Frozen Convenience Noodles: Use of Ultrasound to Study the Influence of Preparation Methods on Their Rheological Parameters

Daiva Daugelaite,[1] Anatoliy Strybulevych,[2] Tomohisa Norisuye,[3] David W. Hatcher,[1,4,†] Martin G. Scanlon,[4]
and John H. Page[2]

ABSTRACT

Cereal Chem. 94(5):892–896

Longitudinal ultrasonic waves were used to investigate effects of preparation and frozen storage time on the rheological properties of noodles. Noodles prepared with and without glucose oxidase (GOx) were flash frozen either immediately after production (raw), after blanching, or after being optimally cooked. From measurements of attenuation, phase velocity, loss and storage moduli (M'' and M'), and $\tan\delta_L$ (M''/M'), it was found that raw noodles, prepared with or without GOx, were most similar overall to fresh noodles when stored frozen for one week. However, blanched noodles were closest to fresh noodles in terms of firmness, as measured by storage modulus, after one week of storage. Frozen storage for four weeks resulted in a significant loss in noodle quality. Stress relaxation measurements of Peleg's K_1 and K_2 parameters showed a significant effect of GOx addition on raw noodles after one week of frozen storage. As shown by K_1 and K_2 parameters, GOx addition delayed noodle texture deterioration associated with frozen aging for blanched and cooked treatments. The combined texture assessment of stress relaxation coupled with simultaneous ultrasonic measurements exhibits good potential for examining how formulation and pretreatment can mitigate the textural quality impairments associated with freezing of convenience noodles.

Wheat products formed as noodles are a widely consumed staple worldwide (Bui and Small 2007; Carini et al. 2014). Demand for frozen convenience noodles, requiring only the addition of hot water, is increasing significantly. The quality expectation of customers is that these products have the same quality and texture as a freshly made noodle. Commercially, this quality must be maintained for one week, but up to a four-week storage period would be ideal.

Many food products that are targeted at convenience food markets are preserved by freezing. The products sold to restaurants or convenience stores can be half (par-) or fully processed foods that are ready to consume after reheating for a few minutes (Hou et al. 2010). Blanched or cooked noodles can be stored for up to one year in the frozen state and used in restaurants or direct to consumers after a short (2 min) thaw and cook in boiling water (Hou et al. 2010). These processed noodles require a shorter boiling time and are healthier than, for example, instant noodles that are preserved by desiccation arising from deep frying processes. Noodles for frozen storage are prepared by cooking or steaming fresh noodles for a time short enough that noodle swelling is prevented (Hou et al. 2010; Lü et al. 2014). The par-cooked noodles are quickly blast frozen at a rate that prevents the large ice crystal formation that disrupts the gluten network and impairs noodle texture. After freezing and packing, noodles are maintained at temperatures at least below –15°C for the required amount of time (Nesvadba 2008).

Noodle quality is judged by its color, opaque appearance, absence of surface defects, and texture (Oh et al. 1983). Convenience noodles should cook rapidly but remain firm and not become soggy or lose solids when staying in the water following cooking (Oh et al. 1983). Many of these textural noodle qualities, such as extensibility, elasticity, and chewiness, depend on the quality of the flour. Starch swelling properties are important, but protein content (range from 9 to 13%) (Fu 2008) and protein quality (e.g., a balanced gluten strength determined by gliadin and glutenin components) (Hatcher 2004), are also important textural quality factors. For example, although protein content contributes to noodle firmness, too strong a protein matrix negatively affects extensibility, leading to challenges during noodle processing (Fu 2008). Noodles that are intended to be frozen need to be prepared from strong, extensible gluten (extensigraph RMax) wheat classes, because freezing and frozen storage negatively impact the elastic network in the gluten as well as the extent of retrogradation of the starch and therefore the resulting cooked noodle texture (Hatcher et al. 2009).

