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# Relationships Between Texture and Rheological Properties in Blanched Apple Slices (var. Granny Smith) Studied by Partial Least Squares Regression

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**Abstract** The effect of steam blanching (90 or 150 s) on linear viscoelastic and compression properties, sensory texture, and micro- and ultrastructure of cut apple was analyzed. All apple samples showed a solid behavior (storage modulus $G'$ > loss modulus $G''$) dominating the viscoelastic response, but both dynamic modules were reduced due to processing. For blanched tissues, the instantaneous elastic compliance $J_0$ and the retarded compliances $J_1$ and $J_2$ increased and the steady-state viscosity decreased. Values of mechanical parameters and texture attributes (except cohesiveness) decreased for blanched tissues. Partial least squares regression analysis (PLS) technique was used to study how texture characteristics (dependent variables) were related to rheological properties (independent variables) of untreated and blanched apples. Sensory hardness and crispness were negatively related to $J_0$, $J_1$, and $J_2$ and positively correlated to $G'$ at intermediate and high frequencies ($\omega$) and $G''$ at low frequencies. Sensory fracturability was positively correlated with $G'$ at $\omega=0.1$ 1/s and $G''$ at $\omega=100$ 1/s. Juiciness and sensory fracturability were positively correlated to instrumental hardness and area 1, and crispness and sensory hardness were positively related to instrumental fracturability. Structure differences (rupture of membranes, decrease in cell-to-cell contact, degradation of
cell walls, changes in microfibril arrangements) could explain some changes observed in rheological properties and texture of blanched apples.

## Introduction

Blanching is usually applied before freezing, dehydration, and sterilization to decrease enzyme activity in fruits. In minimal fruit processing technologies, blanching is applied not only to inactivate enzymes, but also to destroy or injure microorganisms. According to blanching severity (temperature and time of application) and type of fruit, reductions in the initial microbial load (molds, yeasts, and aerobic mesophilic) from 60 to 99 % had been reported (Alzamora et al. 1995).

Blanching provokes changes in the macro-, micro-, and ultrastructure of fruit tissues, which strongly influence rheological behavior and, accordingly, perceived texture. At the cellular level, the three main structural elements that contribute to the mechanical behavior of fruits and vegetables are as follows: turgor pressure (force exerted on the cell wall by the intracellular fluid), cell wall rigidity, and cell–cell adhesion, determined by the integrity of the middle lamella and the plasmodesmata and some components located at the edges of cell faces (Jackman and Stanley 1995; Waldron et al. 1997; Alzamora et al. 2000). Turgor pressure leads to rigidity of the cells and tissues and, together with the cell wall, provides mechanical support to maintain the shape of cells and tissues (Alzamora et al. 2000). In addition, the relative percentage of the different tissues, size, and shape of the cells, ratio of

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cytoplasm to vacuoles, volume of intercellular spaces (which may contain either fluids or interstitial air), type of present solutes, and presence of starch and its state are also important (Ilker and Szczesniak 1990; Alzamora et al. 2008).

In general, the main reported structure changes induced by blanching are as follows: (a) breakage of plasmalemma, which results in a loss of turgor, free diffusion of water, and low molecular weight moieties and a tender and rubbery texture (Thiel and Donald 2000; Lillfort 2001; Alzamora et al. 2008; Waldron et al. 2003); (b) increase in the ease of cell separation, generally attributed to the β-eliminative degradation of pectic polysaccharides (BeMiller and Kumari 1972); (c) loss of fibrillar organization in the walls; and (d) changes in air and liquid volume fractions and in sample size and shape (Alzamora et al. 1997; Chiralt et al. 2001).

Texture has been defined as "the sensory manifestation of the structure of food and the way in which that structure reacts to the applied forces; the specific senses involved being vision, kinaesthesia, and hearing" (Szczesniak 1990). It has also been described as a multiparameter attribute, as evidenced by the large number of terms used to describe it. The classification of texture attributes into categories introduced by Szczesniak et al. (1963) gave rise to a profiling method of texture description, the texture profile analysis (TPA), applicable to both sensory and instrumental measurements.

Rheology measurements have been extensively applied to fruits and vegetables in an effort to understand the relationships between structure, texture, and rheological changes induced by processing (Jack et al. 1995; Martínez et al. 2007). The material parameters of biological tissues at the macroscopic scale are obtained based on macroscopic continuum physics, but these should be considered as apparent material parameters that, in addition to actual physical materials constants of tissue compounds, incorporate also microscopic features (Mebatsion et al. 2008). Because of the complex connections and multivariate interdependencies of structural elements, the material properties of fruit tissues, including mechanical ones, are difficult to predict and explain (Kunzek et al. 1999). Understanding the relationship between food texture perception and food structure is also of increasing importance for companies wishing to produce texturally attractive food products (Wilkinson et al. 2000).

Because of the need to better understand the relationship between structure, rheology, and texture, the specific aims of this study were as follows: (a) to analyze the rheological behavior at small and large deformations (by small-scale dynamic oscillatory shear and creep/recovery tests and large-scale uniaxial compression tests), the texture characteristics (by a trained sensory panel), and the structure (by optical and transmission electronic microscopy observations) of apple tissues blanched in vapor during 90 or 150 s; (b) to examine the correlation between rheological properties and texture attributes using partial minimal squares regression; and (c) to explore how changes in blanched tissue structure were expressed by rheological and sensory parameters.

## Materials and Methods

### Preparation of Samples

Fresh apples (*Malus pumila*, Granny Smith var.; $a_w \approx 0.98$; 10.4–12.2 °Bx and pH 3.3–3.4) were obtained from a local market and stored in refrigeration (4.0±1.5 °C) 12 h until use. Previously, apples had been stored in controlled atmosphere at 4 °C. Before processing, apples were removed from the refrigerator, washed in water and left to reach room temperature (20±1 °C). Then, they were hand-peeled and cut parallel to the main axis using a lathe to obtain parenchyma slabs (0.060 m×0.060 m×0.010 m for control samples and 0.060 m×0.060 m×0.011 m for samples to be treated). Only slices with the required thickness ±0.005 m were used. Ten measurements of the thickness were made at different points with a micrometer (±0.0001 m, Teclock, model SM-124, Japan). Soluble solids were determined with a digital refraction meter model PR-1 (Atago, Tokyo, Japan) and expressed as °Bx at 20 °C. The pH was measured with a digital potentiometer model PerpHecT 310 (ORION, England). Measurements were performed by triplicate.

The same lot of fruit was used in all the experiments in order to minimize the inherent variation due to age and/or cellular structure of the biological tissue and the influence of agronomic practices and time of harvest in the field.

### Blanching Treatment

Blanching was carried out by immersion of fruit slabs in saturated steam for 90 and 150 s. Samples were immediately immersed in distilled water at 4 °C for 20 s and put on blotting paper three times to eliminate surface water (final thickness~0.010 m). Then, a cork borer was used to obtain apple cylinders (0.03 m in diameter).

Apple slices blanched during 90 s (B90) and 150 s (B150) were then examined for rheological properties, texture characteristics, and structure. All treatments were compared to a control (C, fresh apple). Fresh and treated slices were stored at room temperature (20±1 °C) until use for the different analyses.

### Temperature Measurement

The temperature profile in the center of the apple cylinder during blanching was monitored using a T type thermocouple connected with a data logger (Digi-Sense model 69202-30, Barnant Company Division, USA). Measurements were made in triplicate.

## Microscopic Observations

For light microscopy (LM), cubes of fresh and treated apples ($\cong 1$ mm$^3$) were fixed in glutaraldehyde solution (3 g/100 g) and then in 0.1 M potassium phosphate buffer (pH=7.4) overnight at room temperature (20±1 °C). Cubes were then rinsed three times with distilled water, postfixed in OsO$_4$ solution (1.5 g/100 g) at room temperature (20±1 °C), and dehydrated in a graded acetone series prior to be embedded in low viscosity Spurr resin. Sections (1–2 μm thick) of the Spurr-embedded tissue were cut on a Sorvall MT2-B Ultracut microtome and stained with toluidine blue (1 g/100 g) and basic fuchsin (1 g/100 g) solutions (D'Ambrogio de Argüeso 1986). Samples were then examined in a Zeiss Axioskop 2 microscope (Carl Zeiss AG, Jena, Germany) at 20±1 °C. All reagents were from Merck Química Argentina S.A. (Argentina).

