LWT - Food Science and Technology 43 (2010) 525–534

Contents lists available at ScienceDirect

LWT - Food Science and Technology

journal homepage: www.elsevier.com/locate/lwt

Evaluating the impact of thermal and pressure treatment in preserving textural quality of selected foods

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ARTICLE INFO

Article history:
Received 1 February 2009
Received in revised form
21 September 2009
Accepted 28 September 2009

Keywords:
Pressure-assisted thermal processing
High-pressure processing
Texture
Color
Quality

ABSTRACT

A study was conducted to evaluate the efficacy of various combinations of pressure and thermal treatments in preserving textural quality of selected foods. Carrot, zucchini, apricot, red radish, and jicama were used as test samples. Pressure-assisted thermal processing (PATP; 600 MPa, 105 °C), high-pressure processing (HPP; 600 MPa, 25 °C), and thermal processing (TP; 105 °C, 0.1 MPa) experiments were conducted. Role of pressure (600 MPa) in preserving product quality while simultaneously (PATP) or sequentially (HPP-TP) exposed to elevated process temperature (105 °C) was also compared. Instrumental puncture, shear force, color and sensory analyses were utilized to compare the influence of the various process treatments. A crunchiness index (CI), relating product puncture force and stiffness, was able to characterize the severity of the process treatments on various products tested. Among the treatments, TP was the worst at retaining texture, but HPP-TP improved texture retention. In comparison to TP alone, PATP better retained texture and color. Jicama was least influenced by the treatments as compared to products tested. Process treatments investigated degraded the textural quality of zucchini and apricot. Instrumental CI results were also in agreement with the sensory data of carrot, red radish and jicama samples.

1. Introduction

Thermal processing (TP) is the conventional method of food pasteurization and sterilization. While thermally processed products are safe, application of heat impairs food quality. Recent advances in alternative food processing have created new approaches for preserving food without compromising product quality. Among these methods, high-pressure processing (HPP) is a promising food preservation method, wherein the food is exposed to high-pressures for a short duration, with or without the addition of heat, to achieve microbial inactivation. Since pressure treatment does not break covalent bonds, it can retain food quality and fresh characteristics while extending microbiological shelf life. Depending upon the intensity of the pressure-heat treatment, both pasteurization and sterilization effects are possible.

High-pressure pasteurization treatments use pressures about 600 MPa for several minutes at 20–45 °C (Lau & Turek, 2007). High-pressure pasteurization treatments inactivate pathogenic and spoilage bacteria, yeasts, and molds. On the other hand, bacterial spores are resistant to pressure treatment at ambient temperature, even above 1000 MPa (Cheftel, 1995). Pressure-assisted thermal processing (PATP), also referred as pressure-assisted thermal sterilization (PATS) or high-pressure high temperature sterilization (HPHT), involves a combined application of elevated pressures (500–700 MPa) and temperatures (90–121 °C) for a short duration to a preheated food product (Ananta, Heinz, Schlüter, & Knorr, 2001; Margosch, Ehrmann, Gänzle, & Vogel, 2004; Meyer, Cooper, Knorr, & Lelieveld, 2000; Rajan, Ahn, Balasubramaniam, & Yousef, 2006). Pathogenic spores such as *Clostridium botulinum* and varieties of *Bacillus* and *Clostridium* spoilage spores can potentially be inactivated through synergies of heat and pressure (Ahn, Balasubramaniam, & Yousef, 2007; Black et al., 2007; Koutchma, Guo, Patazca, & Parisi, 2005; Margosch et al., 2004; Reddy, Tetzloff, Solomon, & Larkin, 2006; Rovere et al., 1996; Zhu, Naim, Marcotte, Ramaswamy, & Shao, 2008). In Feb. 2009, the Food and Drug Administration (FDA) has approved the filing of pressure-assisted thermal process for production of low acid foods (Food Processing, 2009). Industry is interested in this technology due to shorter thermal exposure times.

It is important to understand the role of simultaneous or sequential application of pressure-thermal treatment, on quality of various products. Pressure pretreatment (50–500 MPa) of vegetables before cooking (at 99.5 °C) was reported to improve texture of the processed product (Kasai, Hatae, Shimada, & Ibuchi, 1995).

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0023-6438/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.lwt.2009.09.022

Pressure pretreatment might have helped improve the texture of the tissue by increasing tissue compactness and promoting biochemical changes associated with texture preservation (Basak & Ramaswamy, 1998; Oey, Lille, Van Loey, & Hendrickx, 2008). On the other hand, pressure, heat and their interactions can influence product quality during PATP. The instantaneous temperature changes induced by adiabatic heating during compression and adiabatic cooling upon decompression (Patazca, Koutchma, & Balasubramaniam, 2007) are often thought to reduce the product's thermal exposure during PATP. Moreover, researchers often conducted PATP experiments at moderate temperature (~105 °C process temperature and 600 MPa). These PATP conditions reportedly provide better texture, color, and flavor and aroma retention compared with traditional retorted products (Hoogland, de Heij, & van Schepdael, 2001; Juiano et al., 2006; Krebbers et al., 2003; Krebbers, Matser, Koets, & Van Den Berg, 2002; Matser, Krebbers, van den Berg, & Bartels, 2004; Zhu et al., 2008). Lau and Turek (2007) reported that pressure sterilization (two pressure pulses at 700 MPa, 105 °C and 1 min pressure holding time for each pulse) provided a fresher, less processed flavor in chicken, salmon, eggs, potatoes, and green beans as a result of less total thermal exposure than traditional retorting. Juiano et al. (2006) observed that combined pressure-thermal treatment at 700 MPa at 105 °C is a promising technique for preservation of shelf-stable egg-based product. Roeck, Sila, Duvetter, Van Loey, and Hendrickx (2008) reported an improved retention of carrot texture processed at 80 °C under 600 MPa. Leadley, Tucker, and Fryer (2008) found that the firmness of PATP green beans subjected to preheating at an initial temperature of 86 °C, followed by two consecutive cycles of pressure treatment at 700 MPa for 2 min was generally twice as high as the samples processed at 121.1 °C in a traditional retort.

A study on food textural quality degradation under similar temperature history with and without pressure can improve our understanding on the role of pressure in protecting textural quality during combined pressure-thermal treatment. Furthermore, it is of interest to develop approaches that will enable comparison of the impact of various pressure or heat treatments on textural quality. As pressure effects on product quality were also found to be a function of product matrix (Matser et al., 2004), documenting the impact of pressure-thermal treatment on several food products would be desired. Therefore, the objective of this research was to compare the impact of pressure, heat, and their combinations in preserving textural quality attributes of selected foods.