One way of preserving the texture of noodles in frozen storage is to use enzymes that promote cross-linking within the gluten network (Bellido and Hatcher 2010). The dough conditioning agent glucose oxidase (GOx) is extensively used in bread doughs (Hanft and Koehler 2006; Whitney et al. 2014). GOx produces the intermediate product hydrogen peroxide, which reacts with free thiol groups in glutenin proteins, creating disulfide bonds and linking ferulic acid residues of arabinoxylan into the gluten structure (Primo-Martín et al. 2003; Hanft and Koehler 2006; Steffolani et al. 2010). GOx also affects the water-extractable proteins, albumin and globulin, by reducing S-H linkages to create S-S links and dityrosine cross-links (Rasiah et al. 2005). However, large amounts of GOx in dough systems cause excessive cross-linking and aggregation of gliadins and an intense gelation of water-soluble arabinoxylans, so that a weaker glutenin network is formed (Bonet et al. 2006). Cryo-scanning electron microscopy (cryo-SEM) studies showed that the protein network is formed from nonuniform gluten fibrils and has an agglomerated coarse structure (Bonet et al. 2006). The doughs are therefore less extensible with a weakened glutenin network. Previous studies on noodles showed that addition of GOx coupled with noodle blanching prior to blast freezing and frozen storage was a reasonable procedure to obtain convenience noodles with a similar quality to that of fresh noodles (Hatcher 2004).

Few studies have been conducted on dough properties at ultrasonic frequencies higher than 10 MHz (Fan et al. 2013). A previous study on cooked yellow alkaline noodles with addition of GOx showed the feasibility of using 11 MHz ultrasound to determine the mechanical properties of refrigerated noodles during storage (Daugelaite et al. 2016). Using such an ultrasonic technique, noodle texture properties were examined nondestructively at a relatively small wavelength.

Because different noodle-processing conditions result in different textures, our objective was to determine if this promising nondestructive ultrasonic technique could evaluate whether different noodle preparation methods, with or without the addition of GOx, could preserve noodle quality for one or four weeks of frozen storage. For this purpose, alkaline noodles were prepared in three

---

[†] Corresponding author. E-mail: dave.hatcher@grainscanada.gc.ca

[1] Grain Research Laboratory, Canadian Grain Commission, Winnipeg, MB, Canada.
[2] Department of Physics and Astronomy, University of Manitoba, Winnipeg, MB, Canada.
[3] Graduate School of Science and Technology, Kyoto Institute of Technology Matsugasaki, Kyoto, Japan.
[4] Department of Food Science, University of Manitoba, Winnipeg, MB, Canada.

https://doi.org/10.1094/CCHEM-11-16-0265-R

ways prior to freezing: raw (right after sheeting), blanched, and cooked. An additional goal of this study was to conduct simultaneous traditional stress-relaxation measurements alongside novel ultrasonic measurements, so that a more holistic determination of the mechanical properties of the noodles could be acquired.

MATERIALS AND METHODS

Sample Preparation. A strong flour blend was milled from two Canada Western Red Spring wheat class varieties to 72% flour extraction with an Allis-Chalmers mill. Flour (50 g), 34% water (w/w), 1% (w/w) NaCl, and 1% (w/w) kansui (9:1 sodium and potassium carbonate) were mixed with a centrifuge mixer (SpeedMixer DAC 150FV, FlackTek, Landrum, SC, U.S.A.) for 30 s at 3,000 rpm (Diep et al. 2014). For samples with GOx, the enzyme was added as 10 GOx U/g of flour (50 mg of GOx) (Sigma-Aldrich, Saint Louis MO, U.S.A.). Out of four mixed dough crumb samples, one aggregated 200 g dough piece was formed and sheeted with an Ohtake laboratory noodle machine (Ohtake, Tokyo, Japan). The mixing process took 2 min in total and was used because it yielded a much better dough crumb with uniform hydration and better reproducibility when assessing raw noodle characteristics. The 200 g noodle dough process with a traditional Hobart mixer requires 7 min to complete and yields an incompletely hydrated dough that lacks uniformity in dough consistency. The rapid method has consistently demonstrated uniform hydration within 30 s. To duplicate commercial practices used to develop the gluten network within the dough sheet, a lamination step followed by seven passes every 45 s was conducted so that a 1.1 mm final dough thickness was attained. The dough sheet was allowed to rest for 1 h in an airtight plastic bag. Afterward, optimum cooking time was determined by cooking a dough disc of 41 mm in diameter (Hatcher et al. 2009).

In this frozen noodle storage study, three treatments investigating processing of noodles prepared with or without GOx were investigated. The "ideal control" noodle for consumer preference was a fresh noodle made without GOx that was cooked immediately after preparation. For comparison, a similar sample was prepared with GOx. Cooked noodles were optimally cooked (8 min in boiling water) and then rinsed for 2 min at 22°C in distilled water to cool and stabilize noodle temperature so as to delay starch swelling (Hou et al. 2010). The blanched noodles (prepared with and without GOx) were also prepared in boiling water, but only for 3 min, followed by the same cooling regime. For both of these pairs of treatments, noodles were dried initially with paper towels, and then any excess moisture was absorbed by thin Kimwipes (Kimberly Clark, Irving, TX, U.S.A.). The third pair of treatments, raw noodles, was not subject to any thermal or drying steps.