For transmission electronic microscopy (TEM) observations, samples immersed in Spurr resin were cut in ultrathin sections (1 μm thick) using a glass knife with a Sorvall MT2-B ultracut microtome, collected on copper grids and double-stained with uranyl acetate and Reynolds lead citrate (Reynolds 1963). Sections were examined using a JEOL JEM-1200 EX II (Japan) transmission electron microscope at an accelerating voltage of 80 kV at room temperature (20±1 °C).

## Sensory Descriptive Analysis

Sensory panel was composed of nine panelists (three males, six females), all between ages of 21 and 38. For their selection, 20 people were recruited from staff of Buenos Aires University based on their interest, availability, previous experience in sensory evaluation, and familiarity in texture concepts and the related terminology. Prior to the sessions, they signed a consent form. During the prescreening procedure, they were evaluated for normal sensory acuity through a basic taste test, a sequential triangle test (Meilgaard et al. 2006), and an intensity ranking test using the hardness scale (Civille and Szczesniak 1973). The panelists who passed the prescreening tests were further trained in the texture profile method, following the procedures described by Civille and Szczesniak (1973) for 35–40 h (2 h per week) with the purpose of recognizing some texture attributes such as hardness (SH), fracturability (SF), cohesiveness (SC), adhesiveness to palate (SA), crispness, and juiciness. The first sessions of training were devoted to explain some texture definitions (Table 1) and become the panelists acquainted with the sensory texture profile method and some scale references extracted from the standard rating scales published by Chauvin et al. (2008), Hough et al. (1994), and Szczesniak and Ilker (1988) (Table 1). In each session, only one rating scale was explained until the panelists fully understood the texture concepts and properly matched each reference with its correspondent value

in the scale. Round-table discussions were then performed to clarify any possible discrepancy and to reach a general consensus between the panelists. The references were periodically refreshed in order to calibrate and check the sensory panel.

On each session, samples were presented to the panelists in white plastic cups coded with random three-digit numbers. The samples were measured in duplicate, presenting three samples per session. They were randomly allotted to sessions, taking care that a sample and its duplicate were not presented in the same session. Within each session, presentation order was randomized among assessors.

In each evaluation, the samples, two known food references taken from the correspondent standard rating scale (Table 1), and the form were provided to the sensory judges. This form included instructions and the line scale corresponding to the evaluated texture attribute with the positions of the references marked on it. A glass of water and unsalted crackers were used by the panelists for rinsing their mouth and cleaning their teeth between sample evaluations. They used evaluation forms and scored intensities on the line scale (0–17, depending on the texture scale). All sessions were conducted in isolated booths under white light.

## Viscoelastic Properties Analysis

Viscoelastic properties were analyzed at 20 °C in a Paar Physica MCR 300 rheometer (Antor Paar GmbH, Graz, Austria) using 0.03-m diameter parallel plates with a rough surface as a sensor system. Temperature was controlled by an external liquid bath thermostat model Viscotherm VT2 (Anton Paar, Graz, Austria). Dynamic oscillatory tests were performed in the controlled strain mode. Prior to a frequency sweep, a strain sweep was carried out at an angular frequency ($\omega$) of 10 s$^{-1}$ to determine the linear viscoelastic range (LVR). The LVR was determined with the Paar Physica US 200 software package (Anton Paar GmbH, Graz, Austria). Thereafter, storage ($G'$) and loss modules ($G''$) were measured in the frequency range 0.1–100 s$^{-1}$ using a strain amplitude value of 0.01 % (within the limits of linearity previously established). Storage modulus values were fitted using a linear regression of log ($G'$) vs. log ($\omega$):

$$\log (G') = n\log (\omega) + k \tag{1}$$

where $n$ is the slope of the regression and $k$ is $G'$ value at 0.1 s$^{-1}$ of angular frequency.

Creep–recovery tests were conducted by applying a constant shear stress of 35 Pa for 100 s. A previous stress sweep by varying the applied stress from 1 to 100 Pa indicated that in the selected condition, the deformation was proportional to the stress applied. After removal of the stress, sample recovery was registered for a period of time of 200 s. Each apple sample

**Table 1** Sensory scales used to train the panel

| Scale | Product (sample size, temperature) | Scale value | Reference |
|---|---|---|---|
| Hardness: force required to compress a substance between molar teeth (in the case of solids) or between tongue and palate (in the case of semi-solids) | Cream cheese (1 cm$^3$, 5–10 °C) | 1 | Hough et al. (1994) |
| | Egg white (boiled 5 min, 0.75 cm$^3$, room) | 2.5 | |
| | Franckfurter (1 cm slice, room) | 5 | |
| | Olive (1 piece, room)[a] | 6 | |
| | Processed cheese (1 cm$^3$, 5–10 °C) | 7 | |
| | Peanut (1 piece, room)[a] | 9.5 | |
| | Chocolate (1 piece, 10–15 °C) | 11 | |
| | Hard candy (1 piece, room) | 17 | |
| Fracturability: force with which a sample crumbles cracks or shatters | Cake (1 cm$^3$, room) | 1 | Hough et al. (1994) |
| | Biscuit layer (1 cm$^2$, room)[a] | 2.5 | |
| | Cracker (1 cm$^2$, room) | 5 | |
| | Sweet toast biscuit (1 cm$^2$, room) | 7 | |
| | Biscuit (1 cm$^2$, room)[a] | 8 | |
| | Thin bread wafer (1 cm$^2$, room) | 10 | |
| | Peppermint drop (1 piece, room) | 12 | |
| | Hard candy (1 piece, room) | 14.5 | |
| Cohesiveness: degree to which a substance is compressed between the teeth before it breaks | Cake (1 cm$^3$, room)[a] | 1 | Hough et al. (1994) |
| | Fruit candy (1 cm$^3$, room) | 3 | |
| | Processed cheese (1 cm$^3$, 5–10 °C)[a] | 5 | |
| | Fruit chew (1 cm$^3$, room) | 8 | |
| | Dried fruit (1 piece, room) | 10 | |
| | Fruit chew 2 (1/2 piece, room) | 12 | |
| | Chewing gum (1 piece, room) | 15 | |
| Adhesiveness to palate: force required to remove the material that adheres to the palate during the normal eating process | Margarine (1 cm$^3$, 5–10 °C)[a] | 1 | Hough et al. (1994) |
| | Peach jam (1/2 teaspoon, room) | 3 | |
| | Caramel jam (1/2 teaspoon, room)[a] | 6 | |
| | Spreading cheese (1 cm$^3$, 5–10 °C) | 8 | |
| | Peanut butter (1/2 teaspoon, room) | 12 | |
| Crispness: the level of sound produced when the sample is bitten between the incisor teeth keeping the lips open | Banana (1 cm slice, room) | 0 | Chauvin et al. (2008) |
| | Apple Gala (1 cm$^3$, room)[a] | 4 | |
| | Apple Granny Smith (1 cm$^3$, room)[a] | 7.5 | |
| | Potato (1 cm$^3$, room) | 10 | |
| | Carrot (1 cm$^3$, room) | 15 | |
| Juiciness: the amount of juice released during the first three bites | Banana (1 cm slice, room) | 0 | Szczesniak and Ilker (1988) |
| | Carrot (1 cm$^3$, room) | 1 | |
| | Mushroom (1 cm$^3$, room) | 2 | |
| | Peas (1 piece, room) | 3 | |
| | Tomato (1 cm$^3$, room) | 4 | |
| | Cucumber (1 cm$^3$, room) | 5 | |
| | Apple Granny Smith (1 cm$^3$, room)[a] | 6 | |
| | Strawberry (1 cm$^3$, room) | 7 | |
| | Melon Rocío de miel (1 cm$^3$, room) | 8 | |
| | Orange (1 cm$^3$, room)[a] | 9 | |
| | Watermelon (1 cm$^3$, room) | 10 | |

[a] Reference standards used in the subsequent sensory evaluations

was subjected to three consecutive creep–recovery assays. The first two trials were conducted in order to remove any surface irregularity in the specimen (Mittal and Mohsenin 1987). Compliance data from creep experiments were fitted by a mechanical model consisting of a spring serially connected with two Kelvin–Voigt elements (each Kelvin–Voigt

element has a spring and a dashpot in parallel) and a dashpot element described by the following equation (Sherman 1970):

$$J(t,\tau) = (J_0) + \sum_{i=1}^{2} (J_i) \left(1 - e^{-t/\lambda_i}\right) + t/\eta_N \qquad (2)$$

where $J(t,\tau)$ is the creep compliance ($J = \gamma(t)/\tau$ with $\gamma(t)$ being the strain at time $t$ and $\tau$ the constant stress applied). $J_0$ is the instantaneous compliance at $t=0$; $J_i$ are the retarded compliances; $\lambda_i$ ($J_i = \eta_i \times J_i$) are the retardation times and $\eta_i$ are the coefficients of viscosity associated with the Kelvin–Voigt elements; $\eta_N$ is the coefficient of viscosity associated with Newtonian flow and its inverse the steady-state fluidity of the material.