2. Materials and methods

2.1. Sample preparation

Baby carrots, zucchini, red radishes, jicamas, and apricots were sourced from a local grocery store. Sufficient quantities were purchased at the same time to minimize the variation in quality (and presumably age/source) of the raw material. The pH values of the carrot, zucchini, red radish, jicama and apricot samples were 5.2, 6.5, 5.9, 5.0 and 3.8, respectively, and the water activity (a_w) of the samples was about 0.99. Carrot (*Daucus carota* subsp. *sativus*) is a root vegetable with a crisp texture when fresh. Zucchini (*Cucurbita pepo*) is a small, fragile summer squash that cannot be stored for long periods. Radish (*Raphanus sativus*) is an edible root vegetable. The raw flesh has a crisp texture and a pungent, peppery flavor. Jicama (*Pachyrhizus erosus*), a warm season legume root crop also called "Yam Bean," is a brown-skinned turnip-shaped root with a crispy texture that is eaten raw or cooked (Gorny & Kader, 2008). The baby carrot (~8 tubers per 100 g of carrot) and red radish (~4 tubers per 100 g of red radish) samples were cleaned and unwanted roots and stems were removed. The zucchini samples were sliced into 2.5-cm thick disks. Jicamas were cut into sticks of 1.3 × 1.3 × 5.1 cm. Apricots were pitted and sliced into two halves. The samples (about 100 g) were vacuum packed in a 1 g/100 ml NaCl solution to prevent nutrient loss during processing. The ratio of sample to NaCl solution was 1:1 (w/v). Each sample was packaged by a vacuum packaging machine (Ultravac, UV 250, Koch Supplies Inc., MO, USA) in a clear Nylon/EVOH/Polyethylene retort pouch with high barrier properties (Win-Pak Ltd., Winnipeg MB, Canada).

2.2. High-pressure processing

All of the high-pressure processing (HPP; 600 MPa, 25 °C) and pressure-assisted thermal processing (PATP; 600 MPa, 105 °C) experiments were carried out using a 5-l capacity, Iso-Lab High-Pressure Food Processor (Stansted Fluid Power Ltd., Essex, UK). A propylene glycol, water mix (1:2 w/v) was used as the pressure transmitting liquid. To reduce the temperature gradient between the samples, surrounding pressure medium and pressure chamber walls, propylene glycol was circulated through the external jacket of the pressure chamber. The following is the summary of various experiments (Fig. 1) conducted to test the efficacy of combined pressure and thermal treatments in preserving quality attributes:

- *HPP*: Samples were pressure treated at 600 MPa and ~25 °C for 5 min pressure holding time. The equipment had 1.9 min compression (come-up) time, and 1.2 min decompression time. For this set of experiments, test samples in the basket were pre-chilled (~4 °C) before pressure treatment so that the in-process temperature achieved was a result of the adiabatic heating and heat exchange with surrounding pressure medium. The pressure vessel was maintained at ~25 °C. Two sets of samples were processed, one for evaluating pressure pasteurization effects, and the other to be subsequently thermally processed (HPP-TP) at 105 °C/0.1 MPa as described under the section on thermal processing. Processed samples were stored in a refrigerated environment until analyzed.
- *PATP-R*: Samples were subjected to pressure-assisted thermal processing (600 MPa at 105 °C) with 1.9 min compression (come-up) time, 5 min holding time and 1.2 min decompression time. The treatment took advantage of the rapid compression and decompression capabilities of the high-pressure equipment. Typical test runs involved preheating (PHT) prepackaged samples at 85 ± 1 °C in a water kettle for about 23 min before being loaded inside the pressure vessel. The pressure transmitting fluid was also preheated to desired initial temperature (~85 °C). Sample temperature during the preheating period was monitored with a K-type thermocouple (Omega Engineering, CT, USA) inserted into the geometric center of the sample. Preheated samples were then filled into a thermally insulated cylindrical sample basket (102 mm dia × 559 mm height) (Stansted Fluid Power Ltd., Essex, UK) and loaded into the high-pressure equipment using a lift mechanism. To minimize heat loss from sample to surroundings during compression and holding time, the pressure chamber temperature was maintained at 95 °C. The temperature of the test samples during various pressure treatments was monitored at the top, center and bottom of the carrier basket using T-type thermocouples (Omega engineering, CT, USA) mounted in the sample pouch using a C-5.2 stuffing box (Ecklund-Harrison Technologies, FL, USA).
- *PATP-SL*: In this experiment, product thermal history during pressure-assisted thermal processing (600 MPa, 105 °C, 5 min holding time) was adjusted to 'match' that of conventional retort processing (described under thermal processing (TP) experiments section). PATP-SL thermal history included 23 min

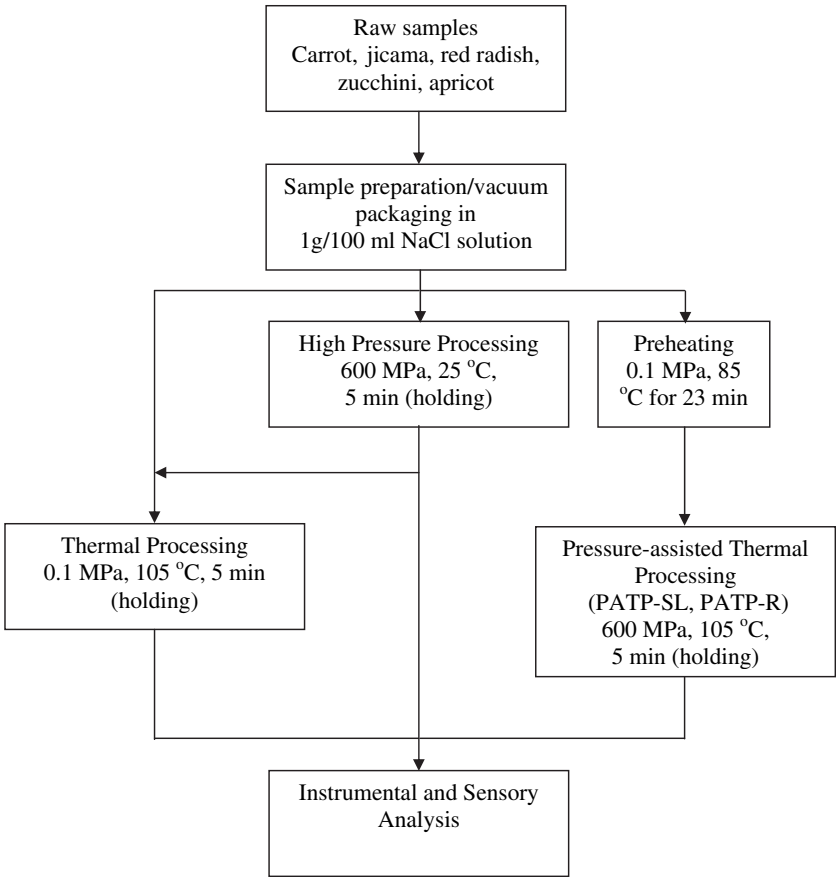

Fig. 1. Schematic diagram outlining various experimental conditions. R and SL designate different compression time of pressure-assisted thermal processing (PATP).

preheating (85 ± 1 °C), 26.6 min step-wise compression, 5 min pressure holding time and 6.3 min decompression times. Accumulated thermal dosage of the sample at different processing conditions was calculated based on the area under respective thermal history curves using the trapezoidal rule. With similar thermal history for PATP-SL and TP samples, the role of pressure in preserving food quality attributes can be evaluated. The initial temperature of the pressure transmitting fluid was also adjusted. After processing, the samples were cooled in an ice-water mix and kept under refrigerated conditions.

