Water status of cooked white salted noodles evaluated by MRI

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Abstract

Transverse relaxation time (T_2)-weighted images and T_2 maps of white salted noodles (WSN) were investigated by magnetic resonance imaging technique. T_2 -weighted images and T_2 maps clearly showed the differences in water status between noodles. The migration of moisture from surface regions to central regions of boiled WSN at different migration rates were investigated during storage. The distribution of T_2 values changed differently depending on the cooking and storage times. The small differences in T_2 values between surface region and central region of noodles cooked for 5 and 15 min were attributed to the limited water absorption during short cooking time, which resulted in high firmness. The changes in starch granules morphology observed under scanning electron microscope and the increase of noodle firmness measured by texture analyzer were significantly affected by the water status in noodles. The water status can be controlled by the cooking time.

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1. Introduction

Noodles are the major wheat products in Asian diet and almost 40% of wheat is used for noodle production in Asian countries (Janto, Pipatsattayanuwong, Kruk, Hou, & McDaniel, 1998). According to raw materials, processing, shape and the ways of retailing and eating, various types of noodles can be found in the markets. White salted noodle (WSN) is one of the most popular types of noodle in Taiwan, which is usually available as fresh (raw) or dried noodle. Recently, the refrigerated or frozen boiled noodles are gaining popularity because of the properties of convenience and readiness for serving. Since boiled WSN is a cooked, gelatinized starchy-based food it is usually characterized by syneresis and

increasing firmness during storage. The changes in the texture and taste of boiled WSN are usually one of the reasons to reject this product by consumers.

Eating quality is a relevant characteristic of noodles. Lots of studies have been performed correlating factors such as flour quality (Nagao et al., 1977; Oda, Yasuda, Okazaki, Yamauchi, & Yokoyama, 1980; Seib, 2000; Wang & Seib, 1996), formulation (Moss, Gore, & Murray, 1987), and starch swelling properties (Crosbie, 1991; Kim & Seib, 1993; Konik, Miskelly, & Gras, 1992, 1993; Liang, 1999), to eating quality of noodles. Several workers have provided evidence that starch with high-swelling property is beneficial to the eating quality of WSN (Baik, Czuchajowska, & Pomeranz, 1994; Crosbie, 1991; Konik et al., 1992; Seib, 2000; Wang & Seib, 1996). Furthermore, the contributions of wheat starch to the eating quality of WSN is complicated by formulations, boiling conditions, and storage. Liang (1999) pointed out that after cooking and rinsing, Udon (one

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type of WSN) made with high-swelling starch gained water up to 75% moisture content, with moisture contents at 65% and 85% for the core and surface parts of the noodles, respectively. The roles of high-swelling starch in WSN included that quickly swollen starches fill pores near the noodle surface during the early stages of cooking, which result in the starch gel resisting erosion by cooking water and decrease cooking loss (Seib, 2000; Liang, 1999). However, the increased firmness of boiled noodles after storage significantly affected the eating quality of noodles and are always the most troublesome problem bothering manufacturers. It has been known that the increases of firmness of starchy-based food are mainly related to the retrogradation of starches. Although there are many factors affecting the degree of gelatinization and retrogradation rate of starch, the most important factors would be the status of water during processing and storage, such as moisture content, water mobility, water distribution and migration (Kojima, Horigane, Yoshida, Nagata, & Nagasawa, 2001; Lai, Schmidt, Chiou, Slowinski, & Day, 1993; Slade & Levine, 1991).

Magnetic resonance imaging (MRI) technique was first developed as a non-destructive method for use in medical research and diagnosis, and the applications of the MRI technique in the field of food science has increased since the last decade (Schmidt & Lai, 1991; Schmidt, Sun, & Litchfield, 1996; Webb, Belton, Gil, & Delgadillo, 2001). The major advantages of MRI are: (1) it is non-destructive and non-invasive; (2) it can provide spatial resolution; (3) it can provide diverse information such as proton density, water mobility, internal structure, chemical diffusion, temperature, and flow. MRI is pretty well regarded as a powerful tool for characterizing water mobility and distribution of foods during processing and storage (Fukuoka, Mihori, & Watanabe, 2000; Kojima et al., 2001; Ruan & Chen, 1998; Stapley, Hyde, Gladden, & Fryer, 1997; Takano, Ishida, Koizumi, & Kano, 2002; Takeuchi, Fukuoka, Gomi, Maeda, & Watanabe, 1997). Although, the texture of boiled WSN evaluated by many objective measurements, such as a texture analyzer equipped with several of probes, has been reported in many works (Guan & Seib, 1994; Oh, Seib, Deyoe, & Ward, 1983; Yun, Rema, & Quail, 1997), little information is available on the relationship of water status and texture changes of cooked WSN during storage. Therefore, the objective of this study was to non-invasively investigate the water status of cooked WSN, which were cooked with different time periods then stored up to 7.5 h at $18 \pm 2^\circ\text{C}$, by using a MRI technique. The firmness of cooked WSN measured by using a texture analyzer and the microstructure of noodles investigated by scanning electron microscope (SEM) were simultaneously carried out and the results were compared with the observations from MRI.