All samples were sealed in airtight freezer bags that were spread in a single layer and flash frozen at –77°C (Forma, 900 series, Thermo Scientific, Waltham, MA, U.S.A.) for 24 h. The samples were then removed and subject to frozen storage (at –18°C) until removed for testing at weeks 1 and 4.

Ultrasonic and Texture Measurements. Ultrasonic and texture measurements were done concurrently as triplicates (staggering measurements on day 1, day 2, and day 3) after zero, one, or four weeks of storage at –18°C. As noted above, for week 0, fresh noodle samples were cooked for 8 min to serve as the ideal control. Prior to testing, noodles were cooled and dried as for preparation for freezing, but with an extra paper towel drying stage. After one or four weeks of storage, all noodles (cooked, raw, or blanched) were cooked for 3 min, rinsed for 2 min at 22°C, and gently dried. The density of raw, cooked, and blanched noodles was determined with a specific gravity bottle.

Ultrasonic transmission measurements were performed in triplicate on each of the three consecutive days, using two 10 MHz Panametrics transducers (Olympus NDT Canada, Edmonton, AB, Canada) mounted on a TA.XTPlus texture analyzer (Texture Technologies, Scarsdale, NY, U.S.A.). Fast Fourier transform analysis of the pulsed ultrasonic waveforms transmitted through the noodle samples was used to extract the phase velocity (v) and attenuation (α) as a function of frequency ($f = \omega/2\pi$). From these data and the measured density, the longitudinal storage modulus M', loss modulus M'', and their ratio $\tan\delta_L = M''/M'$ were also determined (Elmehdi et al. 2004). The details of the measurement set up and analysis are given in Daugelaite et al. (2016).

Stress relaxation measurements were performed concurrently with ultrasonic measurements, as described in detail in Daugelaite et al. (2016).

RESULTS AND DISCUSSION

All ultrasonic data were analyzed at 11 MHz, a frequency that permits probing of the properties of the noodles without possible complications owing to bubble effects (Strybulevych et al. 2007). In a previous study, the principles of ultrasound propagation through noodles were discussed (Daugelaite et al. 2016), and these principles are relevant for this study too. Because the dimensionless parameter $\alpha v/2\omega$ is small for the noodle samples, the dough density and the phase velocity of ultrasound propagating through the noodle are the dominant factors determining the longitudinal storage

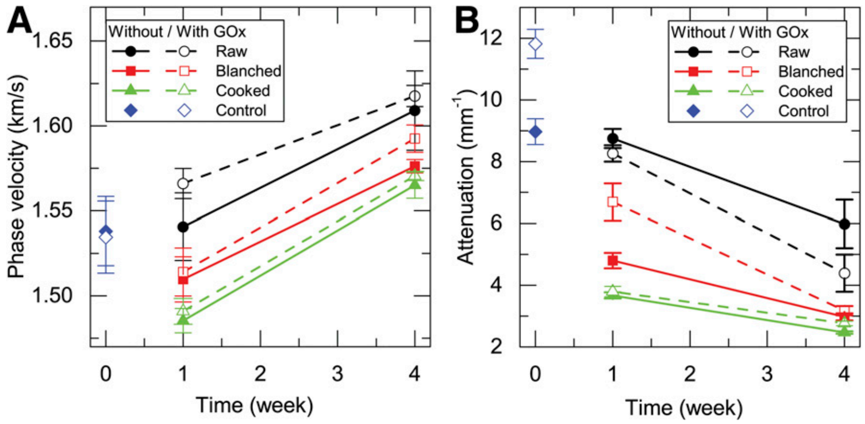

Fig. 1. Effect of storage and glucose oxidase (GOx) addition on phase velocity (**A**) and attenuation (**B**) at 11 MHz as a function of frozen storage time for raw, blanched, and cooked noodles made from Canada Western Red Spring wheat flour without (solid symbols) and with (open symbols) the addition of 10 U/g of glucose oxidase (500 ppm). Also shown are results for fresh noodles with no GOx (solid diamonds), which act as the control, and for fresh noodles with GOx addition (open diamonds). Lines highlight trends with increasing storage time. Uncertainties are the standard error, SD/($n^{0.5}$), where SD is the standard deviation and n is number of replications (minimum of 6).

