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ORIGINAL ARTICLE

Evaluating and correlating the mechanical, nutritional, and structural properties of carrots after multiple freezing/thawing processing

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Abstract This work evaluated and correlated the mechanical and nutritional properties of carrots after five freezing/thawing cycles (FTC). Results showed that after one FTC, the mechanical parameters (hardness, chewiness, springiness, cohesiveness, resilience, and storage modulus) and the glucose and fructose content sharply decreased and the tangent (Tanδ) dramatically increased in samples. The contents of lycopene and lutein reached the maximum level after two FTC. And there were no significant changes in the content of α- and β-carotene (around 90 and 50 mg 100 g^{-1} dry matter, respectively) among all samples. Correlation analysis showed that the mechanical parameters were positively correlated with soluble sugars (fructose, glucose, and sucrose) and negatively with lycopene and lutein Tanδ were negatively related with soluble sugar. These results suggested that the first freezing/thawing condition could be the key factor for obtaining the products with acceptable quality. The changes in macroscopic mechanics could be used to predict the variations of potential nutritional components in tissues during FTC processing. The deteriorated structural changes (i.e. cell wall dissociation and turgidity loss) could be responsible for these results.

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Introduction

Freezing preserves foods better than drying or canning (Parreno and Torres 2005). However, the phenomenon of crystallization/re-crystallization during freezing/thawing processing can cause the loss of food qualities, especially in the case of vegetables and fruits. For instance, the firmness of frozen carrots is reduced by 2.38 N compared with those pretreated by the pulsed electric field (Shayanfar et al. 2014). Up to 33.6% of the polyphenols of frozen strawberries is lost after thawing at 20 °C for 20 h (Oszmiański et al. 2009). Thawing at 4 °C for 24 h causes a more pronounced loss of ascorbic acid and pigment of strawberries than thawing at 20 °C and in a microwave oven (Holzwarth et al. 2012). What's worse is that some frozen foods may be frozen, thawed, and refrozen many times before consumption, such as storage and transportation, repacking in a smaller retailer, retail display, and repeated storage by consumers. These would lead to more serious loss. Nevertheless, due to the limitation of current conditions, multiple freezing/thawing processing (MFTP) may be inevitable. To our knowledge, two works have been concentrated on the quality change of fruits subjected to MFTP. Owcharoen and Charoenrein (2011) have reported the influence of MFTP on the firmness and pectin content of mangoes. Phothiset and Charoenrein (2014) have indicated the contribution of the changes of the microstructure and cell wall components to the firmness of papayas after the treatment of freezing/thawing cycles.

In general, the final qualities of processed fruits and vegetables not only depend on the firmness but also,

probably even more, on the contributions from other mechanical characterizations (e.g. springiness, cohesiveness, elastic modulus, loss tangent) and nutritional aspects. Among the mechanical characterizations, rheological property is a crucial contributor to the food deterioration in the frozen storage (Ohnishi et al. 2003). It can objectively describe the changes in the tissue structure and texture quality, which is a barrier to the consumer acceptance of foods. For example, Loredo et al. (2014) have showed that sensory hardness and crispness are positively related with the storage modulus at intermediate and high frequencies and the loss modulus at low frequencies in blanched apple slices. Besides, different thawing modes can distinctly change the rheological parameters of frozen vegetable purees (Torres and Canet 2001). Rapid freezing and microwave-thawing can acquire ideal oscillator parameters (e.g. storage and loss modulus, complex viscosity) of mashed potatoes (Álvarez et al. 2005). Varying temperature and geometry may also cause different oscillatory rheological properties of mashed potatoes (Álvarez et al. 2007). It can be seen that these studies are limited to frozen/thawed vegetable purees. For frozen vegetable tissues, only a few studies have reported their rheological behaviors. Ohnishi et al. (2003, 2004) have showed that freezing/thawing treatment can decrease the elastic properties of vegetable tissues by one or two orders of magnitude. However, the change process of rheological properties in the vegetable tissues treated by MFTP is still unclear.

Furthermore, increasing reports have showed that there is a relationship between the nutritional components and mechanical attributes in fruits and vegetables. For example, the contents of carotenoids are significantly related with the fibrous and tender textures in carrots (Berger et al. 2008). In sweet potato, the carotenoid contents are obviously related with a wide spectrum of sensory attributes including texture, appearance, taste, and odor (Tomlins et al. 2012). Moreover, regression models have showed that the dry matter contents of sweet potato are correlated to the crumbly texture and watery texture. In fruits like 'Royal Gala' apples, carotenoid absorptions have a relation with the penetrometer firmness (Rowe et al. 2014). For vegetables after the freezing treatment, the more material mass of vegetables is lost, the higher maximal cutting force is required (Góral and Kluza 2009). These findings suggest that in fruits and vegetables, nutritional components could influence the mechanical properties and, in turn, the macroscopic variations of mechanics could act as a crucial indicator for evaluating and selecting products with potential nutritional benefits. However, in frozen-thawed fruits and vegetables their relationship is still unclear. Additionally, in recent years, the consumption of carrots has increased steadily, possibly due to the appreciable amounts of carotenoids, fiber content, and important minerals. Along these lines, using carrots as a model of root vegetables, gaining the detailed information of their mechanical and nutritional properties after MFTP and establishing their relationship could be in favor of providing basic data for the quality control and the improvement of process conditions in practical production of root vegetables.