Data were obtained using a minimum of 10 and 15 replicates for dynamic oscillatory and creep–recovery tests, respectively.

## Compression Properties Evaluation

An Instron Universal Testing Machine model 3345 (Canton, MA, USA), with a 5,000 N compression load cell interfaced with a series data acquisition software (Bluehill 2, v. 2.17, Instron, USA), was used to conduct the texture profile analysis (Bourne 1978). A two-cycle compression was set to 70 % deformation. Tests were performed with a crosshead speed of 0.001 m/s and a 0.035-m diameter cylindrical probe at room temperature (20±1 °C).

The mechanical parameters fracturability ($F$) and hardness ($H$) during the first compression cycle, hardness ($H_2$) during the second compression cycle, area ($A_1$) under the curve during the first compression, area ($A_2$) under the curve during the second compression, cohesiveness (Coh), adhesiveness to palate (Adh), springiness ($S$), gumminess ($G$), and chewiness (Chew) were obtained from the force–time curves, according to the definitions established by Bourne (1978).

The deformability modulus ($E_d$) was calculated using Eqs. (3)–(5) (Calzada and Peleg 1978):

$$E_d = \sigma_R/\varepsilon_R \qquad (3)$$

$$\sigma_R = F(t) \left[(H_0 - \Delta H)/A_0 H_0\right] \qquad (4)$$

$$\varepsilon_R = \ln \left[H_0/(H_0 - \Delta H)\right] \qquad (5)$$

where $F(t)$ is the compression force at time $t$, $H_0$ is the height of the sample before compression, $\Delta H$ is the difference of sample height before compression and during compression, and $A_0$ is the cross-sectional area of the cylinder before compression. The test was replicated a minimum of 20 times and mean values for each parameter were calculated.

## Statistical Analysis

Instrumental and sensory data were expressed as mean±standard deviation of the mean (mean±SD). Storage modulus curves were statistically analyzed to determine significant differences according to the F-Snedocor test for the equality of variances of two populations (Snedecor and Cochran 1989). This test evaluates the significance of the difference between two mean square errors (MSE), one calculated from the overall curve regression (joint data all together) and the other, correspondent to the arithmetical sum of individual MSE.

Three-way analysis of variance (ANOVA) was done to establish the presence or absence of significant differences among texture parameter values according to the factors "treatment," "assessor," and "replicate". Significance level was set at $\alpha < 0.05$. In case of finding significant differences, Turkey's test was performed.

Multivariate analysis of variance (MANOVA) was used to detect rheological data (viscoelastic and compression properties) differences among samples. Significance level was set at $\alpha < 0.05$. In case of finding significant differences, Hotelling corrected for Bonferroni test was performed. Principal component analysis (PCA) of mean ratings for each attribute was used to illustrate the relationship among variables and samples. These statistical analyses were carried out using Infostat v2009 software (Córdoba, Argentina).

Linear partial least squares regression analysis (PLS) was used to analyze the relationships among sensory ($Y$-block) and rheological properties ($X$-block) matrices. Both sensory and instrumental variables were standardized previously to the PLS analysis. The GenStat statistical software (GenStat discovery edition 3, Oxford, UK) was used for these analyses.

## Results and Discussion

### Temperature Evolution

Temperature in the center of the apple slice gradually increased in a rather linear way from 25 °C at 30 s blanching to approximately 98 °C at 70 s blanching (figure not shown). Then, the temperature continued increasing but more slowly, and after 98 s of heating, the temperature was about 100 °C.

### Structural Features

LM and TEM studies were performed to evaluate structure changes produced at the cellular level by the different

blanching treatments. Figures 1 and 2 show LM and TEM microphotographs, respectively, of fresh and treated apple tissues.

Cytological examination of untreated or fresh apple revealed turgid cells with intact plasmalemma and tonoplast and plasma membrane intimately associated with the wall and parietal cytoplasm (Figs. 1a and 2a). Tissue appeared anisotropic and heterogeneous, with intercellular spaces of different sizes and shapes (Fig. 1a). Cell walls appeared with tightly packed and darkly stained fibrillar material, organized in a longitudinal or a loose reticulate pattern according to the region (Fig. 2a). The middle lamella cementing adjacent cells appeared stained (Fig. 2a, b), as well as the plasmodesmata connecting the cytoplasm of neighboring cells (micrographs not shown). Cells exhibited an important cell-to-cell contact degree.

Blanching for 90 s caused disruption of cellular membranes (plasmalemma and tonoplast) with loss of turgor. Cell walls appeared more undulated, mainly in the areas where cell debonding occurred, and less stained (Fig. 1c, d). In TEM, cell walls showed a slight degradation and exhibited lower electron density than in the fresh tissue (Fig. 2c, d). In many areas, the presence of the middle lamella could be observed. An alteration in the arrangement of microfibrils was notorious. Broken membranes and the rest of the cytoplasm were visualized slightly separated from the cell wall.

Concomitant with the greater exposure to 100 °C, the structure of 150 s blanched apples was affected in a more severe way than when heating lasted 90 s (Figs, 1e, f and 2e, f). Membranes appeared highly fragmented. Cell walls were slightly stained and swollen (Fig. 1e, f). In TEM, walls showed very low electron density, but in many areas, a weak



Fig. 1 LM images from fresh and blanched apple tissues. a, b Fresh; c, d blanched, 90 s; e, f blanched, 150 s. is intercellular spaces, v vacuole