- *PHT*: Pressure-assisted thermal process (PATP) requires preheating (PHT) product to certain initial temperature. To document the influence of thermal exposure on product quality during preheating, a set of the samples preheated at 85 ± 1 °C, 0.1 MPa for 23 min were also analyzed. Packaged untreated samples served as the control (CTRL).

2.3. Thermal processing experiments

The TP experiments were conducted in a Surdry SL retort (APR95-l, Abadiano, Spain). Samples were processed using steam immersion. The temperature of processed samples during TP was monitored using data trace probes (Micropack III, Mesa Labs, Lakewood, CO, USA). Samples were processed at 105 °C, 0.1 MPa for a 5 min holding time. The thermal process come-up time was 47.5 min. In another set of experiments, samples that were previously pressure pasteurized (the same day) were subsequently thermally processed (HPP-TP). Immediately after processing, the pressure-pasteurized samples were kept under chilled conditions (~4 °C) and thermally processed within 1 h. All processed samples were refrigerated at 4 °C until analysis.

2.4. Textural changes due to enzymatic activity

A separate set of experiments was conducted to evaluate the role of biochemical changes due to enzymatic activity, rather than the physical changes due to compression under pressure, in preserving product texture during treatment. Carrot samples were used as the model food. The carrots were pretreated by being soaked in a phosphate buffer pH 2.0 containing a 0.0035 mol/L sodium dodecylsulfate (SDS) solution to chemically inactivate the carrot pectinmethylesterase (PME) (Barrett, 2007). In order to estimate the enzyme activity, the soaked sample was incubated in a water bath at 50 °C for 1 h. PME activity was determined from methanol released from the sample during this time. Methanol was determined by the colorimetric reaction with alcohol oxidase and purpald (Anthon & Barrett, 2004). The absorbance was measured at 550 nm by spectrophotometer (Model number 4001/4, Spectronic, Garforth, Leeds, U.K.). Cooked sample (100 °C for 30 min) was used as the baseline for comparison. The enzyme activity of samples was monitored for up to a week during refrigerated storage. After establishing enzyme activity levels, soaked carrot samples without any apparent enzyme activity were then pressure sterilized (PATP-R) or thermally processed (TP) as described before.

2.5. Color measurement

A tristimulus colorimeter (CR-300, Minolta, Osaka, Japan) was used to determine L^* (lightness), a^* (redness or greenness), and b^*

(yellowness or blueness) color values of various food products processed. The apparatus was calibrated using a standard white tile ($Y = 92.6$, $X = 0.3161$, $y = 0.3321$). The samples were placed on the top of the light source (15 mm in opening), and L^*, a^*, and b^* values were directly obtained from the chroma meter. The color data were obtained from six replicates.

2.6. Texture measurement

Samples were cut into cylinders (10 mm dia × 10 mm height) for texture measurement. Puncture and Warner-Bratzler shear tests were conducted using a TA-XT2 Texture Analyser (Stable Micro System) with a load cell of 50 kg ± 1 g at crosshead speeds of 1 mm/s and 1.67 mm/s, respectively. Puncture tests utilized a 2 mm diameter probe. Uniaxial compression tests using a 50 mm diameter probe were also carried out at a crosshead speed of 1 mm/s to compare the role of different texture parameters in describing the sample textural transformation due to various treatments. All the textural measurements were performed approximately 10 times to minimize inherent sample-to-sample biological variations.

2.7. Textural parameter analysis

The force-deformation curve to rupture point obtained from the puncture test was fitted with a third order polynomial and the following texture parameters were extracted using Matlab (Version 7.1.0246, Matworks Inc., MA, USA):

- $\text{Grad}_{\%}$: slope of force-deformation curve for the processed sample at different percentages (10–70%) of maximum puncture force. This value represents the sample stiffness (Bourne, 2002; Gonzalez, 2009; Mohsenin, 1970).
- F: max puncture force of the processed samples (Gonzalez, 2009; Mohsenin, 1970). This represents the sample hardness.

From the knowledge of $\text{Grad}_{\%}$ and F, a crunchiness index (CI) was estimated for various samples as follows:

$$\text{CI} = \frac{F_{\text{treatment}}}{F_{\text{ctrl}}} + \frac{\text{Grad}_{\%\text{treatment}}}{\text{Grad}_{\%\text{ctrl}}} \quad (1)$$

where the subscripts 'treatment' and 'ctrl' refer to process treatment and control sample values, respectively.

2.8. Sensory evaluation

Sensory studies were conducted with seven untrained industrial panelists (three females and four males) with ages ranging from 25 to 55 years. A set of coded samples (CTRL, HPP, PATP-R, PATP-SL, TP, and HPP-TP) from carrot, red radish and jicama was presented to the panelists for comparison. The panelists were asked to rank the sample crunchiness, with 1 being the least crunchy and 7 being the crunchiest.

2.9. Data analysis

Data were analyzed with SAS software, version 9.1.3 (SAS Inst. Inc., Cary, N.C., USA). Least-significant difference (LSD) procedures were used to compare means. Mean differences among treatments were calculated with Fisher's least-significant difference method, with significance at the 5% level ($P < 0.05$).

3. Results and discussions

In this study, our primary interest was to evaluate textural quality attributes of selected products exposed to similar temperature histories with and without pressure. It was not our intent to evaluate whether or not treated products reached commercial sterile conditions. Thermal history (TP, PATP-SL) under the current study would not, by itself, render foods shelf-stable though it would be expected to do so when combined with high-pressure treatment at 600 MPa (PATP-R) and this is the topic of on-going research at various laboratories.

3.1. Sample temperature history

Fig. 2 presents the thermal history of the PATP-R, PATP-SL, and TP samples. The initial temperature of TP samples was approximately 25 °C and subsequently reached the target 105 °C in the retort. PATP-R and PATP-SL samples were preheated (PHT) at 85 °C before pressurization. This enabled the product to reach the target process temperature at the target pressure due to compression.