Therefore, study was conducted to evaluate the changes in carrot mechanical characteristics (from macroscopic-scale texture profile analysis and microscopic-scale dynamic mechanical analysis), carotenoids and soluble sugars content (using high performance liquid chromatography), and cell microstructure (from transmission electron microscope) after MFTP. Furthermore, the relationship between mechanical and nutritional parameters was explored using Pearson's correlation analysis.

Materials and methods

Materials and sample preparation

Carrots were harvested in October in Shanghai, China. Fresh carrots (*Daucus carota* L.) without any physical damage were purchased from a local market. Fresh roots were cut into slices (10 ± 1 mm thickness and 35 ± 2 mm diameter) using a sharp knife. Ten slices were packed in each thin and hermetic bag. After packaging, the samples were sequentially frozen at −70 °C for 12 h in a cryogenic freezer (Revco, Asheville, NC), at −20 °C for 72 h in a chest freezer (MDF-135, Sanyo Electric C o., Ltd, Japan), and thawed at 4 °C for 4 h in a refrigerator. This freezing/thawing cycle (FTC) was repeated up to 5 times, which could include, in a large extent, the information on freezing/thawing processing (Phothiset and Charoenrein 2014).

Texture profile analysis (TPA)

The TPA was conducted in a TA-XT Plus Texture Analyzer (Stable Micro Systems Ltd, Surrey, UK) using a 500 N load cell. A two cycle compression test was performed using an aluminum cylinder probe (50 mm diameter), which was used to compress samples to 40% of their original thickness at a compression rate of 1 mm/s. Hardness1 and hardness2 during the first and second compression cycles, respectively, springiness, cohesiveness, gumminess, chewiness, and resilience were obtained from the force–time curves (Bourne 1978). Twelve measurements were performed for each treatment.

Dynamic mechanical analysis (DMA)

According to our previous method (Xu and Li 2015), the storage (G') and loss (G'') modulus and loss tangent (Tanδ) were measured in a compression configuration on Perkin Elmer DMA 8000 (Waltham, MA, USA). The average value of all points on the sweep curve was considered to be the value of one measurement. Data were reported as the mean value of six measurements for each treatment.

Drip loss measurement

Drip loss of samples was measured according to the method proposed by Phothiset and Charoenrein (2014). The percent values of drip loss were calculated as follows:

$$Drip\ loss(\%) = \frac{Initial\ weight\ of\ raw\ carrot - Weight\ of\ thawed\ carrot}{Initial\ weight\ of raw\ carrot} \times 100\%$$

Soluble sugar determination

For the extraction, 5 ml of deionized water was added to 100 mg of freeze-dried powder and stirred in a hot bath at 80 °C for 20 min. The mixture was centrifuged at 12,000 rpm for 20 min to gain the supernatant. The resulting residues were re-extracted using 4 ml of deionized water. Two supernatants were collected and diluted to 10 ml with deionized water for quantification. After being filtered with 0.45 μm filter unit (Beijing Bomex Co., Beijing, China), a 10 μl of the aliquot was injected into a high performance liquid chromatography (HPLC) system (Series 200, Perkin Elmer, Inc., USA) equipped with a refractive index detector (PE 200, Perkin Elmer, Inc., USA) and an Inertsil amino column (250 × 4.6 mm ID, GL Sciences, Japan). Acetonitrile/water (75:25 v/v) was used as the solvent at a flow rate of 1 ml min^{-1} at 40 °C. Sucrose, fructose, and glucose were quantified using the external standard method (i.e. a mixture of HPLC-grade sucrose, glucose and fructose) and expressed as mg g^{-1} dry matter. Determinations were performed in triplicate.