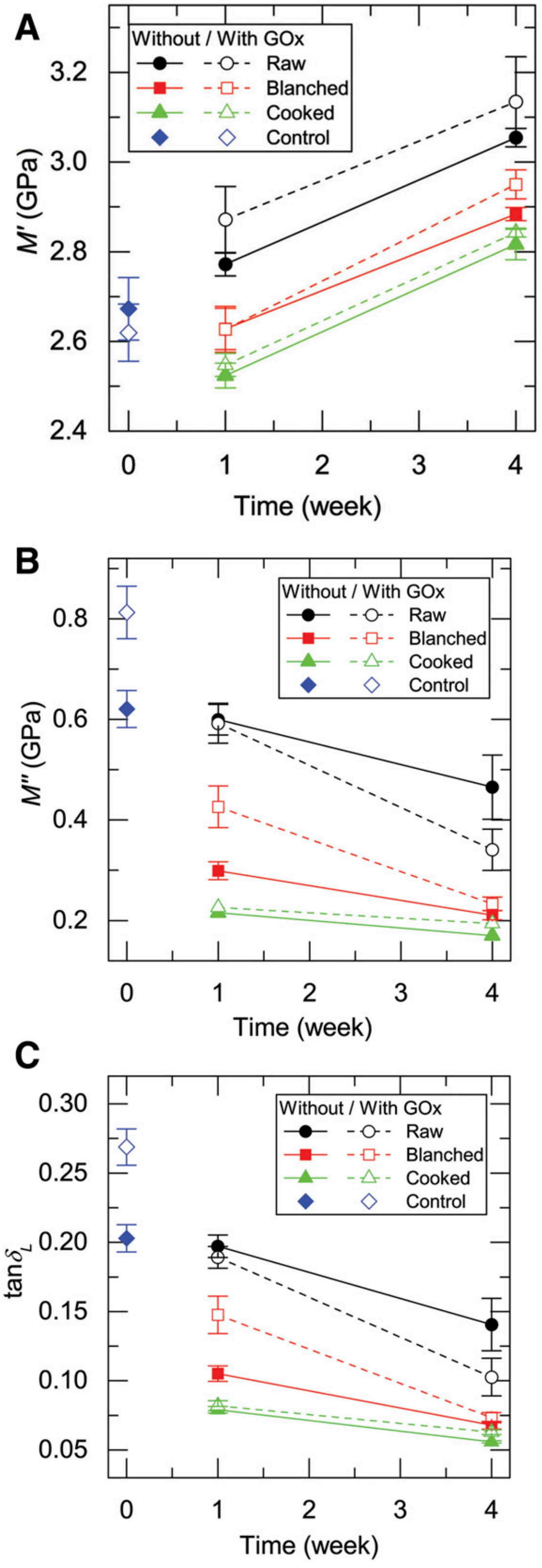

Fig. 2. Effect of storage and glucose oxidase (GOx) addition on M' (**A**), M'' (**B**), and $\tan\delta_L$ (**C**) at 11 MHz as a function of frozen storage time for raw, blanched, and cooked noodles made from Canada Western Red Spring wheat flour without (solid symbols) and with (open symbols) addition of 10 U/g of glucose oxidase (500 ppm). Also shown are results for fresh noodles with no GOx (solid diamonds), which act as the control, and for fresh noodles with GOx addition (open diamonds). Lines highlight trends with increasing storage time. Uncertainties are the standard error, SD/($n^{0.5}$), where SD is the standard deviation and n is number of replications (minimum of 6).

modulus (M'), a parameter that reflects how well the noodle stores the acoustic strain energy of the ultrasonic pulses (Bellido and Hatcher 2010; Fan et al. 2013; Scanlon and Page 2015). Larger values of M' imply a firmer (less compressible) material; therefore, one needs to apply higher stress to achieve a particular longitudinal (elastic) deformation. The loss modulus, M'', is a measure of how effectively acoustic energy is dissipated within the material.

To compare these small strain ultrasonic measurements with conventional large deformation assessments of noodle texture, simultaneous uniaxial stress relaxation tests were conducted. From these, Peleg's stress relaxation parameters, K_1 and K_2, were calculated, for which higher K_1 and K_2 values are associated with firmer food texture (Singh et al. 2006).