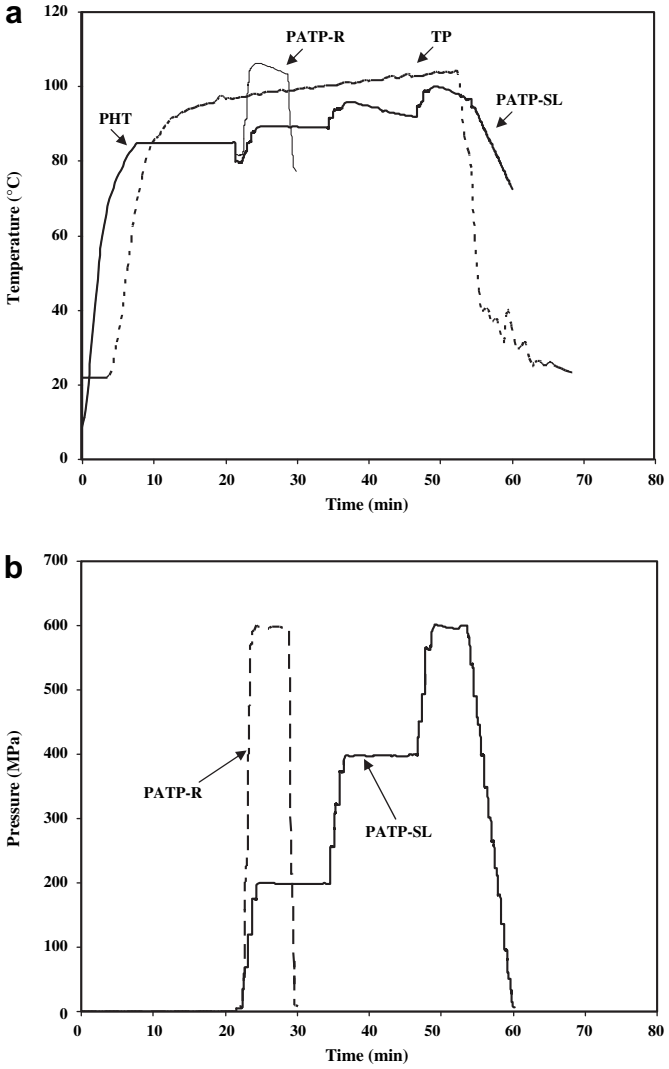

Fig. 2. The temperature (a) and pressure (b) history of pressure-assisted thermal processing (PATP-R: 600 MPa, 105 °C, 5 min; PATP-SL: 600 MPa, 105 °C, 5 min) samples. R and SL designate different compression time of PATP treatments. Additionally, thermal histories of the samples collected during thermal processing (TP: 105 °C, 5 min) and preheating before PATP (PHT; 85 °C, 23 min) are also provided in (a).

The maximum temperature of the pressure-pasteurized samples (HPP) was approximately 25 °C. Among the sterilization treatments (TP, HPP-TP, PATP-R, PATP-SL), PATP-R samples had the lowest accumulated thermal dosage (2461 °C min) while TP and TP-HPP samples had the highest accumulated thermal dosage (5263 °C min). Due to equipment limitations, accumulated thermal dosage of PATP-SL (5160 °C min) sample was slightly lower than that of TP.

PATP-SL samples attained lower process temperatures (98.8 ± 1 °C), possibly due to the heat loss experienced by the samples during the prolonged compression (26.6 min) time used to match process come-up time similar to that of TP. Due to rapid compression and decompression, maintaining process temperature (105 ± 1 °C) was not a hurdle for PATP-R samples. PATP-R samples had 6.7 ± 0.6 °C gradient between the top and bottom of the vessel while the PATP-SL samples demonstrated a 1.6 ± 0.2 °C gradient. The longer compression time (26.6 min) used during PATP-SL might have helped to equilibrate the temperature within the pressure chamber. The current study did not consider the impact of the temperature gradient on the product quality of PATP-R or PATP-SL samples.

3.2. Effect of various treatment on physical appearance of the samples

Visual examination of processed products provided some understanding on the severity of various treatments. Milder "nonthermal" pressure treatment (HPP) at ambient temperature did not significantly impact the sample appearance with the exception of zucchini. HPP significantly softened the zucchini and apricot. In the case of red radish, pressure treatment resulted in diffusion of red pigment into the internal tissue. Processes that had a thermal component (PATP, HPP-TP and TP) degraded quality attributes of the sample. Both TP and PATP disintegrated apricot

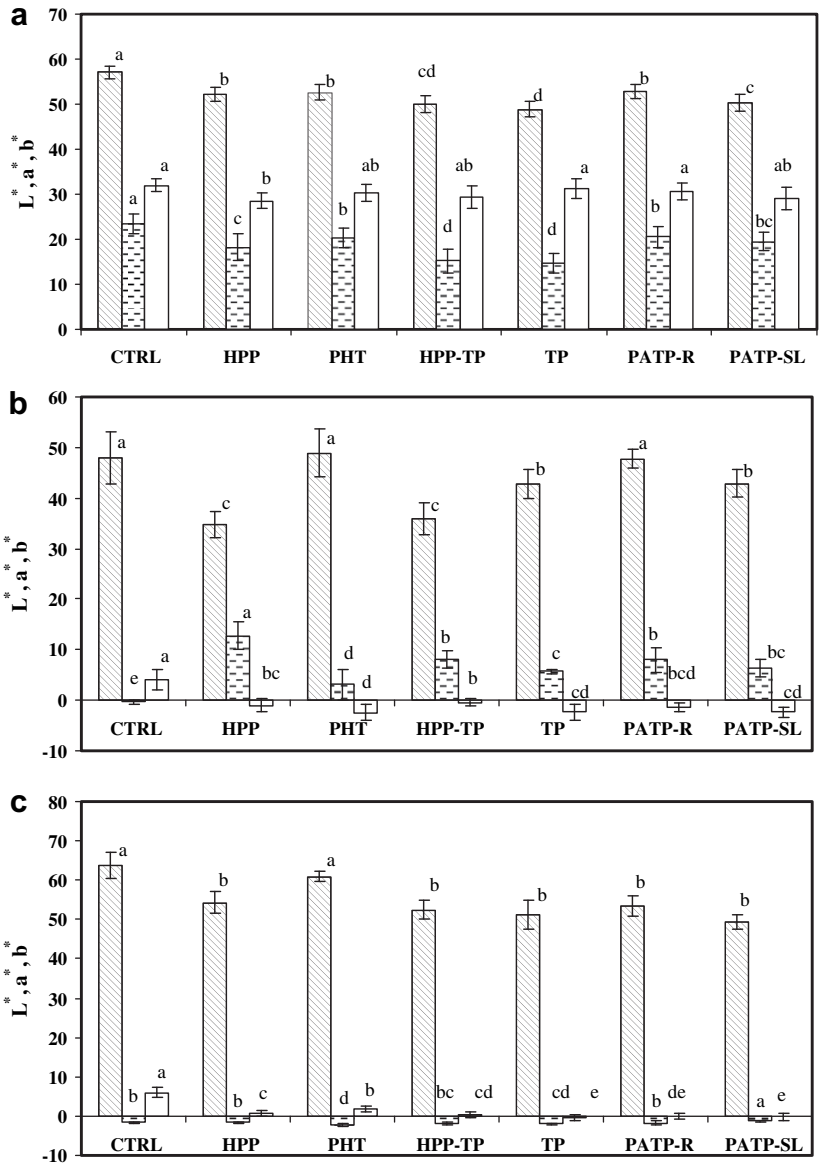

Fig. 3. Color of (a) carrot; (b) red radish and (c) jicama tissues under different processing conditions: CTRL (raw sample); HPP (600 MPa, 25 °C, 5 min); PHT (85 °C, 23 min); HPP-TP (HPP: 600 MPa, 25 °C, 5 min, followed by TP: 105 °C, 5 min); TP (105 °C, 5 min); PATP-R (600 MPa, 105 °C, 5 min); PATP-SL (600 MPa, 105 °C, 5 min). R and SL designate different compression time of PATP treatments. Data were estimated from six replicates. Within the same color parameter, values with different letter are significantly different ($P < 0.05$). ▧ L^*; ▨ a^*; □ b^*.

tissue and samples lost shape. Similarly, zucchini samples were significantly softened and quality degradation was visibly noticed. Consequently, no additional instrumental or sensory quality data for the apricot or zucchini samples were collected. Possibly due to the prolonged soaking time (>36 h) needed for enzyme inactivation in the SDS soaked carrot samples, these samples were significantly softened in comparison to the control. Subsequent TP or PATP treatments further disintegrated the cellular texture of SDS soaked samples. It was decided not to conduct further instrumental or sensory analysis on these SDS soaked samples.