2. Experimental

2.1. Materials

The flour used for WSN making was purchased from a local flourmill (Taichung, Taiwan). The flour contained 8.43% of protein and 0.40% of ash on a dry basis determined according to the AACC methods (AACC, 1995). The wet gluten and dry gluten of flour determined by the method of AACC 38-10 (AACC, 1995) were 21.02% and 7.29%, respectively.

2.2. Preparation of white salted noodle

The WSN was made from 500 g flour by adding 20 g kg^{-1} (on flour basis) NaCl solution at water absorption of 400 g kg^{-1} (on flour basis). Dough was mixed at low speed for 5 min in a KitchenAid desktop mixer (model KSMC50, KitchenAid, MI, USA). The crumbly dough was pressed into a cohesive rectangular block ($15 \times 35 \times 6\text{ cm}$, $W \times L \times H$), and aged for 30 min. The aged dough was passed through a laboratory noodle-making machine (SK-207, New Chung Hou Co., Ltd., Taipei, Taiwan) with an initial gap of 4.14 mm. The dough sheet was folded and sheeted at a 4.14 mm gap for a total of six times. The sheet was packed in a PE plastic bag and aged for another 30 min. The sheet was then progressively reduced by sheeting at a gap of 4.14, 3.53, 3.00 and 2.50 mm. Rough edges were removed twice in between sheeting. The dough sheet was finally cut by a noodle cutter with 9 mm in width after it was aged for another 15 min. Raw noodles (50 mm long) were cooked with boiling distilled water (1:20, w/w) maintained at a rolling boil for five different cooking time (5, 10, 15, 20 and 25 min). After cooking, the cooked noodles were removed and drained for 30 s, then quenched for 30 s in 8°C water (1:10, w/w). The quenched cooked noodles were drained for 30 s, and the length, width and thickness of boiled WSN were measured immediately by using a vernier caliper. The swelling ratio of cooked WSN in the length, width or thickness was calculated by dividing the length, width or thickness of cooked WSN by the length, width or thickness of raw WSN, respectively. The moisture content of cooked WSN was determined by an air-oven method AACC 44-15A (AACC, 1995). After cooking, the WSN were stored in a plastic box for periods ranging from 0.5 to 7.5 h at $18 \pm 2^\circ\text{C}$ and at ambient relative humidity until the measurements of MRI, firmness and SEM being performed.

The effects of cooking time on the moisture content and swelling ratio of cooked WSN were assessed by analysis of variance (ANOVA) using the general linear model of SAS (version 6.11, SAS Institute, Cary, NC),

then significant means were compared by the Duncan test at a level of $p < 0.01$.

2.3. MRI

For the MRI investigation, a special sample holder was designed to fit the MRI gradient coil and shown in Fig. 1. The noodle stripes were fixed on the multi-layers of PVP plate in the sample holder, which was a cylinder (6 cm inner diameter, 7 cm in length) made of acrylic plate. The multiple layers of PVP plates, which can be easily slid in and out, was allowed to investigate many stripes of noodles at the same time.

MRI was performed on a Bruker BioSpec 3T system (Ettlingen, Germany) equipped with a S116 mini-gradient coil (7 cm in inner diameter). All the images were acquired in the plane perpendicular to the longitudinal side of noodles using a two-dimensional (2D) Fourier transform technique. A standard spin-echo (SE) sequence was used to produce T_2 -weighted images ($TE = 15$ ms, $TR = 3000$ ms). The multi-echo (CPMG) sequence was used to calculate the proton transverse relaxation time (T_2) maps. The multi-echo sequence parameters were repetition time (TR) = 3000 ms, eight echo times (TE) = 15, 30, 45, 60, 75, 90, 105, 120 ms, pixel matrix = 256×256 , field of view (FOV) = 60×60 mm, and slice thickness = 5 mm. The spatial resolution was $234 \mu\text{m}$. The measurement time was 12.8 min for one acquisition. For each sequence the gain and FT scale parameter were kept constant. The T_2 was calculated according to the Marquardt algorithm using a monoexponential fitting model. All the MRI measurement were performed at 18 ± 2 °C in duplicates.