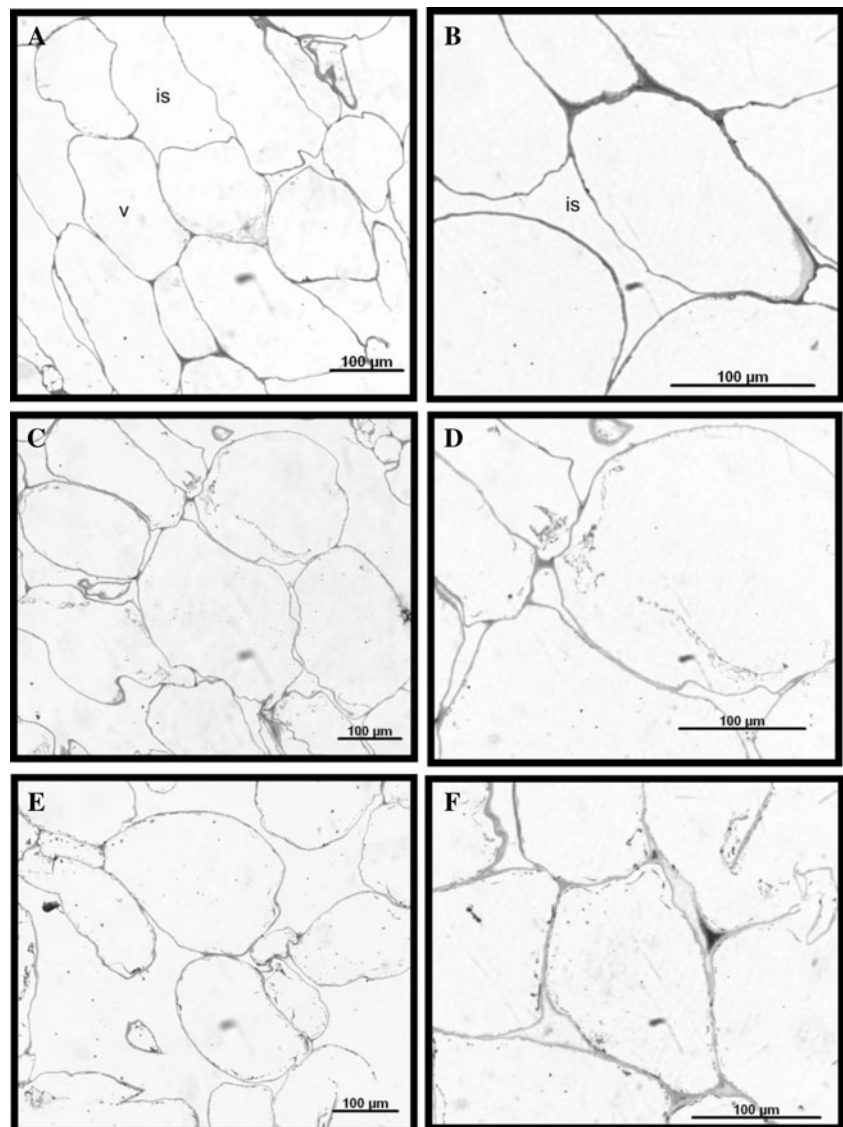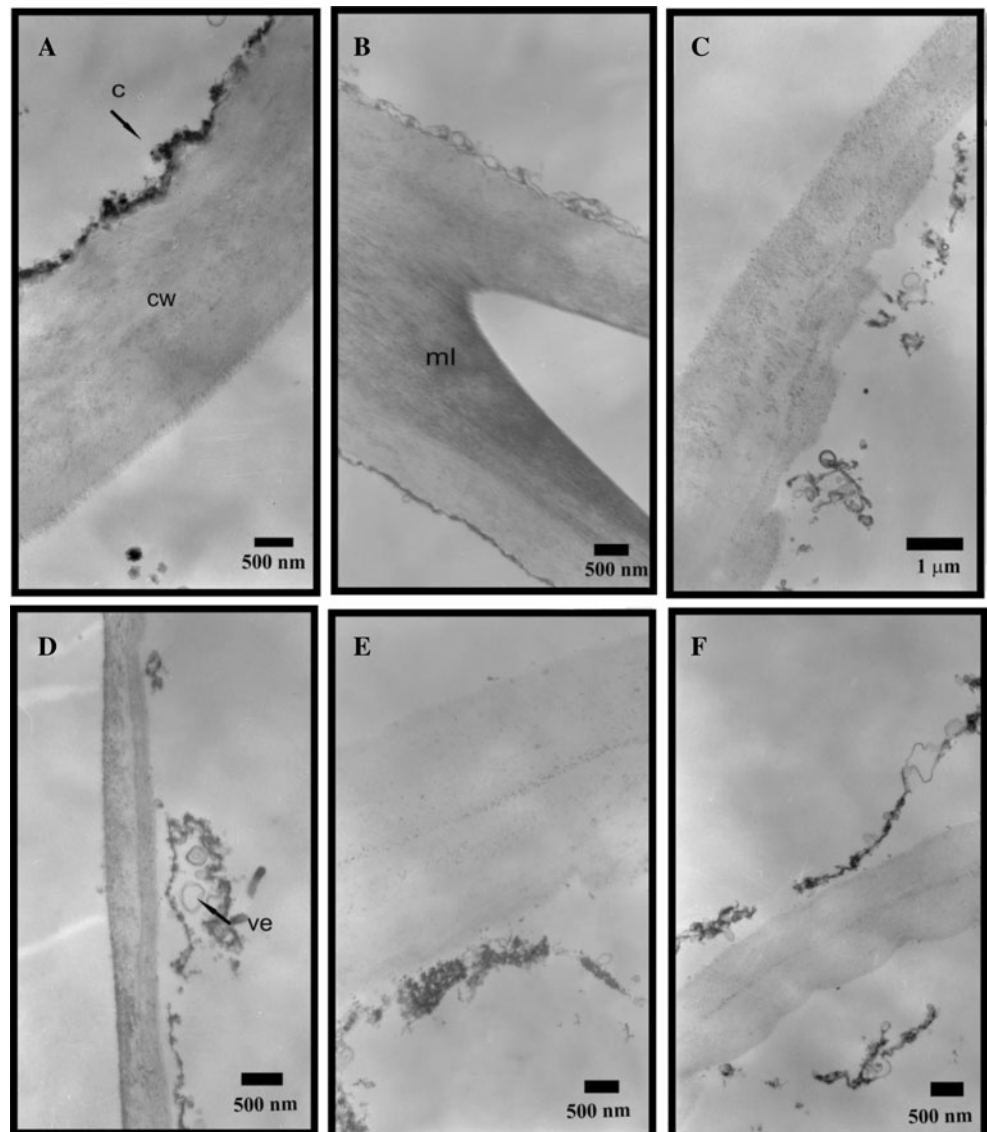**Fig. 2** TEM images from fresh and blanched apple tissues. **a**, **b** Fresh; **c**, **d** blanched, 90 s; **e**, **f** blanched, 150 s. *cw* cell wall, *c* cytoplasm, *ml* middle lamella, *ve* vesicle



middle lamella could be noted (Fig. 2e, f). Cells have more spaces between them and have less contact with neighboring cells (Fig. 1e). However, cells were still in contact with each other through plasmodesmata, which appeared moderately stained (TEM micrographs not shown), and in the triangular spaces between three cells (Fig. 1f).

Sensory Texture

Table 2 showed the three-way analyses of variance with their respective interactions (treatment×assessor; treatment×replicate; assessor×replicate) for each texture attribute. The analyses revealed significant differences among the samples (treatment) for all the texture descriptors tested. There were no significant differences among panelists for the evaluated texture attributes of apple samples, thus showing consistency in the evaluations (Table 2, assessor factor). For some

attributes like hardness, cohesiveness, crispness, and juiciness, no significant differences were found corresponding to the single factor "replicate" and the interaction factors "assessor×replicate" and "treatment×replicate". These results indicated that the judges conducted homogeneous and consistent measurements, and the treatments were reproducible giving no significant differences among the replicates.

Means and standard deviations of evaluated attributes in fresh and blanched apple samples are presented in Table 3. Sensory hardness, crispness, and juiciness showed significant differences between fresh and blanched apple samples and between B90 and B150 samples. Assessors perceived a decrease in hardness, crispness, and juiciness in the treated samples determining an inverse relationship between the texture attribute and blanching time.

Sensory fracturability of blanched samples diminished significantly with respect to control, and the loss of fracturability