3.3. Impact of process treatment on sample color

The influence of different treatments on the tissue color of carrot, red radish and jicama is given in Fig. 3. For carrot, all treatments resulted in reduced L^* values as compared to control samples (Fig. 3a). The a^* value of TP and HPP-TP carrots were lower than that of PATP samples. Examination of b values of carrot samples (Fig. 3a) under these conditions indicated that the treatments except HPP did not significantly ($P > 0.05$) influence b^* values. Pressure treatment at low and moderate temperatures had limited effect on color pigments such as chlorophyll, carotenoids, and anthocyanin (Oey et al., 2008). Other researchers (Chen, Peng, & Chen, 1995; Kim, Park, Cho, & Park, 2001; Nguyen, Rastogi, & Balasubramaniam, 2007) also reported that carrot carotene was more stable under pressure treatment than under TP.

For the red radish samples, the skin and tissue had different response to different processing conditions. In comparison to untreated samples, various treatments (HPP, PATP-R, PATP-SL, HPP-TP, and TP) increased L^* value, decreased a^* and b^* values of the radish skin (data not shown). The processing impact on red radish tissue color is shown in Fig. 3b. Samples subjected to pressure treatment (HPP) and pressure treatment followed by thermal processing (HPP-TP) had lower L^* value of the tissue than control and other treatments. In addition, for pressure treated (HPP, HPP-TP, PATP-R, PATP-SL) and TP samples, a^* value of the tissue color increased significantly ($P < 0.05$), most probably due to diffusion of red color pigment following the disruption of the cellular structure (Fig. 3b).

Among the products tested, jicama color was least influenced by the treatments (Fig. 3c). Except preheat samples, pressure or heat treatments (HPP, HPP-TP, TP, PATP-R, PATP-SL) slightly decreased L^*, b^* values as compared to control samples but there was no significant difference among these treatments ($P > 0.05$).

3.4. Influence of different process conditions on textural quality

Fig. 4 presents the typical force-deformation curve of the carrot, red radish and jicama samples after the different treatments. As the puncture probe penetrated into the untreated samples, a steep initial slope (i.e., stiffness) was observed. The puncture force reached a maximum value and then decreased to a lower value after tissue rupture. PATP, TP and, HPP treated carrot samples also showed similar force-deformation curves, but the magnitude of the slope and maximum rupture force differed from the control due to texture transformation. In addition, after the yield point (tissue fracture), different treatment-sample combinations resulted in different characteristic peaks. This may be due to the resistance of different vegetable cell layers (Gonzalez, 2009).

The texture parameters (F, $Grad_{20\%}$) extracted from the puncture tests are given in Fig. 5. Depending on the processing methods, the texture of the vegetable samples are affected in different ways. The TP samples, as expected, had the most textural degradation: the maximum puncture force of the carrot, red radish and jicama samples were 0.5, 1.3, and 4.3 N, respectively (Fig. 5a). The

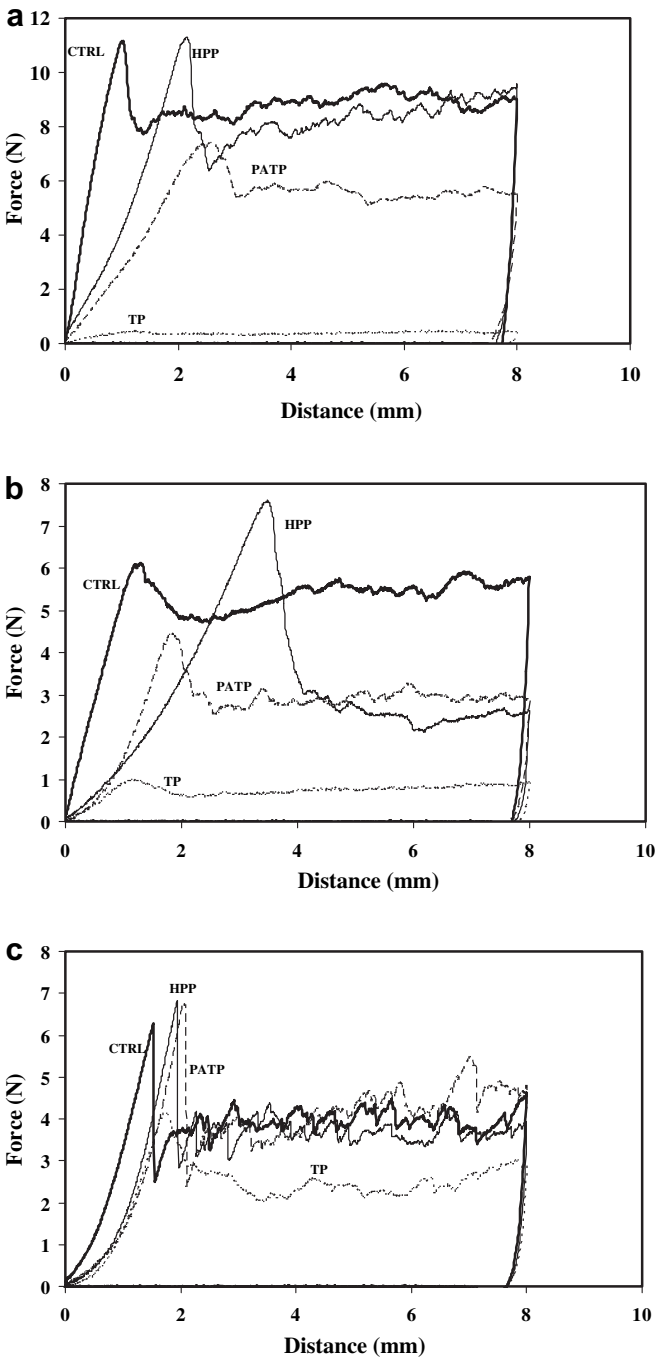

Fig. 4. Sample force-deformation curves for (a) carrot, (b) red radish and (c) jicama samples treated by various process conditions: CTRL (raw sample); HPP (600 MPa, 25 °C, 5 min); TP (105 °C, 5 min); PATP (600 MPa, 105 °C, 5 min).

mechanical strength of vegetable cells is provided by the cell wall and the turgor pressure within the cell. Thermal treatments soften the tissue by decreasing turgor pressure (Greve et al., 1994), and by solubilizing cell wall pectic substances, which separate the vegetable cells (Van Buren, 1979).