The heterogeneity of T_2 maps was expressed as the profiles of T_2 values on the central cross-section of cooked WSN that was carried out using homemade programs and Excel[®]. The T_2 map analysis was achieved from the T_2 histogram representing the T_2 value from 0 to 160 ms and the amount of pixel at a specific T_2 values. The histogram frequency was normalized by the total pixel numbers to prevent from any distortion of the histogram due to the different size of noodle MRI images.

Fig. 1. Sample holder for MRI: (a) acrylic cylinder (6 cm inner diameter, 7 cm in length); (b) lid; (c) multiple layers of PVP plates.

2.4. Texture analysis

Surface firmness and cutting firmness of cooked WSN were measured by using a texture analyzer (TA-XT2i, Stable Micro Systems, Surrey, UK) with the probes,

Table 1

The moisture content and swelling ratio of cooked white salted noodles with different cooking time

Cooking time (min)	Moisture content (%)	Swelling ratio ^a		
		Length	Width	Height
0	34.1 ± 0.3 ^a	—	—	—
5	55.7 ± 0.2 ^b	1.20 ± 0.01 ^a	1.26 ± 0.01 ^a	1.02 ± 0.03 ^a
10	60.1 ± 0.3 ^c	1.22 ± 0.06 ^a	1.32 ± 0.04 ^{ab}	1.00 ± 0.05 ^a
15	63.4 ± 0.2 ^d	1.25 ± 0.01 ^a	1.34 ± 0.04 ^{bc}	1.11 ± 0.06 ^b
20	66.1 ± 0.1 ^e	1.26 ± 0.04 ^a	1.41 ± 0.03 ^c	1.12 ± 0.06 ^b
25	68.8 ± 0.3 ^f	1.33 ± 0.04 ^b	1.49 ± 0.05 ^d	1.34 ± 0.04 ^c

^a The swelling ratio was calculated by dividing the length, width or thickness of cooked WSN by the length, width or thickness of raw WSN, respectively. The mean values in the same column with the different letters are significantly different ($p < 0.01$).

Fig. 2. T_2 -weighted images of cooked WSN with different cooking time (5, 10, 15, 20, and 25 min) and storage time, (a) 0.5 h, (b) 1.5 h, (c) 2.5 h, and (d) 7.5 h.

Fig. 3. T_2 maps of cooked WSN with different cooking time (5, 10, 15, 20, and 25 min) and storage time, (a) 0.5 h, (b) 1.5 h, (c) 2.5 h, and (d) 7.5 h.

the pasta firmness/stickiness rig (HDP/PFS) and the light knife blade (A/LKB-F), respectively. Peak force was recorded as firmness (g). The probe was attached to a 5 kg load cell. The measurements and data processing were run by the texture expert for Windows version 1 software (Stable Micro Systems, Surrey, UK). Both measurements were determined by performing the compression test mode with forwarding speed and withdrawal speed of 10 mm s^{-1} for probes. The surface firmness measurements were performed by compressing 1.9 mm in depth from the surface of two noodle strands with the compressing speed of 0.5 mm s^{-1} . The cutting firmness measurements were performed by cutting two strands of cooked WSN with the cutting speed of 0.2 mm s^{-1} . Seven replicates were measured and the higher and the lower

values were discarded, so that data were the means for five measurements with their standard deviations.

2.5. Scanning electron microscopy

Microstructure of the cross-section of noodles was investigated using SEM (JSM-6300, Jeol Co., Japan) at 10 kV accelerating voltage. A 5 mm length noodle was rapidly frozen in liquid N_2 for 30 s, followed by freeze-drying for 3 days (Moss, 1974). The dried noodle was fractured by folding and mounted on a stainless steel specimen stub with the cross-section face up. The mounted sample were then dried at 40°C for 3 h before Au/Pd coating for 3 min at 10 mA by using an ion sputter (ion Sputtering Device JFC-1100E, Jeol Co., Japan).

Fig. 4. Profiles of T_2 values along the central line on cross-section of cooked WSN with different cooking and storage time.