Carotenoid determination

Methanol (6.3 ml) and 60% potassium hydroxide solution (700 μl) were added to 100 mg of freeze-dried powder, swirled, and put in a hot bath at 60 °C for 30 min. Subsequently, 6 ml of Tris Buffer grade (containing 50 Mm Tris solution, 1 M sodium chloride solution, pH 7.5) was added to the mixture and swirled. After standing at 4 °C for 10 min, 16 ml of chloroform was added to the mixture and swirled. After standing at a cold ice for 10 min, the mixture was centrifuged at 4000 rpm at 4 °C for 15 min. These procedures were repeated twice to ensure the maximum extraction. Finally, the organic phase, containing carotenoids, were dried under nitrogen and dark conditions. The extracts were re-dissolved with hexane and filtered through a 0.22 μm filter unit before HPLC analysis. Carotenoids were separated on a YMC-carotenoid S-5column (250 × 4.6 mm). The injection volume was 60 μl. The mobile phase consisted of three different solvent mixtures: A, methanol, B, 0.2% ammonium acetate solution: methanol (28:80 v/v), and D, methyl tert-butyl ether. The gradient elution was used at a flow rate of 1 ml min^{-1}: 0–12 min, Isocratic elution (95%A and 5%B); 12–17 min, 95–80%A, 5%B, and 0–15%D; 17–27 min, 80–50%A, 5%B, and 15–45%D; 27–37 min, 50–25%A, 5%B, and 45–70%D; 37–50 min, 25%A, 5%B, and 70%D; 50–55 min, 25–95%A, 5%B, and 70%-0D; and 55–70 min, 95%A and 5%B. The detection was carried out at 446 nm at 25 °C. Quantification was conducted by the external standard method (i.e. a mixture of HPLC-grade β-carotene, α-carotene, Lycopene, and lutein) and expressed as mg 100 g^{-1} dry matter. Determinations were performed in triplicate.

Transmission electron microscope (TEM)

Based on our previous method (Xu and Li 2015) with minor modification, specimen microstructure was examined at an accelerating voltage of 30 kV using a Tecnai G2 Spirit Biotwin TEM (FEI, Hillsboro, OR).

Statistical analyses

One-way analysis of variance (ANOVA) was performed to evaluate the difference among the treatments. All data were expressed as mean ± standard deviation (SD). Significance level was set at $P < 0.05$. Pearson's correlation analysis was conducted by combining the data from all treatments to address the associations between mechanical parameters (including the TPA and DMA parameters) and nutritional parameters (involving the contents of carotenoids and soluble sugars). Statistical analyses were performed with SAS v9.1 (SAS Institute, Cary, NC, USA).

Results and discussion

Cell microstructure

In raw tissues (Fig. 1a), a large vacuole with intact tonoplast occupied most of the protoplast. Cell walls exhibited tightly packed and longitudinally organized fibrillar