**Table 2** Three-way analysis of variance for the evaluated texture attributes

| Source | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Hardness | | | | | |
|   Assessor | 3.61 | 7 | 0.50 | 2.45 | 0.072 |
|   Treatment | 59.29 | 2 | 29.64 | 140.13 | <0.0001 |
|   Replicate | 0.02 | 1 | 0.02 | 0.10 | 0.758 |
|   Assessor × treatment | 6.52 | 14 | 0.47 | 2.20 | 0.076 |
|   Assessor × replicate | 2.3 | 7 | 0.33 | 1.55 | 0.230 |
|   Treatment × replicate | 0.1 | 2 | 0.05 | 0.24 | 0.790 |
|   Error | 2.96 | 14 | 0.21 | | |
| Fracturability | | | | | |
|   Assessor | 1.65 | 7 | 0.23 | 2.61 | 0.060 |
|   Sample | 84.38 | 2 | 42.19 | 492.02 | <0.0001 |
|   Replicate | 0.48 | 1 | 0.48 | 5.60 | 0.033 |
|   Assessor × treatment | 8.37 | 14 | 0.60 | 6.98 | 0.001 |
|   Assessor × replicate | 0.16 | 7 | 0.02 | 0.27 | 0.955 |
|   Treatment × replicate | 0.08 | 2 | 0.04 | 0.44 | 0.650 |
|   Error | 1.2 | 14 | 0.09 | | |
| Cohesiveness | | | | | |
|   Assessor | 0.36 | 7 | 0.05 | 1.8 | 0.165 |
|   Sample | 30.07 | 2 | 15.04 | 526.2 | <0.0001 |
|   Replicate | 0.05 | 1 | 0.05 | 1.75 | 0.207 |
|   Assessor × treatment | 0.93 | 14 | 0.07 | 2.32 | 0.063 |
|   Assessor × replicate | 0.58 | 7 | 0.07 | 2.4 | 0.077 |
|   Treatment × replicate | 0.17 | 2 | 0.09 | 2.97 | 0.084 |
|   Error | 0.4 | 14 | 0.03 | | |
| Crispness | | | | | |
|   Assessor | 1.06 | 7 | 0.15 | 0.36 | 0.914 |
|   Sample | 33.19 | 2 | 16.6 | 38.94 | <0.0001 |
|   Replicate | 0.93 | 1 | 0.93 | 2.17 | 0.163 |
|   Assessor × treatment | 29.97 | 14 | 2.14 | 5.02 | 0.002 |
|   Assessor × replicate | 7.93 | 7 | 1.28 | 2.63 | 0.058 |
|   Treatment × replicate | 0.45 | 2 | 0.23 | 0.53 | 0.599 |
|   Error | 5.97 | 14 | 0.43 | | |
| Juiciness | | | | | |
|   Assessor | 0.74 | 7 | 0.11 | 0.74 | 0.640 |
|   Sample | 11.41 | 2 | 5.71 | 40.02 | <0.0001 |
|   Replicate | 0.02 | 1 | 0.02 | 0.12 | 0.738 |
|   Assessor × treatment | 4 | 14 | 0.29 | 2.01 | 0.103 |
|   Assessor × replicate | 1.52 | 7 | 0.22 | 1.52 | 0.238 |
|   Treatment × replicate | 0.09 | 2 | 0.05 | 0.33 | 0.725 |
|   Error | 2 | 14 | 0.14 | | |

$p < 0.05$ indicates significant differences

*SS* sum of square, *df* degree of freedom, *MS* mean square, *F* Fisher statistic, *p* probability

**Table 3** Texture parameters (mean values and standard deviation) for fresh and blanched apple tissues evaluated by the sensory panel

| Treatment | SH | SF | SC | Crispness | Juiciness |
|---|---|---|---|---|---|
| C | 6.9±0.6 a | 7.9±0.7 a | 1.6±0.5 a | 7.6±0.1 a | 5.98±0.27 a |
| B90 | 5.9±0.9 b | 5.6±0.6 b | 2.7±0.8 b | 6.2±0.6 b | 5.22±0.46 b |
| B150 | 4.4±1.1 c | 4.3±0.5 c | 3.9±0.7 c | 4.3±0.4 c | 4.58±0.38 c |

Means in same column with the same letter are not significantly different ($p < 0.05$, Tukey)

*SH* sensory hardness, *SF* sensory fracturability, *SC* sensory cohesiveness

factor showed significant differences. The assessors found difficult in assessing the fracturability of apple samples. For this reason, round-table discussions were performed to clarify any possible discrepancy and to reach a consensus. Thybo and Martens (1998) and Garcia Loredo et al. (2011, 2013) also reported that trained assessors found it difficult to assess the fracturability of cooked potatoes and osmotically dehydrated apples and pears treated with UV-C light/$H_2O_2$, respectively, when using the texture profile method.

Cohesiveness showed significant differences between apple samples. The blanching process slightly increased apple cohesiveness, the increase being greater for B150 samples. The assessors informed that all apple samples did not present adhesiveness to the palate.

Dynamic Oscillatory Shear Behavior

Linear viscoelastic limits ranged between 0.001 and 0.0085 % for fresh apple and between 0.001 and 0.11 % for blanched ones. Accordingly, a strain value equal to 0.005 % was selected for frequency sweep test to assure linearity for all samples. Table 4 summarized $G'$ and $G''$ values for fresh and heated apples. All apple samples had a solid behavior with $G'$ exceeding $G''$ over the entire frequency range, indicating a dominant solid behavior. The $G'$ pattern across the frequency spectra indicates an elastic, cross-linked network. Statistical analysis of storage modulus curves showed significant differences among control and blanched samples and between blanched

**Table 4** Storage and loss modules for fresh and blanched apple tissues

| Treatment | $\omega$=100 1/s | $\omega$=10 1/s | $\omega$=1 1/s | $\omega$=0.1 1/s |
|---|---|---|---|---|
| Storage modulus $G'$ (kPa) | | | | |
|   C | 468±109 | 417±96 | 381±89 | 338±84 |
|   B90 | 88.9±9.7 | 77.9±8.7 | 69.3±7.8 | 60.6±7.1 |
|   B150 | 59.4±14.4 | 52.1±12.4 | 45.7±11.1 | 39.3±9.7 |
| Loss modulus $G''$ (kPa) | | | | |
|   C | 42.4±9.9 | 31.2±7.8 | 31.4±7.2 | 42.6±13.1 |
|   B90 | 10.8±1.3 | 7.26±1.05 | 7.25±1.05 | 9.62±1.98 |
|   B150 | 8.05±1.75 | 5.31±1.24 | 4.9±1.2 | 5.6±1.6 |

increased as the severity of the blanching process increased. There were no significant differences to the interaction factors "assessor × replicate" and "treatment × replicate." "Replicate"

samples. Blanching provoked a decrease in $G'$ and $G''$ values in the entire frequency range. The linear dependence of $G'$ with the angular frequency was slightly modified after treatments: $n$ values were $0.04\pm0.01$, $0.060\pm0.002$, and $0.06\pm0.01$ for C, B90, and B150 apple samples, respectively. This slight decrease in $n$ values indicated that blanching caused a loss of rigidity in the gel network. The dependence of $G''$ with frequency was more complex. The curves of log $G''$ versus log $\omega$ consisted of one shallow negative (nearly a plateau) slope at low frequencies and a positive slope at high frequencies.

The values of tan $\delta$ of blanched apples ($G''/G'=0.09$–$0.159$) were slightly higher than those of control samples ($G''/G'=0.07$–$0.13$) for all frequencies, indicating that the blanching process increased the viscous component regarding the elastic one.

## Creep Behavior

Blanching treatment caused relevant changes in both creep and recovery response (Fig. 3). For the time scale of the experiments, creep response of fresh and treated tissues was well characterized (correlation coefficient$>0.999$) by the mathematical model represented by Eq. (2) and the corresponding parameters are shown in Table 5. According to the interpretation of Sherman (1970), $J_0$ would be related to those bonds of structural units that are elastically stretched when the stress is applied and show instantaneous and complete recovery when the stress is removed. $J_i$ parameters would be related to bonds that break and reform at different rates, the weaker bonds breaking at smaller values of time than the stronger ones. They show retarded elastic recovery. The linear region of Newtonian compliance $1/\eta_N$ would be related to those bonds that are ruptured during the shear creep step and the time required for them to reform is longer than the creep–recovery period; the released units will flow and part of the structure is not recovered. Creep parameters showed
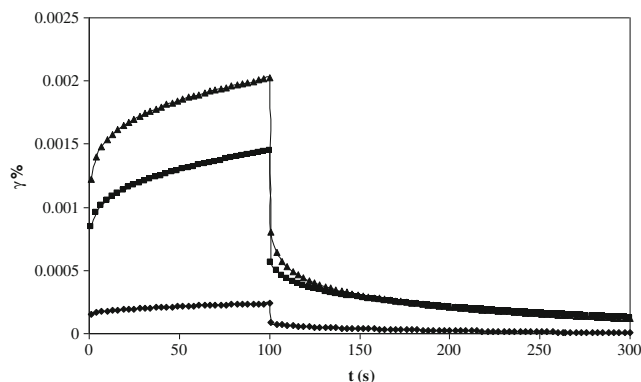


**Fig. 3** Experimental creep/recovery curves for fresh and blanched apple tissues. *Black diamonds*, fresh; *black squares*, blanched, 90 s; *black triangles*, blanched, 150 s

significant differences ($F_{12,\ 40}=6.83$; $p<0.0001$) between fresh and treated samples and also between blanched apples.