The control noodles were prepared without GOx and cooked for 8 min immediately after preparation to attain optimal cooked noodle texture (Hatcher et al. 2009); these samples served as the ideal control noodle. To attain optimal texture in the fresh noodle prepared with GOx, a slightly longer cooking time of 8.5 min was necessary. This can be explained by the formation of a tighter gluten network with GOx, which slows down water migration as well as restricting embedded starch granules from swelling during cooking (Oh et al. 1985).

For the fresh noodles (zero frozen storage), no significant differences in phase velocity were observed owing to the addition of GOx (Fig. 1A), but the attenuation coefficient increased significantly (Fig. 1B) with the GOx treatment (or its resulting effect on changes in noodle properties owing to the slightly longer cooking time). As a result of changes in attenuation coefficient but essentially no changes in velocity, significant differences between the loss modulus M'' and the $\tan\delta_L$ values of the two types of noodles were observed (Fig. 2B and C), but not for M' (Fig. 2A). The large strain assessments associated with stress relaxation mirrored those of M'' and $\tan\delta_L$, with both K_1 and K_2 being significantly higher for the GOx-formulated noodles compared with the ideal control (Fig. 3).

A desirable texture of alkaline noodles is one in which they are firm and elastic (springy). Both gluten and starch play important roles in this texture. In the model of a cooked noodle described by Ross et al. (1997), two phases are evident: a continuous gluten polymeric phase, in which amylose (leached out from starch granules) resides, and a second discontinuous phase made up of partially gelatinized starch particles embedded in the continuous phase. Because the cooking process induces starch swelling, an enhanced noodle texture is obtained from the GOx treatment, in which the degree of starch swelling is restricted by the denser and stronger gluten (Kojima et al. 2004). Hence, the addition of GOx increased noodle elastic firmness, and a firmer "bite" was imparted to the cooked noodle texture.

Effect of GOx on Raw Noodles During Frozen Storage. In the absence of GOx, changes in the ultrasonic properties of flash frozen raw noodles stored for one week were small compared with the control. With GOx addition, significant differences in both phase velocity and attenuation coefficient (Fig. 1), as well as the derived mechanical parameter M' (Fig. 2A), occurred after one week of frozen storage. When frozen storage was extended to four weeks, the trend of increasing velocity and decreasing attenuation observed at one week was amplified (Fig. 1) so that significant differences in the mechanical properties of raw noodles (with and without GOx) were evident by four weeks of frozen storage (Fig. 2) compared with one week storage and with the control. Nevertheless, GOx addition did not make the measured rheological properties of stored noodles closer to the control noodles, and it generally did not slow down the evolution in textural properties that occurred between one and four weeks of frozen storage.

The ultrasonic assessment of the effects of GOx addition during frozen storage was essentially mirrored by the large strain evaluations of noodle properties. Significantly higher values for Peleg's stress relaxation parameters K_1 and K_2 (Fig. 3) for raw noodles treated with GOx and kept in frozen storage for one week indicate firmer texture in line with the M' assessment derived from ultrasonic measurements (Fig. 2A). After longer frozen storage, raw noodles were significantly firmer than after one week of storage, but the GOx firming effect indicated by K_1 and K_2 disappeared, an outcome contrasting with the differences seen in M'' and the M''/M' ratio after four weeks of frozen storage (Fig. 2B and C).

Although freezing and frozen storage affect both primary components of dough—the gluten (Nicolas et al. 2003; Wang et al. 2014) and the starch (Tao et al. 2016)—gluten is the main component that determines good textural and mechanical properties of the doughs, and it deteriorates during prolonged frozen storage. NMR studies showed that the fraction of water associated with the gluten matrix is more mobile and is weakly bound to dough components (Esselink et al. 2003). Extensive cryo-SEM and magnetic resonance imaging studies conducted on frozen bread dough showed that prolonged storage at –20°C damages dough structure at the molecular level, owing to gluten matrix dehydration and ice crystal growth (Esselink et al. 2003). As a result, cryo-shrinkage of the gluten network occurs, and growing bulk ice disrupts the gluten peptide chains that are responsible for gluten strength (Kontogiorgos and Goff 2006; Wang et al. 2015). Even though noodle dough has substantially less water than bread dough, the longer frozen storage results in inhomogeneous water distribution within the noodle, and the short 3 min cooking time does not allow full noodle dough rehydration.