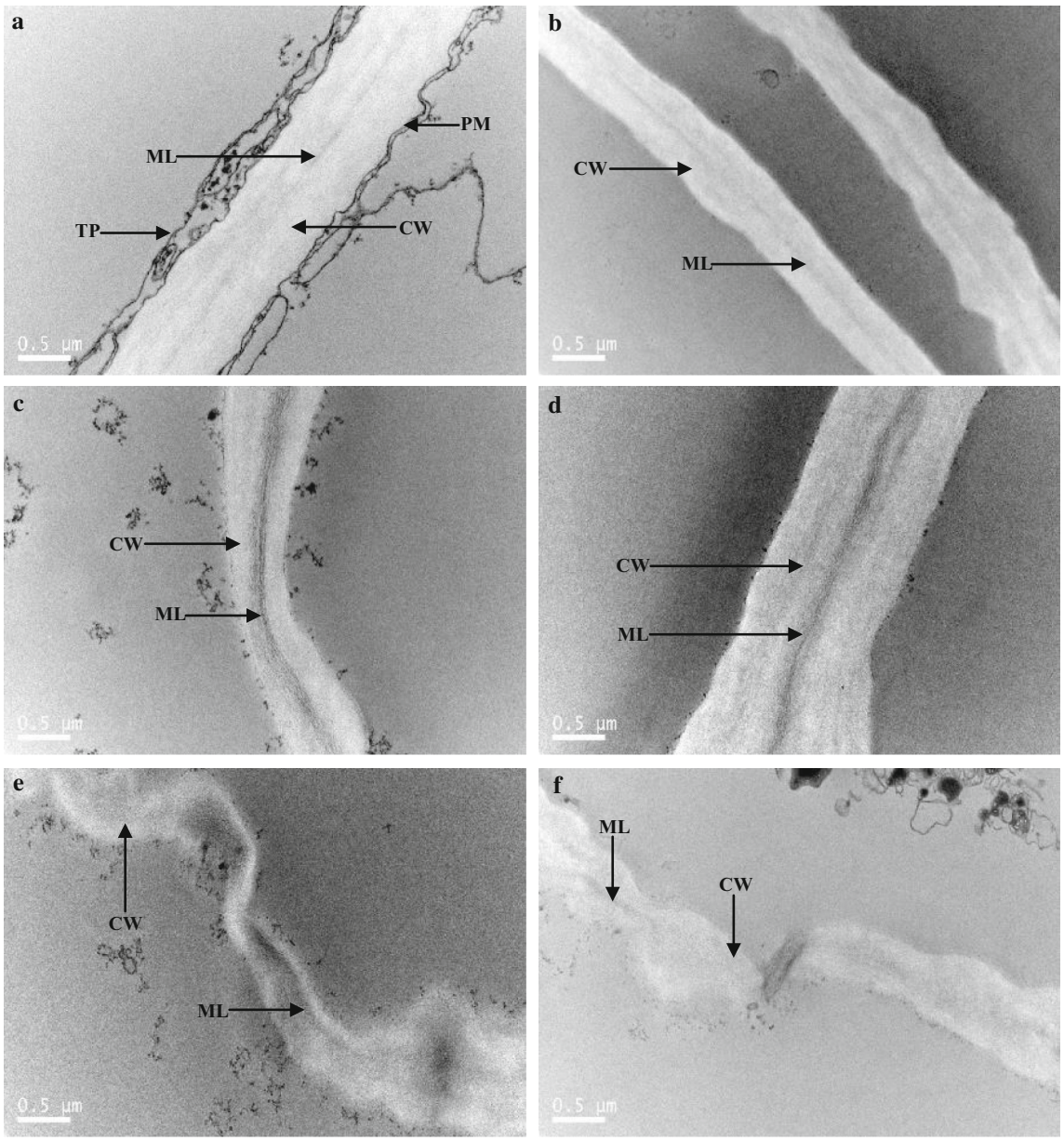

Fig. 1 Transmission electronic microscopy images of carrot tissues. **a**: Raw tissue; **b–f**: tissues treated by one, two, three, four, and five freezing/thawing cycle, respectively. *ML* middle lamella, *CW* cell wall, *CM* cell membrane, *PM* plasmalemma, *TP* tonoplast

materials, and a well-limited middle lamella. The plasma membrane was intact and close to cell walls. After one FTC (Fig. 1b), none of plasma membrane and tonoplast was detected in these treated cells. Cell walls became swollen and deformed. These features suggested that after the first freeze/thawing the hemicellulose-cellulose network structure of cell walls became loose as a result of the depolymerization of matrix glycan (Brummell 2006). The vacuoles and cell membrane disappeared together with a severe loss of turgor pressure. These could cause the collapses and damages of cells and large intercellular spaces between cells in tissues. After two and three FTC (Fig. 1c, d), the reticulate fibrilar pattern of cell walls became striated and progressively loosed. The central zone appeared denser, representing the presence of middle lamella and the separation of adjacent cell walls. After four and five FTC (Fig. 1e, f), cell walls were dramatically deformed and broken, and the middle lamella nearly disappeared. With increasing numbers of FTC the materials of cell walls and middle lamella were progressively deteriorated. One cause could be due to the magnification of mechanical injury from the repeated formation and melt of ice crystals after multiple FTC. Another cause could be from the reactivation of some cell wall-degrading enzymes (e.g. pectinase,

polygalacturonase) after thawing. Thus, repeatedly thawing could prolong the time of the chemical reaction between enzymes and substrates, finally causing more destruction of the materials.

TPA parameter

Texture attribute is an important barrier to the consumer acceptance of foods. The TPA is a profiling method of texture description. Hardness 1, hardness 2, and chewiness of samples decreased with increasing FTC (Fig. 2a). After one FTC, the values of hardness 1, hardness 2, and chewiness were decreased by 57.65, 63.20, and 79.35, respectively, as in comparison with those from raw samples, whereas after five FTC their total values were reduced by 77.27, 82.86, and 90.57%, respectively. It could be seen that their sharp decreases mainly occurred after one FTC. Similarly, the springiness, cohesiveness, and resilience sharply decreased after one FTC (Fig. 2b). Concretely, after one FTC the values of springiness, cohesiveness, and resilience were lowered by 25.27, 33.96, and 62.67%, respectively, relative to raw samples. After five FTC their total values were lowered by 35.16, 36.67, and 75.33%, respectively.

The mechanism of these changes could be explained mainly by the loss of cell turgidity and the degradation of cell wall components. After one FTC, no intact

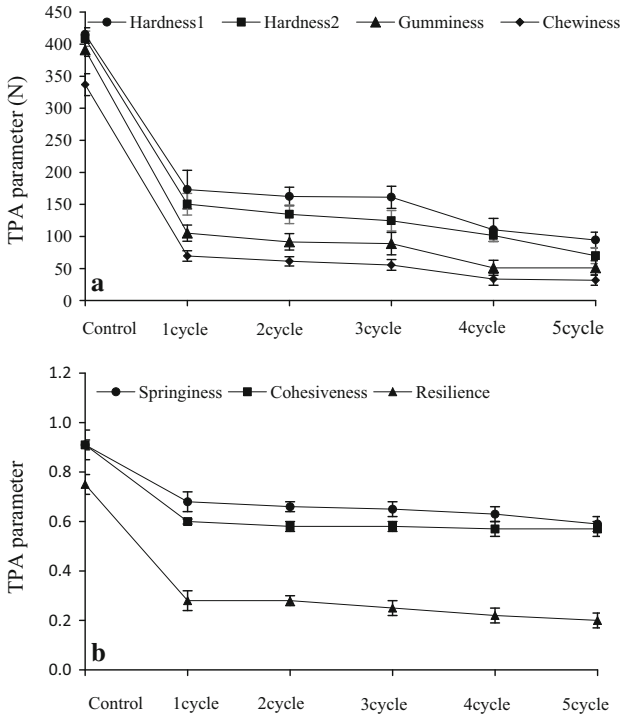

Fig. 2 Texture profile analysis (TPA) attributes of carrots. Control: raw tissue; *1*, *2*, *3*, *4*, and *5* cycle: the first, second, third, fourth, and fifth freezing/thawing cycle