3. Results and discussion

3.1. Water absorption and swelling of WSN during cooking

Table 1 shows the moisture content and swelling ratio of boiled WSN, which were cooked for 5, 10, 15, 20 and 25 min. The water absorption of WSN during cooking increased significantly with the increases of cooking time. When WSN was cooked for 20 min the central white core of the noodles disappeared by visual observation and the moisture content was 66.12%. Kojima et al. (2001) reported the similar results of the moisture contents of 3 mm square Japanese noodles which contained 60.9%, 67.3% and 69.0% when cooked in tap water for 8, 16 and 24 min, respectively. The swelling ratios of WSN also significantly increased with the increases of cooking time with the tendency of width > length > height. The high width swelling of WSN compared to the swelling

of length and height of cooked WSN is mainly due to the geometric factors of WSN, i.e., short distance of water penetration across the width of WSN and large surface area of cross-section of WSN.

3.2. MRI images of WSN under different cooking and storage time

The degree of gelatinization and rate of retrogradation of starch in food systems were significantly affected by the amount of water absorption during cooking and water status during storage, which resulted in modifying the starch gel network structure of WSN and changing the texture and eating quality of boiled WSN (Crosbie, 1991; Liang, 1999; Seib, 2000). Figs. 2 and 3 are the T_2 -weighted images and T_2 maps of cross-section of WSN during storage. The degree of swelling of WSN under various cooking times could be obviously observed on the images. Because the MRI signal intensity

Fig. 5. T_2 histograms of cooked WSN with different cooking time and storage time.

is not a simple effect, the signal intensity was depended on both water concentration and the degree of starch gelatinization of the cooked noodles. Non-homogeneous water status was clearly investigated in all noodles and was attributed to the differences in amount of water absorption during cooking, migration rate of water molecules during storage, and degree of protein denaturation, starch gelatinization and retrogradation. General speaking, two distinguished regions, a bright surface area in which highly hydrated and gelatinized WSN and a dark central area in which limited hydrated and gelatinized WSN were observed for all noodles stored up to 7.5 h (Fig. 2). The T_2 maps (Fig. 3) also showed that the area of brightness increased with the increase of cooking time and storage time. The decreases of brightness in surface region and the increases of brightness spots in central region revealed the results of water migration from the highly hydrated surface region to the limited hydrated central region. Therefore, both water concentration and water mobility changed as functions of spatial location and time.

In order to investigate the phenomena of water migration and quantify the water mobility of WSN during storage, the T_2 profiles of central cross-section of WSN was shown in Fig. 4. These profiles showed that there were large differences in T_2 values between surface region and core region of noodles. The differences of T_2 values at surface area and central area increased with the increase of cooking time but decreased with the increase of storage time. Initially, the T_2 values of surface region of WSN were about 60, 90, 100 and 120 ms for the noodles cooked for 5, 15, 20 and 25 min, and the T_2 values of central region were about 15–35 ms in all noodles when they were stored for 0.5 h. After 2.5 h of storage, the T_2 values of surface area were about 60–80 ms and T_2 values of central area were about 20–40 ms, except for the WSN cooked for 5 min. After storage for 7.5 h, the surface T_2 values were about 40, 60, 70 and 80 ms for WSN cooked for 5, 15, 20 and 25 min. Although T_2 values at the central regions of WSN were not significantly different during storage, fewer variations of T_2 value were observed for the WSN cooked for 25 min (Fig. 4(d)) than WSN cooking for 5 min (Fig. 4(a)) when they were stored for 1.5 h. The water migration from surface region to central region were significant observed in 20 and 25 min cooked WSN but not in 5 and 10 min cooked WSN because higher total water absorption when WSN was cooked for longer time. Limited water restricted the gelatinization of starch of noodle and resulted in uneven degrees of starch gelatinization and protein denaturation of noodles. These could be further proved by SEM micrographs, in which the starch granules maintained intact (Fig. 7(a) and (b)).

Fig. 5 showed the distribution of T_2 values of cross-section of WSN. In general, the T_2 value distribution varied from a broader multi-peak to a narrow single-

peak for the cooked WSN when stored for 7.5 h with the exception of the 25 min cooked WSN. The major T_2 value of 5 min cooked WSN was 32 ms (27%) after storage for 0.5 h and it was shifted to 24 ms (38%) after storage for 7.5 h. The major T_2 values of WSN cooked for 15 and 20 min were the same (32 ms) and not changed during storage. The frequency of major T_2 value increased from 18% to 40% when stored for 7.5 h for both noodles. But, the ranges of T_2 distribution were different between 15 min cooked WSN (8–144 ms) and 20 min cooked WSN (16–152 ms) when stored for 0.5 h. After stored for 7.5 h, the ranges of T_2 distribution of both noodles decreased, i.e., 16–96 and 16–116 ms for 15 and 20 min cooked WSN. The major T_2 value of 25 min cooked WSN shifted from 32 (19%) to 40 ms (31%) and the ranges of distribution were decreased from 16–152 to 24–128 ms after storage of 7.5 h.