The relatively large standard deviation values associated with creep parameters observed in Table 5 had been previously reported in the literature (Mittal and Mohsenin 1987; Pitt 1992; Alzamora et al. 2008) and attributed to many factors, such as variability and heterogeneity of fruit tissues, age, differences in intercellular space interconnectivity and cell size, etc.

The instantaneous elastic compliance ($J_0$) increased five- and ninefold for 90 and 150 s blanched tissues, respectively, revealing a decrease in the instantaneous elastic module $E_0$ ($1/J_0$). Furthermore, the retarded compliances ($J_1$ and $J_2$) and the steady-state viscous compliance ($t/\eta_N$) of treated tissues showed a similar behavior (approximately seven-, ten-, and eightfold increase, respectively) regarding the fresh tissue. Creep parameters, in agreement with $G'$ and $G''$ values, revealed that blanching treatment provoked a decrease in elasticity and network strength, and also an increase in fluidity, being this behavior slightly more accentuated in 150 s blanched apples.

Retardation times (i.e., the time required for the strain on structural elements associated with viscoelastic behavior to reach 63 % of their maximum strain) of both Voigt units differed approximately in one order of magnitude for all apple samples. Retardation time $\lambda_1$ slightly decreased for treated tissues, whereas retardation time $\lambda_2$ (which reflects the viscoelastic behavior of tissues over relatively short times) was similar for all samples.

The relative contribution of each type of compliance to the overall compliance was similar for blanched and untreated apples, ranging 55–60 % for instantaneous compliance, 16–17 and 9–12 % for retarded compliances ($J_1$ and $J_2$, respectively), and 14–17 % for steady-state viscous compliance. This similarity was expected since blanching affected in a similar way elastic, viscoelastic, and steady-state viscous compliances.

Principal component analysis explained the spatial relationships of the six creep parameters for each apple sample. The first two principal components explained 82.8 and 17.2 % of the variance, respectively, in the PCA of the creep data. The first contrasted $J_0$, $J_1$, and $J_2$ positively and $\eta_N$ and $\lambda_1$ negatively. The second axis was positively defined by $\lambda_2$. Blanched apples, placed to the right of the graph (biplot not shown), were mainly characterized by an increase in $J_0$, $J_1$, and $J_2$ and a decrease in $\eta_N$ and $\lambda_1$. Fresh apple, placed to the left of the graph, showed high $\eta_N$ and $\lambda_1$. Again, a clear separation in the spatial relationships between apples blanched during 90 and 150 s was noted.

## Mechanical Properties Evaluation

Figure 4 shows typical compression–time curves for fresh and treated samples. Compression curves of fresh apples showed

**Table 5** Viscoelastic parameters (mean values and standard deviation) derived fitting Eq. (2) to compliance curves from creep phase for fresh and blanched apple tissues

| Treatment | $J_0$ (1/Pa) (×10$^5$) | $J_1$ (1/Pa) (×10$^5$) | $J_2$ (1/Pa) (×10$^5$) | $\lambda_1$ (s) | $\lambda_2$ (s) | $\eta_N$ (Pa s) (×10$^{-7}$) |
|---|---|---|---|---|---|---|
| C | 0.25±0.05 | 0.07±0.02 | 0.039±0.007 | 24.6±5.8 | 2.34±0.41 | 15.1±6.8 a |
| | 59.5 %[a] | 15.6 %[a] | 9.3 %[a] | | | 15.6 %[a] |
| B90 | 1.57±0.22 | 0.49±0.05 | 0.31±0.03 | 22.6±1.9 | 2.58±0.28 | 1.97±0.29 b |
| | 56.3 %[a] | 17.5 %[a] | 12.1 %[a] | | | 14.2 %[a] |
| B150 | 2.2±0.4 | 0.69±0.14 | 0.47±0.09 | 20.6±1.2 | 2.4±0.1 | 1.79±0.32 c |
| | 54.8 %[a] | 16.8 %[a] | 10.7 %[a] | | | 17.6 %[a] |

Different letters in each row indicate significant differences at $p \leq 0.05$ between treatments according to the Hotelling multiple comparison test based on Bonferroni correction, $\alpha = 0.05$

[a] Percent contribution to the overall compliance at the end of the creep phase

the typical shape of hard materials, with abrupt rupture peaks. Blanched samples showed an increase in force less abrupt than untreated apple and an increase in the deformability to rupture, requiring less force to obtain the same strain. Thiel and Donald (2000) and Lillfort (2001) reported that blanching in fruit and vegetable tissues produces a loss of hardness due to the disruption of cell membranes and loss of turgor. When cells lose their turgor, they are more deformable resulting in a softer and rubbery texture.

Table 6 shows means and standard deviations of compression parameters corresponding to fresh and treated samples. Significant differences ($p<0.0001$) were observed among all samples. All mechanical parameters (fracturability, hardness, hardness 2, area 1, area 2, cohesiveness, springiness, gumminess, chewiness, and deformability modulus) decreased for the treated apples, and this decrease was greater as blanching time increased. Blanching provoked a tissue softening, reflected by lower hardness and fracturability values, and less force to achieve the same deformation, which resulted in a less work to rupture.

The instrumental cohesiveness pattern did not correlate with the sensory rating. In a previous work, Garcia Loredo

and Guerrero (2011) found that some sensory ratings assigned to food samples when assessors evaluated cohesiveness scales did not properly correlate with instrumental measurements. A cohesive sample which exhibits little or no springiness (such as apple) will have very low values for $A_2/A_1$ because there will be scarce contact surface between the probe and the sample during the second compression. Meullenet et al. (1998) reported that the evaluation of the $A_2/A_1$ ratio was dependent on the evaluation of $d_2/d_1$ ratio (i.e., springiness of the product) and that there was a poor correlation between instrumental and sensory cohesiveness in samples without springiness.

By using principal component analysis, the relationship between mechanical parameters and apple samples was examined. The first component PC1 explained 94.4 % of data variability and was represented positively by hardness, hardness 2, modulus of deformability, work done in the first compression (area 1), work in the second compression (area 2), springiness, gumminess, and chewiness. The second component PC2 explained 5.6 % of data variability and was positively defined by cohesiveness and negatively by fracturability. The corresponding scores in the biplot for the first two components (figure not shown) showed a clear separation between control and blanched apples and also between apples heated during 90 and 150 s. The location of treated samples in the graph showed a decrease in all mechanical parameters because of the treatments, more accentuated as heating time increased.

Partial Least Squares Regression Analysis

PLS regression analysis was performed using sensory attributes as *y*-variables and rheological parameters as *x*-variables.

*Mechanical Spectrum*

About 93.8 and 95.1 % of variability in the sensory characteristics could be explained by storage and loss modules at different frequencies ($\omega$=0.1, 1, 10, 100 1/s), respectively, using the PLS regression model with two PLS factors.
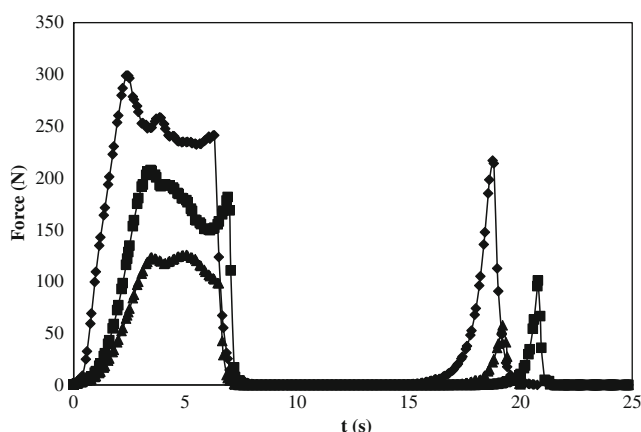


**Fig. 4** Typical force/time curves for fresh and blanched apple tissues. *Black diamonds*, fresh; *black squares*, blanched, 90 s; *black triangles*, blanched, 150 s