vacuoles and cell membrane appeared and the network structure of cell walls became loose (Fig. 1). These meant that a great of fluids (mainly free water) in vacuoles was lost, accompanied with a severe loss of cell turgidity. Likewise, the increases of the cell wall permeability as the consequence of the degradation of cell wall components and the disruption of cell membrane could also cause an instant loss of cell turgidity. Finally, cells collapse and the cell-to-cell cohesion and contact lost in tissues. And the processed tissues could become more deformable producing a softer and rubbery texture (Loredo et al. 2014). Similarly, after vacuum-boiled treatments potato tissues become lower hardness and cohesiveness because of the cell turgidity loss (Iborra-Bernad et al. 2014). Besides, cell wall components (especially cellulose) possess the function of maintaining the rigidity and resistance of tissues. The degradation of cell walls could directly decrease the firmness (Owcharoen and Charoenrein 2011). Hence, only after one FTC, all of the texture parameters sharply decreased. These results suggested that texture qualities were sensitive to the freezing/thawing processing. The first temperature fluctuation could be enough to destroy them. Thus, the first freezing/thawing condition could be the key factor for gaining products with acceptable texture quality.

DMA parameter

Because of the complex connections and multivariate interdependencies of structural elements, the texture properties of biological tissues are difficult to predict and explain.

The incorporation of the microscopic-scale features (i.g. rheological parameters) and the macroscopic-scale TPA parameters could be of increasing importance for producing texturally attractive vegetable products (Martínez et al. 2007). In all samples, G' was higher than G'' over the entire frequency range (Fig. 3). This feature showed an elastic and cross-linked structure in carrots. The G' of all samples had a weaker dependency on the sweep frequency and there were no obvious trends with increasing frequency (Fig. 3a, b). On the other hand, in frozen-thawed samples, the G'' and Tanδ exhibited distinct uptrends with increasing frequency and their dependencies on the frequency were more complex (appearing some clear shifts) relative to raw samples (Fig. 3c, d, e). These different behaviors emphasized the internal structure and mechanistic differences after MFTP.

The values of G' and Tanδ of raw samples were 8.26×10^6 Pa and 0.17. After one FTC, the G' value of samples was sharply decreased by one order of magnitude compared with raw samples (Fig. 4). Subsequently,

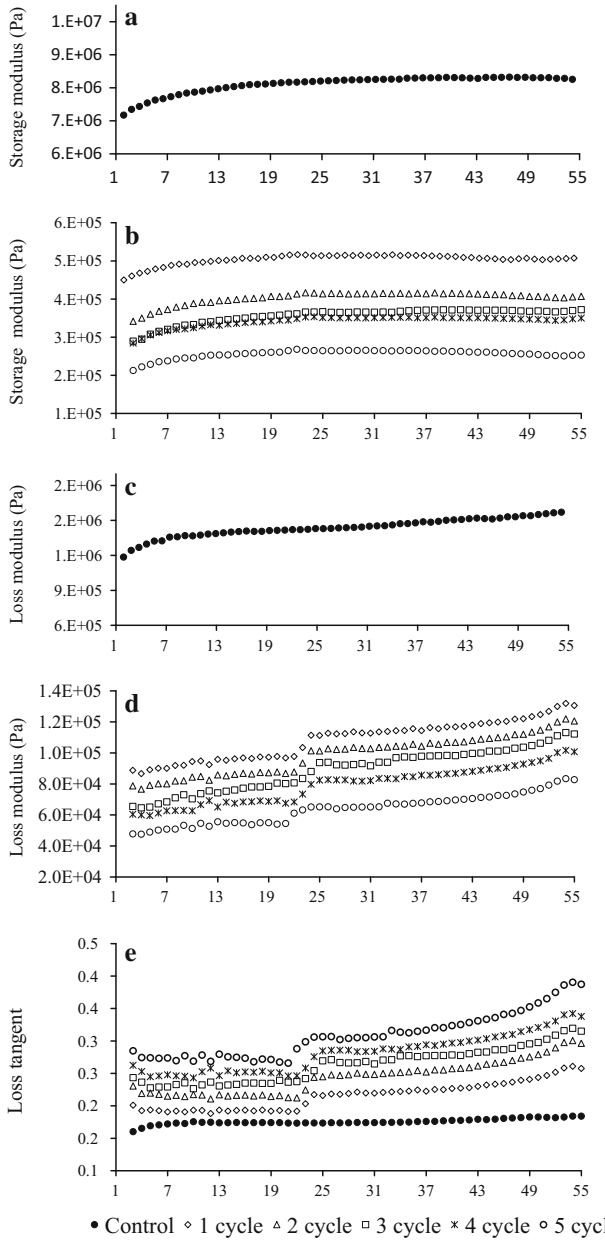

Fig. 3 Frequency spectra for loss and storage modulus and loss tangent of carrots. Control: raw carrots; *1*, *2*, *3*, *4*, and *5* cycles: the first, second, third, fourth, and fifth freezing/thawing cycle