Pressure treatment at room temperature (HPP) increased the puncture force value of the red radish samples, while decreasing it slightly for the carrot samples (Fig. 5a). Basak and Ramaswamy (1998) suggested that the most probable reason for textural improvement under high-pressure processing is due to

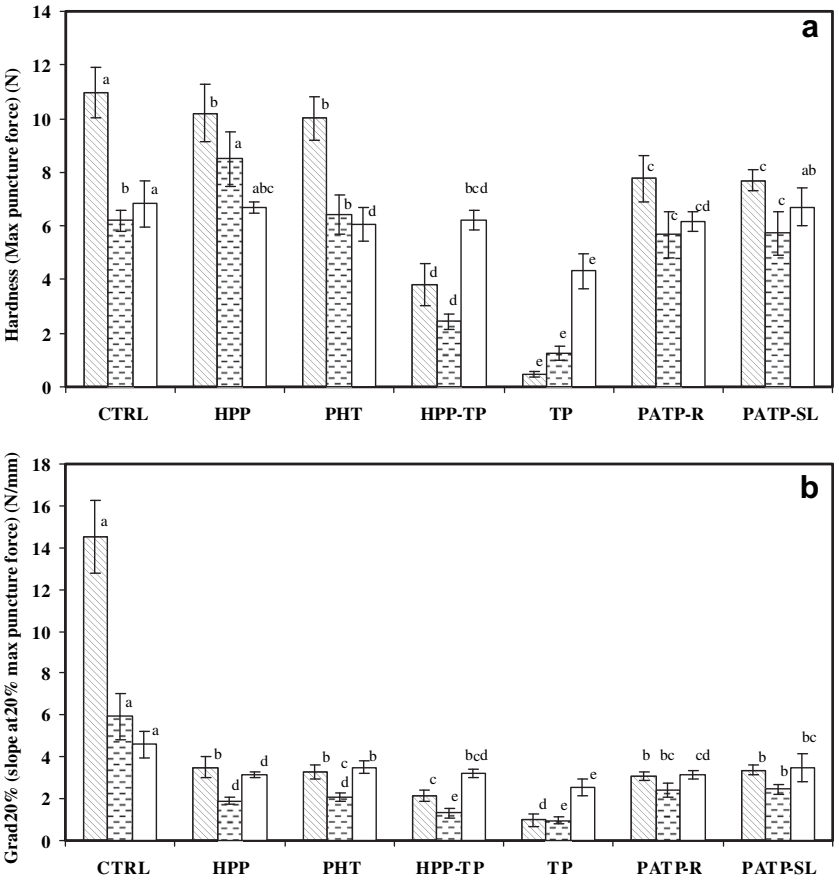

Fig. 5. Effects of different processing conditions on the texture of carrot, red radish and jicama measured by puncture test (a) max puncture force; and (b) slope of force-deformation curve at 20% max puncture force. CTRL (raw sample); HPP (600 MPa, 25 °C, 5 min); PHT (85 °C, 23 min); HPP-TP (HPP: 600 MPa, 25 °C, 5 min, followed by TP: 105 °C, 5 min); TP (105 °C, 5 min); PATP-R (600 MPa, 105 °C, 5 min); PATP-SL (600 MPa, 105 °C, 5 min). R and SL designate different compression time of PATP treatments. Data were estimated from 10 replicates. Within the same sample, values with different letter are significantly different ($P < 0.05$). ▧ carrot; ▩ red radish; □ jicama.

pectinmethylesterase (PME) activity and increased compactness of the cellular structure as a result of the elimination of air from the tissue.

Preheating at 85 °C decreased the puncture force of carrot and jicama ($P < 0.05$). PATP red radish and carrot samples had lower puncture values than those of the control and preheated samples, but had higher values than those of the TP and HPP-TP samples. For these PATP samples (carrot, red radish), there was no significant difference ($P > 0.05$) in hardness due to either the regular (PATP-R) or slow (PATP-SL) compression time. Roeck et al. (2008) suggested that the textural preservation of carrot samples processed at high pressure and high temperature may be due to the inhibition of the β-elimination reaction, i.e., split of glycosidic bonds of pectin at high temperature catalyzed by hydroxyl ion (Van Buren, 1979), either by high pressure/high temperature or by the lower degree of esterification of the pectin substance. In addition, the lowly-methylated pectin might form networks by binding with Ca^{++}, hence contributing to textural preservation. Araya et al. (2007) reported the degradation of pectin in cooked samples but not in pressurized samples. Studies of the microstructure of carrot samples showed that while tissue failure of the raw sample was mainly due to cell breakage, and failure of the thermally treated sample due to cell separation, PATP samples exhibited both mechanisms (Roeck et al., 2008).

Jicama samples seemed to have a sturdier texture than that of carrot and red radish samples and jicama samples were minimally impacted by various treatments. The PATP-SL treatments did not further decrease puncture force values as compared to control sample. The HPP, HPP-TP and PATP-R samples had the same hardness. The jicama samples were also more resistant to TP (Figs. 4c and 5). In comparison to the carrot samples, the stiffness of jicama and red radish samples was less influenced by the various treatments, most likely due to their sturdier cellular structure. On the other hand, a considerable loss of stiffness was observed with all the processed or preheated carrot samples. The HPP carrot samples became more rubbery (i.e., reduced $Grad_{20\%}$) but retained hardness (Fig. 5). Finally, it is interesting to note that pressure pretreatment followed by thermal processing (HPP-TP) better preserved the hardness of all the processed vegetables in comparison to the TP samples. High-pressure pretreatment prior to thermal processing has been found to improve the texture of cooked vegetables (Kasai et al., 1995; Rastogi, Nguyen, & Balasubramaniam, 2008; Sila, Smout, Truong, & Hendrickx, 2004; Sila et al., 2007).

3.5. Crunchiness index

Puncture test results (Fig. 5) do not provide comprehensive data for comparing the impact of various processes on product texture. Therefore, efforts were made to identify additional instrumental textural parameters that can be used for this purpose. Earlier studies on high-pressure processed foods used a variety of textural parameters to describe pressure-thermal effects with mixed results. Basak and Ramaswamy (1998) used the slope of a linear section of the compression curve to describe hardness. Roeck et al.

Table 1
Comparison of different textural tests for high-pressure processed (HPP) carrot samples.

Textural measurement	Control (fresh sample)	HPP (600 MPa, 25 °C, 0 min)	HPP (600 MPa, 25 °C, 5 min)
Uniaxial compression test			
Compressive force (*N*)			
At 30% strain	182.5 ± 14.8^{a}	123.4 ± 8.9^{b}	128.2 ± 11.9^{b}
At 50% strain	191.0 ± 8.6^{b}	216.8 ± 13.6^{a}	175.9 ± 17.6^{c}
At 75% strain	211.1 ± 6.4^{b}	221.8 ± 15.6^{a}	179.6 ± 5.8^{c}
WB shear test			
Max shear force (*N*)	102.4 ± 6.3^{c}	104.2 ± 10.8^{b}	108.2 ± 6.7^{a}

Data with same letters in the row do not differ significantly from each other, whereas data with different superscripts differ significantly at the probability level $P < 0.05$. Data were estimated from 10 replicates. Time (0 and 5 min) refers to duration under pressure.