Traditionally, the optimal cooking time of raw or dried noodles is empirically decided by the observation when the uncooked central core of noodles has just disappeared (Shibata, 1984). That is, the optimal cooking time of WSN prepared in this study was ca. 20 min judged by vision. The MRI results shown in Fig. 5 indicated that the major T_2 values of noodles cooking for 15–25 min were around 32 ms but the distribution of T_2 values was getting narrower when the storage time was getting longer. Although the distributions of T_2 values were not easy to distinguish the WSN having been under, optimal or over cooked, the distributions of T_2

Fig. 6. (a) Surface firmness and (b) cutting firmness of cooked WSN with different cooking and storage time.

values revealed the characters of water status of boiled WSN during storage. It was interested to notice that the water migration and redistribution was observed all the time in all noodles, and no consistent moisture contents or the same water mobility in noodles was observed even stored up to 7.5 h.

3.3. Texture and SEM of cooked WSN with different cooking and storage time

Fig. 6 showed the surface firmness and cutting firmness of WSN cooked for 5, 10, 15, 20 and 25 min and stored up to 7.5 h at 18 ± 2 °C. The surface firmness of noodles decreased with increases of boiling time but increased with increasing in storage time up to 2 or

3 h for WSN cooked for 5 min or longer (Fig. 6(a)). The 5 min cooked WSN showing the largest surface firmness right after cooking than others was attributed to the short cooking time that resulted in low water absorption and limited hydration. Since the surface firmness measured the force required to compress the 1.9 mm depth from the surface of WSN, the transitions of surface firmness of cooked WSN from increasing to decreasing during storage periods was partially due to the loss of surface water. The transition times of surface firmness of cooked WSN during storage agreed with the findings in the MRI T_2 profiles (Fig. 4(b)–(d)), in which the differences of T_2 values between surface and central regions of 15, 20 and 25 min cooked WSN were significantly decreased. The cutting firmness of all noodles decreased

Fig. 7. SEM micrographs of fresh cooked WSN with different cooking time: (a) 5 min, surface; (b) 5 min, center; (c) 15 min, surface; (d) 15 min, center; (e) 20 min, surface; (f) 20 min, center; (g) 25 min, surface; (h) 25 min, center (bar —) = 10 μ m; arrow (→) = starch granule).

with the increases of cooking time during the whole storage period (Fig. 6(b)). During the storage, the increases of cutting firmness with increases of storage time of WSN were attributed to the retrogradation of starch gel (Liang, 1999; Seib, 2000).

As observed by SEM micrographs (Fig. 7), the starch granules at highly hydrated surface region considerably swelled and did not retain their original granular form, while some of intact starch granules could be also observed in the limited hydrated central regions. Because there was not enough water taken by 5 min cooked WSN, many starch granules remaining intact in both surface and core regions (Fig. 7(a) and (b)). Even cooked for 15 min the some starch granules could also be observed in central region (Fig. 7(d)). The longer cooking time caused higher water absorptions that provide much more water for starch gelatinization and protein denaturation. The higher degrees of starch gelatinization and protein denaturation were observed in both surface and central region of 20 and 25 min cooked WSN (Fig. 7(e)–(h)).

It has been reported that the characteristic texture of boiled noodles was greatly affected by the moisture distribution and the homogenization of moisture content inside noodles after holding was responsible for the loss of elasticity and viscosity of noodles (Kojima et al., 2001; Liang, 1999; Seib, 2000). Although only the surface and cutting firmness of boiled WSN was observed in this study, the characterization of water mobility of cooked WSN during storage was well responsible for the changes of hardness of noodles. The optimal cooking time ensures that the optimal moisture content for starch gelatinization which can be monitored by the distribution of T_2 values. Besides, the profile of T_2 values during storage is helpful in investigating the water migration that corresponded well with the changes of hardness of noodles during storage.

4. Conclusion

The MRI is a powerful technique to investigate the water characteristics of cooked WSN during storage non-invasively and non-destructively. The results shown in this study provide important information for the relationship between the water status, resulting from water distribution and migration during the cooking and storage, and the changes of noodles' texture. The hardness of cooked WSN during storage was well corresponded with the water migration observed by the changes of T_2 profiles and distribution. Besides, the sample holder designed for MRI observation, holding up to several strands of noodles for analysis would be effective for rapid multi sample analysis, enabling statistical analysis of samples and/or treatment. More studies should be also conducted to correlate the water characterization to

the eating quality of noodles such as elasticity, stickiness and extensibility.

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