphism, granule size, morphology, and gelatinization temperature, but increased the degree of crystallinity. Waxy wheat AP had a significantly larger molecular weight and a greater dispersed molecular density than did APs of other wheat starches. Waxy wheat AP did not contain ELC that was synthesized progressively by GBSSI in normal wheat AP. Differences in pasting properties between waxy and normal wheat starches were greater than that between waxy and normal maize starch counterparts, which were attributed to phospholipid contents in normal wheat starches.

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