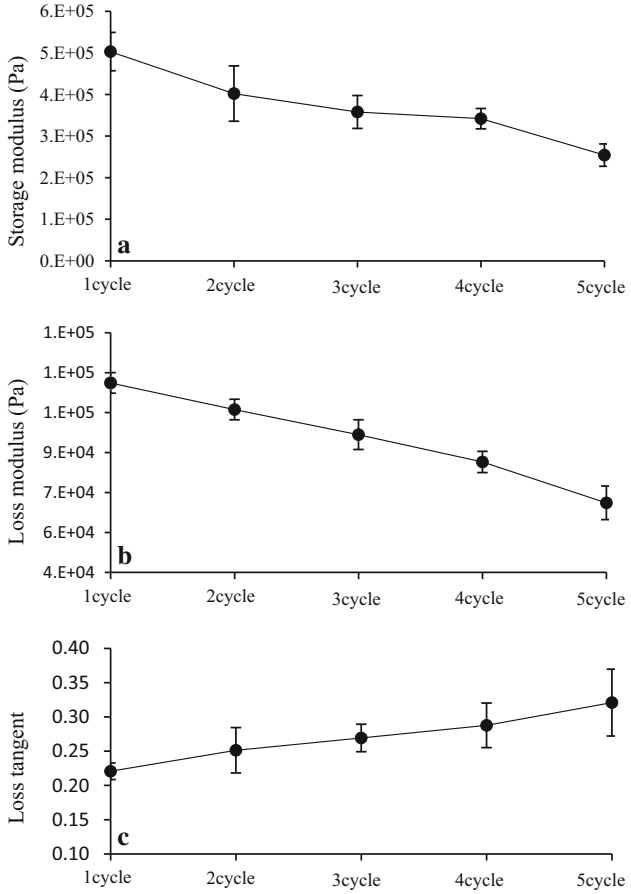

Fig. 4 Changes of storage (**a**) and loss (**b**) modulus and loss tangent (**c**) of processed carrots. *1*, *2*, *3*, *4*, and *5* cycle: the first, second, third, fourth, and fifth freezing/thawing cycle

sample G' gradually decreased with increasing FTC. The sharp decreases revealed that after one FTC, samples became less elasticity and their cross-linked structures were destroyed. Besides, the Tanδ presents the dissipation and the irreversibility of internal changes in samples. It gradually increased with increasing FTC, meaning the successive increases of internal damages of tissues. Wu and Guo (2010) have indicated that the loss of cell turgidity may induce the decreases of elastic response of Korla pears. Besides, the reformation of ice crystals during freezing/thawing processing could make the tightly-bound hemicellulose shifting into the loosely bound matrix glycan and the long-chain pectin transforming into the short-chain ones, finally causing an increase of soluble pectin and loosely bound hemicellulose (Phothiset and Charoenrein 2014). These changes might also have been resulted from the hydrolysis of some cell wall-degrading enzymes released from damaged cells. The degradation of the cell wall components (e.g. hemicellulose, pectin) could directly reduce their elastic strength and aggravate the internal losses in carrots (Xu and Li 2015). Similarly, thermal pretreatment could lower the yield stress and G' through decreasing the cell–cell adhesion and dispersion particle (e.g. cell wall materials) sizes in carrot dispersions (Lopez-Sanchez et al. 2011). In our study, after the first FTC, both cell turgor pressure and cell wall materials were subjected to a severe loss. Hence, sample G' sharply decreased and Tanδ dramatically increased. These suggested that the first FTC could also be the crucial processing for obtaining the ideal elastic texture, in accord with the ones of TPA parameters.

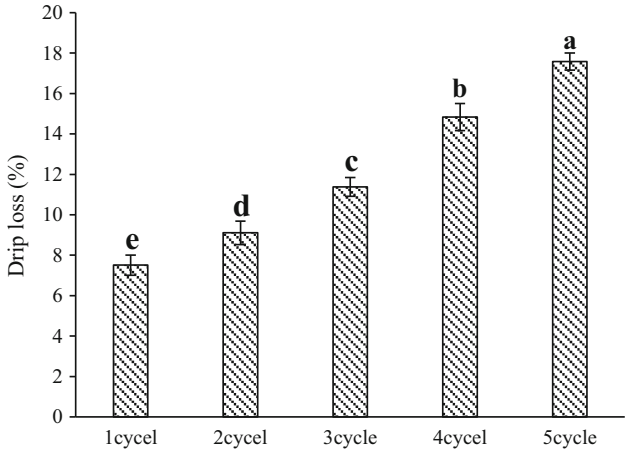

Fig. 5 Drip loss of thawed carrots. *1*, *2*, *3*, *4*, and *5* cycles: the first, second, third, fourth, and fifth freezing/thawing cycle. Letters above the bars (**a**–**e**) indicate changes in drip loss among the 5 treatments by one-way ANOVA ($P < 0.05$)