**Table 6** Compression parameters (mean values and standard deviation) for fresh and blanched apple tissues

| Treatment | $F$ (N) | $H$ (N) | $H_2$ (N) | $A_1$ (J) | $A_2$ (J) | $S$ (–) | Coh (–) | $G$ (N) | Chew (N) | $E_d$ (N/mm²) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C | 317.3±22.1 | 317.3±22.1 | 225.4±19.8 | 1.39±0.13 | 0.13±0.01 | 0.66±0.05 | 0.10±0.01 | 30.64±3.73 | 20.34±3.49 | 1.96±0.35 | a |
| B90 | 194.9±14.8 | 194.9±14.8 | 81.75±11.07 | 0.7±0.07 | 0.04±0.01 | 0.47±0.04 | 0.05±0.01 | 10.02±1.35 | 4.7±0.92 | 0.67±0.08 | b |
| B150 | nd | 116.7±27.6 | 64.54±11.67 | 0.44±0.1 | 0.03±0.01 | 0.41±0.08 | 0.07±0.01 | 7.98±1.84 | 3.32±0.99 | 0.36±01 | c |

Different letters in each row indicate significant differences at $p \leq 0.05$ between treatments according to the Hotelling multiple comparison test based on Bonferroni correction, $\alpha = 0.05$

*nd* not detected

According to PLS analysis, fracturability, crispness, and hardness were the best explained sensory properties by the models using storage and loss modules as rheological properties (53, 46.1, and 45.8 % of the variance explained, respectively, by storage modulus and 48.3, 45.8, and 45.2 % of the variance explained, respectively, by loss modulus).

The positions of $G'$ and $G''$ at different frequencies and sensory parameters through PLS 1 and PLS 2 factors are observed in Fig. 5a, b, respectively. Sensory hardness and crispness were positively related to storage modulus at intermediate ($\omega = 1$ 1/s) and high ($\omega = 10$ 1/s and $\omega = 100$ 1/s) frequencies, and sensory fracturability was positively correlated with $G'$ at $\omega = 0.1$ 1/s (Fig. 5a). Sensory hardness and crispness were positively related to $G''$ at low frequencies ($\omega = 0.1$ 1/s and $\omega = 1$ 1/s), and sensory fracturability was positively correlated with $G''$ at high frequencies ($\omega = 100$ 1/s) (Fig. 5b).

### Creep Parameters

Ninety-one percent of variance in sensory attributes was explained through creep parameters using the first two PLS factors. Approximately 88.5 and 2.2 % of the variability was
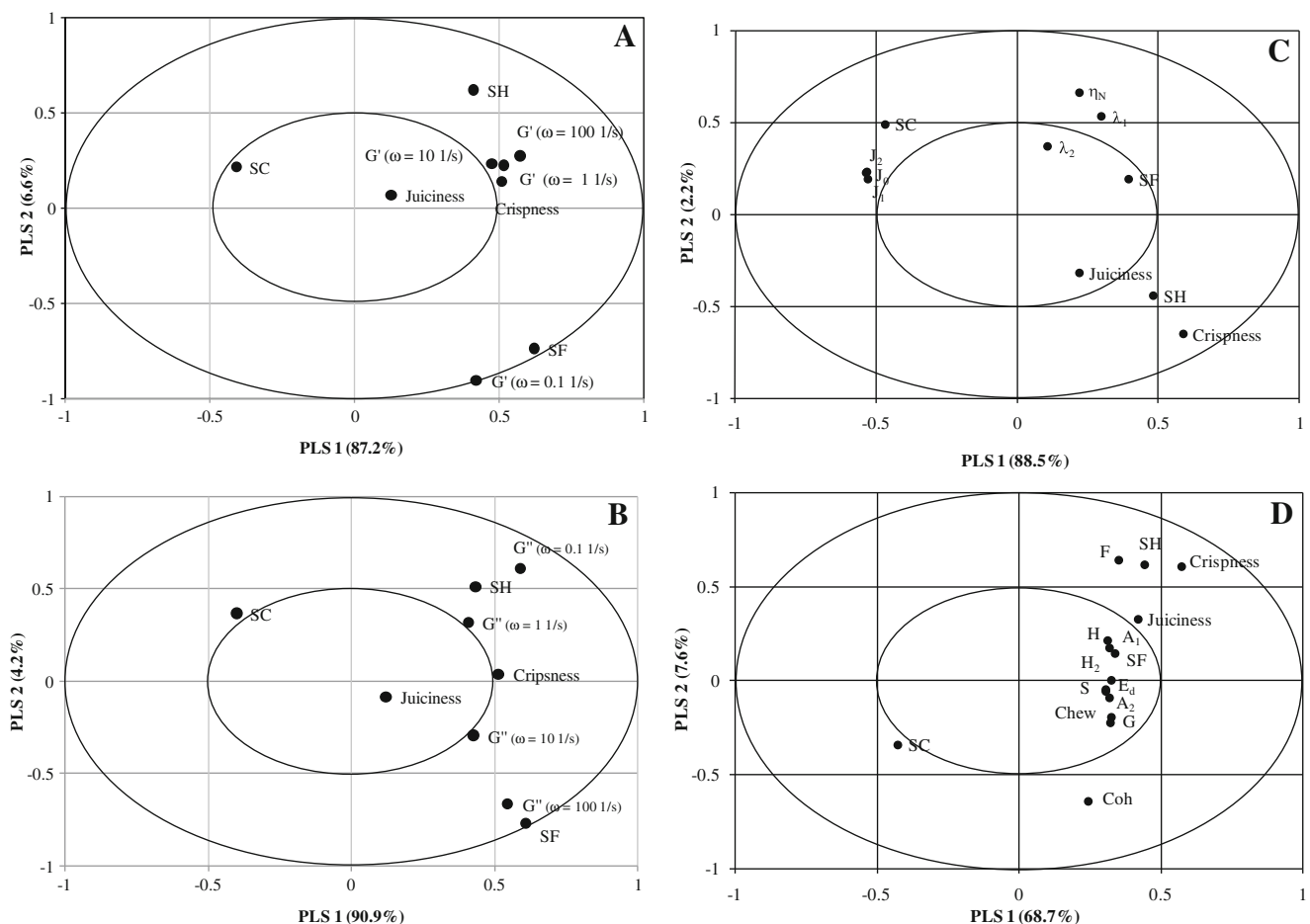


**Fig. 5** Plots of $X$-loadings and $Y$-loadings of fresh and blanched apple tissues. **a** Storage modulus at different frequencies, **b** loss modulus at different frequencies, **c** creep parameters, **d** mechanical parameters

explained by PLS factor 1 and PLS factor 2, respectively. Crispness, hardness, fracturability, and cohesiveness were the best explained sensory properties (approximately 75.9, 44.7, 49.6, and 47.1 % of the variance explained, respectively) and juiciness was the least explained (13.4 %).

Analyzing the location of the variables (texture attributes and creep parameters) through PLS 1 and PLS 2 factors (Fig. 5c), it was observed that instantaneous and retarded compliances ($J_0$, $J_1$, and $J_2$) were positively correlated to cohesiveness and negatively related to hardness and crispness.

*Compression Parameters*

About 76.4 % of the variability in sensory attributes could be explained by mechanical measurements using PLS regression model with two PLS factors. Approximately 68.8 % of the variability was explained by PLS factor 1 and 7.6 % by PLS factor 2. An inclusion of more than two PLS factors did not improve the prediction (data not shown), and therefore, the remaining PLS factors were omitted in the prediction.

According to this model, crispness and hardness were the best explained attributes (approximately 71.5 and 45.8 % of the variance explained, respectively), while cohesiveness, juiciness, and fracturability were less representative (approximately 37.1, 36.1, and 22.7 % of the variance explained, respectively).

Analyzing the location of texture attributes and mechanical parameters through PLS 1 and PLS 2 factors (Fig. 5d), it was observed that instrumental fracturability was positively correlated to crispness, juiciness, and sensory hardness and negatively related to sensory cohesiveness. Moreover, instrumental hardness and area 1 were positively correlated to sensory fracturability.

Integration of Structure, Rheological Properties, and Texture Perception

All assayed tests (instrumental texture profile analysis, oscillatory and creep–recovery tests, sensory evaluation) were sensitive, distinguishing structure differences among fresh and blanched apples. Moreover, they also allowed discriminating between the structure of B90 and B150 samples.