Insights on the mechanism of textural quality changes can be gleaned from the previous work of Hatcher (2004). Significantly higher values of maximum cutting stress and longer relaxation times were recorded for raw noodles stored for four weeks at −18°C prior to cooking, compared with the control. Significant decreases in water uptake were also observed. Thus, in this study, a cooking time of 3 min for the raw noodles kept in frozen storage would lead to even less water absorption. The cause of this moisture migration is from inside the noodle to its exterior during frozen storage. Therefore, similar to bread dough, water available for the thawed dough does not rehydrate the gluten network because the gluten has lost its water-holding capacity.

Effect of Blanching and Cooking on Noodle Properties Following Frozen Storage. The results for the longitudinal storage modulus, which is the ultrasonic parameter most directly related to noodle firmness, showed that blanched noodles preserved the texture of noodles during freezing compared with cooked noodles and also preserved it throughout frozen storage for one week (Fig. 2). Specifically, the texture-preserving effect of blanching was such that no significant difference in M' was observed between the control sample and those blanched and stored frozen for one week (Fig. 2A). However, the other rheological parameters of blanched noodles differed after one week of storage compared with the control, and all evolved significantly as the storage time was increased to four weeks. Texture changes over time, as measured by M' and M'', were approximately the same. The blanched noodle structure and moisture content variation are similar to spaghetti: moisture content is lower in the core and increases toward the noodle exterior (Irie et al. 2004). The core of the noodle is not gelatinized, because it has a low moisture content (approximately 34% w/w in our case), whereas the exterior possesses a moisture content of 65% (Kojima et al. 2004), and freezing largely preserves the differential moisture distribution. Recooking for 3 min after frozen storage does not necessarily allow water penetration into the core of the blanched noodles. The ultrasonic results for cooked noodles show that there is considerable noodle deterioration during frozen storage (see, for example, the low $\tan\delta_L$ values in Figure 2C), suggesting that fully cooked noodles are not well suited to freezing and frozen storage.

The addition of GOx enhances the firming that takes place during frozen storage for the blanched noodles (Fig. 2A). However, no enzymatic effect was evident in M' for the cooked noodles. In contrast, enzyme effects were evident in large strain tests on both cooked and blanched noodles subject to frozen storage. The results for the stress relaxation K_1 for blanched noodles with or without GOx did not show significant differences after one week of frozen storage, but after four weeks K_1 was significantly higher for the blanched noodles with the GOx. The stress relaxation parameter K_2 for the blanched noodles showed an increase owing to GOx addition after one and four weeks of frozen storage. By contrast, the K_1 and K_2 values for cooked noodles subject to frozen storage at −18°C from one to four weeks showed a greater variation than the values for the blanched noodles, and they were not generally close to the control. From these results, it is concluded that blanching of noodles is a good pretreatment method for frozen storage (Hatcher 2004).

A comment on freezing method is warranted because of the textural damage observed in the frozen noodles. Cryo-temperatures used to freeze noodles for 24 h at –77°C caused an indirect effect on the frozen noodle quality and the overall results compared with freezing at –40°C. Storage at –77°C is cold enough to produce ice nuclei, but the environment is viscous enough to limit detectable ice growth. These nuclei will be expected to grow when the environment becomes warm and fluid enough. Consequently, there will be more damage done during warming rather than during freezing.

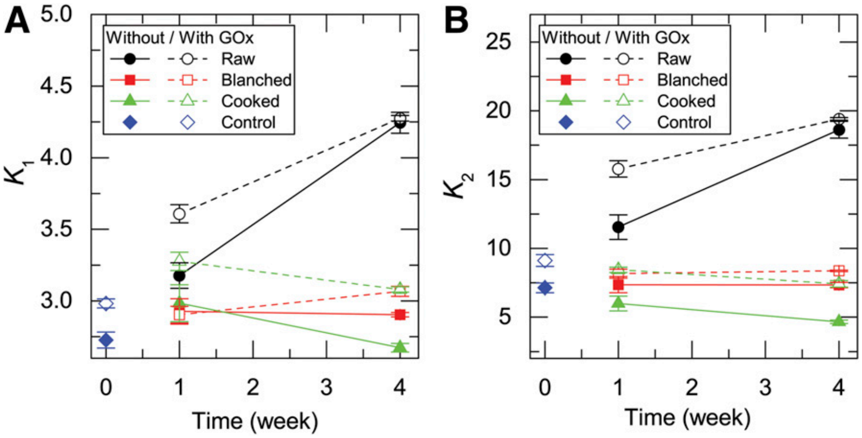

Fig. 3. Peleg's K_1 (**A**) and K_2 (**B**) values derived from the linearization of the stress relaxation curves simultaneously measured with the ultrasonic data as a function of frozen storage for raw, blanched, and cooked noodles made from Canada Western Red Spring wheat flour without (solid symbols) and with (open symbols) addition of 10 U/g of glucose oxidase (GOx) (500 ppm). Also shown are results for fresh noodles with no GOx (solid diamonds), which act as the control, and for fresh noodles with GOx addition (open diamonds). Lines highlight trends with increasing storage time. K_1 represents the initial rate of relaxation, and K_2 represents the extent of relaxation. Uncertainties are the standard error, SD/($n^{0.5}$), where SD is the standard deviation and n is number of replications (minimum of 6).