(2008) reported hardness as the force required to compress the sample to 70% thickness. Araya et al. (2007) used compression force to 30% strain and cutting force to 75% strain to compare the texture of high-pressure treated samples. Sila, Smout, Elliot, Van Loey, and Hendrickx (2006) also described hardness as compression force to 30% strain. When the compressive force at 30% strain was used, Araya et al. (2007) reported an initial textural loss after high-pressure treatment at ambient temperature as compared to the control sample. These findings were similar to those obtained by Basak and Ramaswamy (1998), who used the slope of the linear section of the force-deformation curve. However, the cutting force of the HPP sample was higher than the control sample (Araya et al., 2007). The compression, shear or puncture forces are dependent on the strain level and the shape of the force-deformation curves. Therefore, parameters obtained at different strain levels may give opposite conclusions. Furthermore, many studies have found that the pressure treated samples are transformed into a "rubbery" state (Araya et al., 2007).

Thus, the suggested texture represented by compression/puncture or shear force alone may not be a complete indication, especially since the textural transformations were observed in corresponding changes in both stiffness (slope of the linear section of the force-deformation curve) and hardness (force required to deform sample) of the samples, but these two parameters do not always follow the same trend. Table 1 presents the textural parameters of carrots obtained from compression and shear tests. The compressive forces at different strain levels lead to different conclusions about the "hardness" of the HPP samples. At 30% strain, the compressive force showed a decrease, but at 50% and 75% strain, the compressive force increased at 0 min holding time and decreased at 5 min holding time. For the WB shear test, the max shear force did not have the same drastic difference between the control and HPP samples at 0 and 5 min holding time. The length of the force-deformation curve can be used to estimate the extent of jaggedness or rupture intensity during the test (Norton, Mitchell, & Blanshard, 1998). However, the calculated lengths for various treatments did not provide any meaningful comparison (Table 2). These parameters either represented only a part of the textural transformation after high-pressure processing (rupture force, slope) or were unable to give a strong discriminative index (length of the force-deformation curve).

Table 2
Comparison of crunchiness index values against sensory crunchiness ranking as influenced by various pressure-thermal treatment.

Crunchiness index							
	% Of max puncture force	Control	HPP	PATP-R	PATP-SL	HPP-TP	TP
Carrot							
	10%	2.00^{a} (± 0.22)	1.20^{b} (±0.19)	0.94^{c} (±0.10)	1.03^{c} (±0.10)	0.60^{d} (±0.16)	0.12^{e} (±0.06)
	20%	2.00^{a} (± 0.22)	1.17^{b} (±0.19)	0.92^{c} (±0.10)	0.93^{c} (±0.10)	0.49^{d} (±0.16)	0.11^{e} (±0.06)
	30%	2.00^{a} (± 0.23)	1.22^{b} (±0.17)	0.96^{c} (±0.10)	1.04^{c} (±0.11)	0.64^{d} (±0.18)	0.11^{e} (±0.05)
	40%	2.00^{a} (± 0.19)	1.27^{b} (±0.18)	0.99^{c} (±0.11)	1.08^{c} (±0.12)	0.67^{d} (±0.16)	0.10^{e} (±0.03)
	50%	2.00^{a} (± 0.18)	1.33^{b} (±0.14)	1.04^{c} (±0.13)	1.13^{c} (±0.13)	0.70^{d} (±0.14)	0.23^{e} (±0.03)
	60%	2.00^{a} (± 0.18)	1.42^{b} (±0.21)	1.11^{c} (±0.14)	1.21^{c} (±0.13)	0.74^{d} (±0.15)	0.09^{e} (±0.03)
	70%	2.00^{a} (± 0.17)	1.55^{b} (±0.18)	1.21^{c} (±0.14)	1.32^{c} (±0.16)	0.80^{d} (±0.13)	0.17^{e} (±0.03)
	Length of *F–D* curve	39.41 (± 4.15)	37.28 (±3.49)	31.69 (±1.78)	32.10 (±2.72)	26.99 (±1.82)	24.32 (±0.52)
Perceived crunchiness by the sensory panelists[a]		Control	>HPP	>PATP-R	~PATP-SL	>HPP-TP	>TP
Red Radish							
	10%	2.00^{a} (± 0.24)	1.64^{b} (±0.23)	1.25^{c} (±0.28)	1.36^{c} (±0.26)	0.61^{d} (±0.14)	0.37^{e} (±0.11)
	20%	2.00^{a} (± 0.23)	1.69^{b} (±0.29)	1.33^{c} (±0.30)	1.34^{c} (±0.28)	0.61^{d} (±0.13)	0.36^{e} (±0.11)
	30%	2.00^{a} (± 0.19)	1.98^{a} (±0.22)	1.48^{b} (±0.32)	1.61^{b} (±0.29)	0.65^{c} (±0.14)	0.41^{d} (±0.11)
	40%	2.00^{a} (± 0.22)	2.05^{a} (±0.27)	1.58^{b} (±0.33)	1.72^{b} (±0.30)	0.67^{c} (±0.14)	0.42^{d} (±0.12)
	50%	2.00^{a} (± 0.22)	2.13^{a} (±0.24)	1.68^{c} (±0.35)	1.82^{b} (±0.31)	0.69^{d} (±0.15)	0.43^{e} (±0.12)
	60%	2.00^{b} (± 0.21)	2.20^{a} (±0.23)	1.79^{c} (±0.36)	1.93^{b} (±0.33)	0.71^{d} (±0.15)	0.44^{e} (±0.12)
	70%	2.00^{b} (± 0.22)	2.28^{a} (± 0.23)	1.90^{b} (±0.38)	2.04^{b} (±0.35)	0.72^{c} (±0.16)	0.45^{d} (±0.12)
	Length of *F–D* curve	29.51 (± 1.83)	31.74 (±2.64)	30.46 (±2.79)	31.02 (±1.51)	24.85 (±0.78)	24.35 (±0.50)
Perceived crunchiness by the sensory panelists[a]		Control	> HPP	>PATP-R	~PATP-SL	>HPP-TP	>TP
Jicama							
	10%	2.00^{a} (± 0.17)	1.49^{b} (±0.16)	1.48^{b} (±0.17)	1.57^{b} (±0.24)	1.44^{b} (±0.19)	1.00^{c} (±0.24)
	20%	2.00^{a} (± 0.28)	1.66^{b} (±0.16)	1.59^{b} (±0.16)	1.74^{b} (±0.23)	1.61^{b} (±0.19)	1.18^{c} (±0.26)
	30%	2.00^{a} (± 0.19)	1.65^{b} (±0.16)	1.70^{b} (±0.17)	1.75^{b} (±0.22)	1.58^{b} (±0.19)	1.10^{c} (±0.26)
	40%	2.00^{a} (± 0.25)	1.70^{b} (±0.17)	1.78^{b} (±0.17)	1.81^{b} (±0.22)	1.63^{b} (±0.19)	1.13^{c} (±0.26)
	50%	2.00^{a} (± 0.22)	1.76^{b} (±0.17)	1.85^{b} (±0.18)	1.87^{b} (±0.22)	1.68^{b} (±0.20)	1.15^{c} (±0.25)
	60%	2.00^{a} (± 0.21)	1.82^{a} (±0.17)	1.93^{a} (±0.18)	1.94^{a} (±0.22)	1.73^{a} (±0.22)	1.17^{b} (±0.26)
	70%	2.00^{a} (± 0.18)	1.88^{a} (±0.18)	2.01^{a} (±0.19)	2.00^{a} (±0.23)	1.79^{a} (±0.29)	1.20^{b} (±0.26)
	Length of *F–D* curve	50.59 (±7.15)	42.47 (±2.93)	46.33 (±3.928)	47.08 (±3.57)	39.58 (±3.26)	29.41 (±3.61)
Perceived crunchiness by the sensory panelists[a]		Control	> HPP	~PATP-R	~PATP-SL	~HPP-TP	>TP

Data with same letters in the row do not differ significantly from each other, whereas data with different superscripts differ significantly at the probability level $P < 0.05$. Data were estimated from 10 replicates.