Creep curve parameters and storage modulus values have been suggested to be associated with some structural components of fruit tissue, indicating changes at the cellular level when the tissue is processed (Jackman and Stanley 1995; Martínez et al. 2007; Alzamora et al. 2008). Flow parameters and storage modulus seem to be affected by the turgor level in cells, the displacement of the cellulose microfibrils through the amorphous matrix of the wall, the flow of vegetal matrix, the concentration of the molecular components (especially cellulose), or combination of these (Alzamora et al. 2008). Cellulose (the main component of the cell wall), turgor pressure, and air occluded in the matrix were suggested to be

responsible of the elastic behavior of tissues and the changes in values of $G'$ and $J_0$.

B90 and B150 samples showed a decrease in $G'$ and $J_0$ values with respect to fresh apple. These differences in the mechanical spectrum could be related to alterations observed in the tissue structure, such as membrane rupture with consequent loss of turgor, and degradation of cell walls (Figs. 1 and 2). Although both blanching treatments provoked the loss of turgor, elastic component of 150 s blanched samples would decrease as compared with 90 s blanched ones due to the greater degradation of wall components, as observed in Figs. 1 and 2e, f.

Creep parameters were analyzed taking into account the structural model proposed by Jackman and Stanley (1995) and successfully used by Alzamora et al. (2008), García Loredo et al. (2011), Gómez et al. (2011), Gómez et al. (2012), and Vicente et al. (2012) to explain creep response of apples subjected to osmotic dehydration, short wave ultraviolet light, or pulsed light. Instantaneous elastic compliance $J_0$ would be related to the combination of turgor and primary cell wall strength as dictated by cellulose, as previously mentioned. Viscoelastic compliances $J_1$ and $J_2$ could be attributed to time-dependent changes in pectins and hemicelluloses, respectively. Steady-state viscosity could be related to cell wall fluidity arising from exosmosis and/or solubilization and degradation of polymers and less water binding capacity due to treatments.

$J_1$ and $J_2$ significantly increased due to blanching, being the increase more marked in B150 tissue. Observations with TEM for treated cells showed walls with little definition of the middle lamella and microfibril degradation in some areas. These structure changes, more accentuated as severity of blanching treatment increased, would account by the observed increase in $J_1$, $J_2$, and $1/\eta_N$ capacitances. The decrease in $\lambda_1$ showed by blanched apples also reflected the weakening of bonds associated to the middle lamella.

All mechanical parameters decreased due to blanching processes. Numerous structure changes may have a significant impact on compression behavior. The mechanical of blanched tissues can be explained in part by the loss of turgor. Fresh tissues containing turgid cells are crisper and characterized by greater stiffness ($>E_d$) and lower resistance to deformation than tissues containing cells with low turgor pressure. Turgid tissues exhibit lower work-of-fracture than nonturgid ones (Waldron et al. 2003). Besides loss of turgor, softening ($<H$) and loss of fracturability of treated tissues occurred as a result of a weakening of intercellular adhesion, reorientation of cellulose fibrils, and degradation of wall biopolymers. In addition, loss of rigidity ($<E_d$) directly correlated with removal of air in the intercellular spaces and modifications in the cellulose–hemicellulose network.

PLS analysis found clear correlations between rheological properties and sensory attributes. Sensory hardness and

crispness were negatively related to instantaneous ($J_0$) and retarded ($J_1$, $J_2$) elastic compliances and positively correlated to storage modulus at intermediate and high frequencies and loss modulus at low frequencies. Sensory fracturability was positively correlated with $G'$ at $\omega=0.1$ 1/s and $G''$ at $\omega=100$ 1/s. Juiciness and sensory fracturability were positively correlated to the instrumental hardness and area 1 (mechanical parameters). Sensory cohesiveness was positively correlated to $J_0$, $J_1$, and $J_2$ compliances.

It is not easy to understand the micro- and ultrastructure–sensory texture relationship because of the multimodal dependence of sensory properties with structure features. Considering structure-based explanation of the viscoelastic and mechanical parameters and PLS correlations, all structure changes affected each of the sensory properties.

Sensory juiciness is a multidimensional perception that includes the following: force with which the juice squirts out, total amount of juice released on chewing, flow properties of the pressed liquid, and the consistency contrast between liquid and suspended cell debris (Szczesniak and Ilker 1988). Prerequisites to juiciness include not only high water content but organized cellular network with proper turgor and integrity, low viscosity, and little suspended solids in the expressed liquid and cell walls mechanically weaker than the middle lamella. Tissue failure can involve cell separation or cell rupture (or a combination of both phenomena), depending on whether cell walls are stronger than the forces holding cells together or forces adhering cells to another are stronger than the cell walls, respectively (Waldron et al. 2003; Lillfort 2001). Harker et al. (2006) observed that juice release in apples was dependent on the breakdown of individual cells and varied between firm and soft apples. According to these authors, in firm apples (control), tissue fracture would be associated with breakage of individual cells resulting in the release of cytoplasm fluids. In soft apples (such as B90 and B150 samples), the type of breakdown would be mainly cell-to-cell debonding. Individual cells did not always break open and release their contents, resulting in a mealy apple. The present results would be in agreement with the observations of Harker et al. (2006): a decrease in juiciness was observed in parallel with the degradation of cell walls and middle lamella and a consequent increase in cell separation in blanched apples. However, in spite of the reduction in cell-to-cell adhesion (in different degree according to the severity of blanching), plasmodesmata and electronic dense edge of cells observed in microscopic images could act as points of wall rupture in blanched tissues where most of the wall have separated, ensuring cell breakage (Waldron et al. 2003). So, tissue fracture of treated apples would involve a combined mechanism.

It is well known that measurements in the viscoelastic range involve probing the structure of the sample in a nondestructive manner, whereas instrumental analysis using uniaxial compression applies large deformations resulting in fractures, ruptures, and irreversible deformations of the tissues (Kealy 2006). Thus, texture profile analysis measurements mimic more closely those performed in the mouth, where movement of the teeth involves large-scale, multidirectional deformations, whereas viscoelastic response can give an indication of the initial experience of a consumer. However, the most noteworthy observation from the present results is that instrumental measurements in the linear viscoelastic range seemed to correlate better to sensory assessments than instrumental compression parameters, except in the case of juiciness, where a better degree of correlation was found between fracturability and juiciness. Viscoelastic measurements also proved very successful for correlating with panel cohesiveness, which did not correlate with compression parameter determined in the uniaxial compression test. This good approximation of rheometric parameters to the actions of the human mouth is in agreement with our previous results in apple and pear tissues (Gómez et al. 2012; García Loredo et al. 2013) and could suggest that initial human experience in contact with the fruit would be very important in terms of consumer texture perception. Gomez et al. (2012) studied the correlation between rheological properties and texture in apple tissue treated with pulsed light and reported that crispness was negatively correlated to instantaneous and retarded compliances ($J_0$, $J_1$, and $J_2$). The steady-state viscosity ($\eta_N$) was negatively correlated to juiciness and some TPA parameters with sensory hardness and fracturability. Garcia Loredo et al. (2013) reported clear correlations between rheological properties (creep and mechanical parameters and sensory attributes) using PLS analysis in pear tissue treated with $H_2O_2$/UV-C light. Sensory hardness was negatively related to instantaneous ($J_0$) and retarded ($J_1$, $J_2$) elastic compliances and positively correlated to the modulus of deformability ($E_d$). Accordingly, both types of tests (using small and large deformations) would be needed for predicting texture attributes of a fruit.

## Conclusions

Changes in tissue structure and in TPA as well as dynamic and creep behavior were evidenced due to blanching treatments. Sensory differences detected among fresh, B90, and B150 apple samples were significant. PLS analysis found clear correlations between rheological parameters (creep, dynamic, and uniaxial compression tests) and sensory attributes (hardness, crispness, juiciness, cohesiveness, fracturability). Rheological behavior could be partially ascribed to observed changes in micro- and ultrastructure, i.e., breakage of membranes with loss of turgor ($<E_d$, $H$, $H_1$, and $G'$; $>J_0$) and degradation of cell wall and middle lamella ($<E_d$ and $\lambda_1$ and$>J_1$, $J_2$, and $1/\eta_N$).

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