Drip loss

After one FTC, the value of sample drip loss was 7.51% (Fig. 5), probably owing to the disruption of ice crystals to cell membranes and cell walls. With increasing FTC, sample drip loss was progressively increased ($P < 0.05$). This indicated that the repeated melting and reformation of ice crystals could allow more cell collapse. More cell sap could be released from damaged cells after thawing.

Soluble sugar

In raw samples, the sucrose content was largest, followed by glucose, and the fructose content was lowest (Fig. 6). In treated samples, sucrose exhibited a gradual decrease with increasing FTC. Its content was lost by 32.05% after five FTC. The contents of glucose and fructose sharply decreased after one FTC and decreased slightly when the FTC number was added. Concretely, relative to raw samples, the levels of glucose and fructose were reduced by 47.35 and 38.35%, respectively, only after one FTC, whereas their total contents were lowered by 55.77 and 45.32%, respectively, after five FTC. One main reason could be that soluble sugars were water-soluble. They could be lost to the blanching water due to the destruction of cells (Volden et al. 2008). After one freezing/thawing treatment, cell structure was severely damaged and the water-holding capacity of cells dramatically decreased. Thus, a great of monosaccharide (i.e. glucose and fructose) together with the water were easily released from the damaged cells of samples. And the content of sucrose, a disaccharide, showed a progressive decrease because of the increasing collapse, separation, and damages of cells with freezing and thawing over and over.

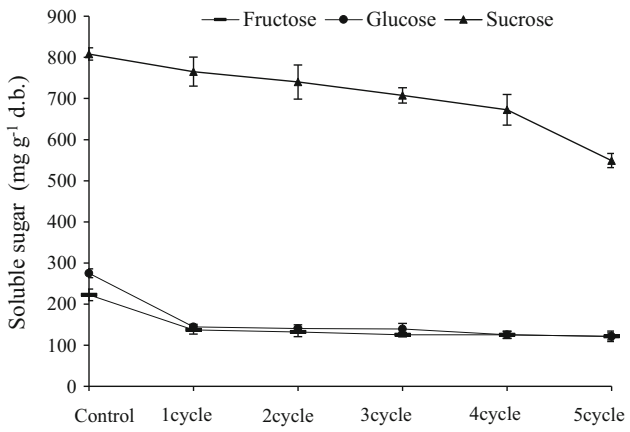

Fig. 6 Changes of the contents of fructose, glucose, and sucrose of raw and processed carrots. Control: raw carrots; *1*, *2*, *3*, *4*, and *5* cycles: the first, second, third, fourth, and fifth freezing/thawing cycle

Carotenoid

Carotenoids, lipophilic pigments, have provitamin A activity and antioxidant capacity. Raw carrots contained predominantly β-carotene, a substantial amount of α-carotene, and a low amount of lycopene and lutein (Fig. 7). Freezing may increase or decrease carotenoids of vegetables and fruits (Dalla Nora et al. 2014). In our case, the contents of α- and β-carotene varied slightly around 90 and

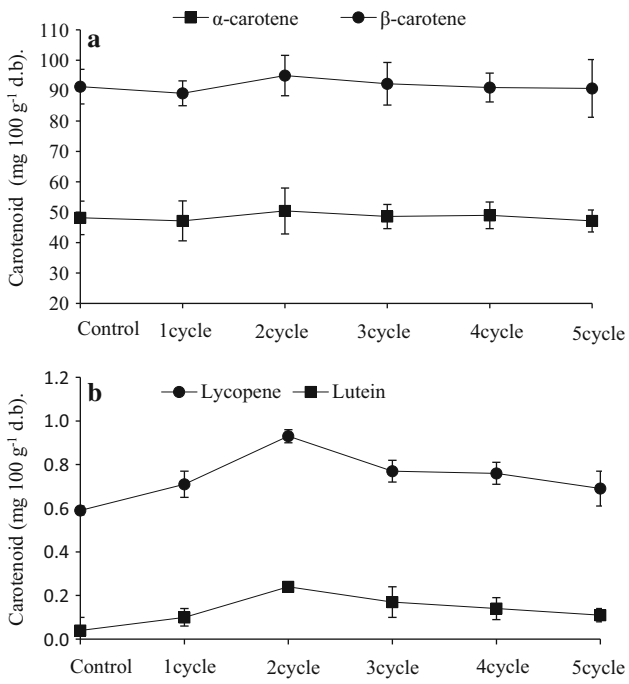

Fig. 7 Changes of the contents of β-carotene, α-carotene, Lycopene, and lutein of raw and processed carrots. Control: raw carrots; *1*, *2*, *3*, *4*, and *5* cycles: the first, second, third, fourth, and fifth freezing/thawing cycle