Freezing noodles at –77°C for 24 h results in a completely frozen product, and that may cause noodle cracking. This type of damage was not observed in our case.

Frozen storage has more severe effects on the texture of cooked noodles because absorbed water content is the highest compared with the raw and blanched noodles. Addition of GOx did not help to preserve cooked noodle firmness throughout the frozen storage.

CONCLUSIONS

Convenience frozen noodles, made by flash freezing of raw noodles immediately after sheeting, display equivalent rheological parameters after storage for one week at –18°C compared with those of freshly made noodles. Blanching the noodles before freezing gives the best noodle firmness after storage for one week. Frozen storage for four weeks of flash frozen noodles results in a decline in rheological parameters, regardless of pretreatment or lack of it. Simultaneous measurements of both ultrasonic and relaxation parameters provide good insight and quantitative results on the effects of noodle pretreatments and aging during frozen storage of convenience noodles.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the Strategic Grants Program of the Natural Sciences and Engineering Research Council of Canada.

LITERATURE CITED

Bellido, G. G., and Hatcher, D. W. 2010. Ultrasonic characterization of fresh yellow alkaline noodles. Food Res. Int. 43:701-708.

Bonet, A., Rosell, C. M., Caballero, P. A., Gomez, M., Perez-Munuera, I., and Lluch, M. A. 2006. Glucose oxidase effect on dough rheology and bread quality: A study from macroscopic to molecular level. Food Chem. 99:408-415.

Bui, L. T. T., and Small, D. M. 2007. Folates in Asian noodles: III. Fortification, impact of processing, and enhancement of folate intakes. J. Food Sci. 72:C288-C293.

Carini, E., Curti, E., Cassotta, F., Najm, N. E. O., and Vittadini, E. 2014. Physico-chemical properties of ready to eat, shelf-stable pasta during storage. Food Chem. 144:74-79.

Daugelaite, D., Strybulevych, A., Scanlon, M. G., Page, J. H., and Hatcher, D. W. 2016. Use of ultrasound to investigate glucose oxidase and storage effects on the rheological properties of cooked Asian noodles. Cereal Chem. 93:125-129.

Diep, S., Daugelaite, D., Strybulevych, A., Scanlon, M. G., Page, J. H., and Hatcher, D. W. 2014. Use of ultrasound to discern differences in Asian noodles prepared across wheat classes and between varieties. Can. J. Plant Sci. 94:525-534.

Elmehdi, H. M., Page, J. H., and Scanlon, M. G. 2004. Ultrasonic investigation of the effect of mixing under reduced pressure on the mechanical properties of bread dough. Cereal Chem. 73:708-711.

Esselink, E. F. J., Van Aalst, H., Maliepaard, M., and van Duynhoven, J. P. M. 2003. Long-term storage effect in frozen dough by spectroscopy and microscopy. Cereal Chem. 80:396-403.

Fan, Y., Scanlon, M. G., and Page, J. H. 2013. Influence of internal interfacial area on nanosecond relaxation of wheat gluten proteins as probed by broadband ultrasonic spectroscopy. Colloids Surf. B. 112: 466-473.

Fu, B. X. 2008. Asian noodles: History, classification, raw materials, and processing. Food Res. Int. 41:888-902.

Hanft, F., and Koehler, P. 2006. Studies on the effect of glucose oxidase in bread making. J. Sci. Food Agric. 86:1699-1704.

Hatcher, D. W. 2004. Influence of frozen noodle processing on cooked noodle texture. J. Texture Stud. 35:429-444.

Hatcher, D. W., Dexter, J. E., and Fu, B. X. 2009. Refrigerated storage of yellow alkaline durum noodles: Impact on color and texture. Cereal Chem. 86:106-112.

Hou, G. G., Otsubo, S., Okusu, H., and Shen, L. 2010. Noodle processing technology. Pages 99-140 in: Asian Noodles: Science, Technology, and Processing. G. G. Hou, ed. Wiley: Hoboken, NJ.