[a] The notation "X > Y" indicated that sample processed by treatment "X" has a greater crunchiness (as perceived by the panelists) than the sample processed by the treatment Y. Similarly, "X ~ Y" indicated both treatments X and Y resulted in samples with very similar crunchiness (as perceived by panelists).

The F_{max} and Grad obtained from the puncture tests partly indicated changes in the texture of processed samples. The combination of both parameters into a unified parameter (denoted as crunchiness index or CI) gave a better overall indication of the textural transformation during HPP and PATP (Table 2). During the puncture test, depending on the extent of the texture change, the slope of the force-deformation curve may experience an initial low slope due to the elastic compaction followed by a deflection when the slope increased up to the rupture point. The difference in slope may yield the various values of the crunchiness index. Therefore, the slope at different percentages of max puncture force was investigated to determine the range in which the crunchiness index most closely matched the sensory data. For the carrot samples, a crunchiness index based on the slope of the force-deformation curve up to 70% of the max puncture force was able to discriminate among processed sample textural qualities in the same manner as the sensory test (Table 2). However, for the red radish samples, a crunchiness index calculated beyond 20% of the max puncture force was not able to provide meaningful information with respect to the texture transformation when compared against sensory data. In addition, at a low strain level, the change in force/deformation slope may also be due to other factors such as sample misalignment, in which the sample slides before the probe really penetrates the samples. As a result, a slope at 20% of max puncture force was used to express the crunchiness index.

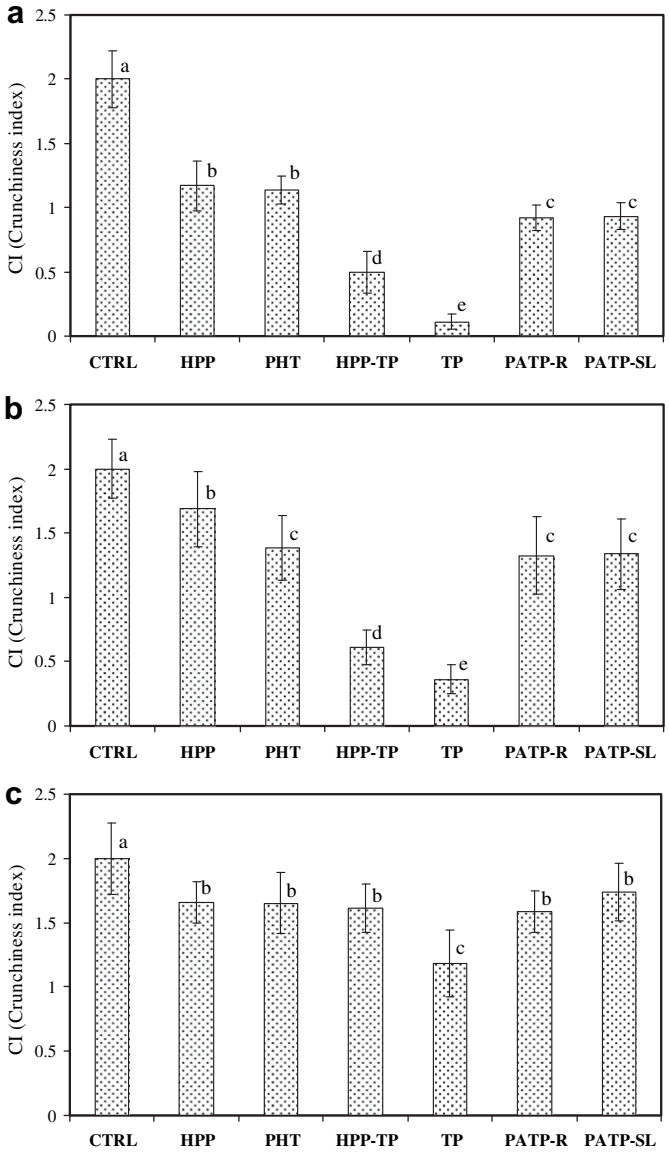

Fig. 6. Crunchiness index for (a) carrot; (b) red radish and (c) jicama samples processed by pressure treatment (HPP: 600 MPa, 20 °C, 5 min), preheat (PHT: 85 °C, 23 min), thermal process (TP: 105 °C, 5 min), and pressure-assisted thermal process (PATP-R: 600 MPa, 105 °C, 5 min; PATP-SL: 600 MPa, 105 °C, 5 min). R and SL designate different compression time of PATP treatments. Data were estimated from 10 replicates. Values with different letter are significantly different ($P < 0.05$).

Fig. 6 presents the crunchiness index of control, HPP, PATP, TP samples and their combined treatments. Unprocessed control samples had a maximum crunchiness index of 2. Possibly due to exposure to harsher thermal treatment for a prolonged time, TP carrot, red radish and jicama samples had the smallest crunchiness index values of 0.11, 0.36 and 1.18, respectively (Fig. 6). Both PATP treatments had significantly higher crunchiness (0.92–1.74) values compared to TP for all the samples ($P < 0.05$). Pressure pretreatment followed by TP samples also had improved crunchiness values (0.49–1.61) compared to TP samples, but generally lower than PATP samples (Fig. 6).

4. Conclusion

Pressure treatments better retained sample color than thermal treatments and it was product dependent. Among the treatments (TP, PATP, HPP, HPP-TP), HPP best preserved textural quality attributes of carrots, red radish and jicama. Both PATP-SL and PATP-R better preserved product quality than the TP samples. The beneficial effects may come from the densification of the tissue due to pressurization or biochemical changes of the pectic substances. Pressure treatment followed by thermal processing (HPP-TP) can improve textural quality of thermally processed samples. Among the products tested, jicama was least susceptible to textural damage. The crunchiness index can be used as an effective tool for comparing the instrumental textural quality of samples subjected to various process treatments.

Acknowledgments

Support for this research was provided, in part, through a Kraft Foods enhancement grant from the Center for Advance Processing and Packaging Studies (CAPPS), and USDA-CSREES-NRICGP grant 2005-35503-15365, by the Ohio Agricultural Research and Development Center (OARDC), and by The Ohio State University. Authors also thank Prof. Diane Barrett, University of California Davis for helpful comments. References to commercial products or trade names are made with the understanding that no endorsement or discrimination by The Ohio State University is implied.

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