50 mg 100 g^{-1} dry matter with increasing FTC. For α and β-carotene contents, there is no significant difference between all samples (i.g. raw and treated carrots). The contents of lycopene and lutein were enhanced after one and two FTC, giving them the largest presence after the second FTC. Subsequently, their contents decreased gradually with increasing numbers. The increases at the initial stage could be the consequence of the accumulation from the carotenogenesis due to the intact enzyme systems. These related enzymes could be reactivated after thawing and the time of carotenogenesis catalyzed by them could be lengthened through thawing two times. Another reason might be that the extraction becomes easy after the processing. However, repeatedly thawing process may allow more carotenoids (released from severe cell ruptures) to the enzyme oxidation degradation (Fish and Davis 2003; Leong and Oey 2012). Hence, a subsequent decrease of the contents of lycopene and lutein of samples occurred. Although there were decreasing trends in their contents with increasing number, these decreases could not counteract the increases at the initial stage. Hence, compared with raw samples, the contents of lycopene and lutein showed an increase after five FTC.

Correlation between mechanical and nutritional parameters

Table 1 showed that in carrot treated by MFTP, the mechanical parameters (hardness 2, chewiness, springiness, cohesiveness, resilience, and G') were positively correlated with the soluble sugars (i.g. fructose, glucose, and sucrose) and negatively related to the carotenoids (i.g. lycopene and lutein) ($P < 0.05$). The Tanδ showed a negative correlation with fructose, glucose, and sucrose ($P < 0.05$). These results are inconsistent with the reports by Berger et al. (2008) and Tomlins et al. (2012). Concretely, in sweet potato, the crumbly texture presents a negative relationship with the carotenoid content and a positive one with dry matter (e.g. sugar) content (Tomlins et al. 2012). Carrots with high carotenoid content were more solid and less tender (Berger et al. 2008). One main reason for this difference could be the damages of internal structure (i.g. the turgidity loss and cell wall degradation) of carrot tissues from freezing/thawing processing. Because of these damages, mechanical properties like hardness and G' decreased and Tanδ increased, together with the loss of soluble sugars. And lycopene and lutein contents finally showed an increase compared with raw samples because of the accumulation. Hence, they showed a negative correlation with the mechanical parameters. But the selected carrot (Berger et al. 2008) and sweet potato (Tomlins et al. 2012) are both raw biological tissues without any processing. Their chemical and physical properties are mainly regulated by large molecules (e.g. proteins, carbohydrate, and lipids). Collectively, in frozen-thawed carrots the mechanical and nutritional parameters showed a relationship, which could be used to evaluating and selecting products with potential nutritional benefits through the macroscopic variations of mechanics.

Conclusion

The MFTP caused dramatic changes of both mechanical and nutritional qualities of carrots. After one FTC, all of the TPA parameters, the G', and the glucose and fructose contents sharply decreased and the Tanδ obviously increased in carrots, which suggested that the first freezing/thawing condition could be the key factor for obtaining products with acceptable quality. The lycopene and lutein contents achieved the maximum level after two FTC. And MFTP showed no significant influence on the contents of α- and β-carotene of carrots. Correlation analysis showed that the changes of mechanical attributes could be used to

Table 1 Correlation coefficients between mechanical (from texture profile analysis and dynamic mechanical analysis) and nutritional (carotenoids and soluble sugars) attributes of repeatedly frozen/thawed carrots

Coefficient	α-carotene	β-carotene	Lycopene	Lutein	Fructose	Glucose	Sucrose
Hardness 1	0.054	−0.136	0.170	0.304	0.133	0.168	0.180
Hardness 2	0.040	−0.043	−0.526*	−0.605*	0.964*	0.975*	0.712*
Springiness	0.022	−0.022	−0.484*	−0.536*	0.927*	0.938*	0.626*
Cohesiveness	−0.017	−0.015	−0.618*	−0.664*	0.969*	0.987*	0.624*
Gumminess	−0.008	−0.059	−0.549*	−0.613*	0.961*	0.974*	0.673*
Chewiness	−0.032	−0.012	−0.553*	−0.630*	0.965*	0.987*	0.650*
Resilience	−0.009	−0.009	−0.543*	−0.588*	0.954*	0.976*	0.662*
Storage modulus	−0.023	−0.018	−0.598*	−0.666*	0.964*	0.980*	0.583*
Loss modulus	0.001	−0.011	−0.590*	−0.658*	0.954*	0.975*	0.580*
Loss tangent	−0.088	−0.081	0.312	0.381	−0.616*	−0.696*	−0.732*

* Linear correlation was significant at $P < 0.05$

predict the changes of potential nutritional components of tissues during FTC processing. The deteriorated structural changes (i.e. turgidity loss and cell wall dissociation) could be responsible for these results.

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