Irie, K., Horigane, A. K., Naito, S., Motoi, H., and Yoshida, M. 2004. Moisture distribution and texture of various types of cooked spaghetti. Cereal Chem. 81:350-355.

Kojima, T. I., Horigane, A. K., Nakajima, H., Yoshida, M., and Nagasawa, A. 2004. T_2 map, moisture distribution, and texture of boiled Japanese noodles prepared from different types of flour. Cereal Chem. 81: 746-751.

Kontogiorgos, V., and Goff, H. D. 2006. Calorimetric and microstructural investigation of frozen hydrated gluten. Food Biophys. 1:202-215.

Lü, Y. G., Chen, J., Li, X. Q., Ren, L., He, Y. Q., and Qu, L. B. 2014. Study on processing and quality improvement of frozen noodles. Food Sci. Technol. 59:403-410.

Nesvadba, P. 2008. Thermal properties and ice crystal development in frozen foods. Pages 1-25 in: Frozen Food Science and Technology. J. A. Evans, ed. Blackwell Publishing: London, U.K.

Nicolas, Y., Smit, R. J. M., Van Aalst, H., Esselink, F. J., Weegels, P. L., and Agterof, W. G. M. 2003. Effect of storage time and temperature on rheological and microstructural properties of gluten. Cereal Chem. 80: 371-377.

Oh, N. H., Seib, P. A., and Chung, D. S. 1985. Noodles. III. Effect of processing variables on quality characteristics of dry noodles. Cereal Chem. 62:437-440.

Oh, N. H., Seib, P. A., Deyoe, C. W., and Ward, A. B. 1983. Noodles. I. Measuring the textural characteristics of cooked noodles. Cereal Chem. 60:433-438.

Primo-Martín, C., Valera, R., and Martinez-Anaya, M. A. 2003. Effect of pentosanase and oxidases on the characteristics of doughs and the glutenin macropolymer (GMP). J. Agric. Food Chem. 51:4673-4679.

Rasiah, I. A., Sutton, K. H., Low, F. L., Lin, H. M., and Gerrard, J. A. 2005. Crosslinking of wheat dough proteins by glucose oxidase and the resulting effects on bread and croissants. Food Chem. 89:325-332.

Ross, A. S., Quail, K. J., and Crosbie, G. B. 1997. Physicochemical properties of Australian flours influencing the texture of yellow alkaline noodles. Cereal Chem. 74:814-820.

Scanlon, M. G., and Page, J. H. 2015. Probing the properties of dough with low-intensity ultrasound. Cereal Chem. 92:121-133.

Singh, H., Rockall, A., Martin, C. R., Chung, O. K., and Lookhart, G. L. 2006. The analysis of stress relaxation data of some viscoelastic floods using a texture analyzer. J. Texture Stud. 37:383-392.

Steffolani, M. E., Ribotta, P. D., Pérez, G. T., and León, A. E. 2010. Effect of glucose oxidase, transglutaminase, and pentosanase on wheat proteins: Relationship with dough properties and bread-making quality. J. Cereal Sci. 51:366-373.

Strybulevych, A., Leroy, V., Scanlon, M. G., and Page, J. H. 2007. Characterizing a model food gel containing bubbles and solid inclusions using ultrasound. Soft Matter 3:1388-1394.

Tao, H., Wang, P., Ali, B., Wu, F., Jin, Z., and Xu, X. 2016. Fractionation and reconstitution experiments provide insight into the role of wheat starch in frozen dough. Food Chem. 190:588-593.

Wang, P., Chen, H., Mohanad, B., Xu, L., Ning, Y., Xu, J., Wu, F., Yang, N., Jin, Z., and Xu, X. 2014. Effect of frozen storage on physicochemistry of wheat gluten proteins: Studies on gluten-, glutenin- and gliadin-rich fractions. Food Hydrocolloids 39:187-194.

Wang, P., Jin, Z., and Xu, X. 2015. Physicochemical alterations of wheat gluten proteins upon dough formation and frozen storage—A review from gluten, glutenin and gliadin perspectives. Trends Food Sci. Technol. 46:189-198.

Whitney, K., Ohm, J. B., and Simsek, S. 2014. Addition of glucose oxidase for the improvement of refrigerated dough quality. Cereal Chem. 91:548-553.

[Received November 5, 2016. Accepted May 29, 2017.]