Effects of Pretreatments on the Diffusion Kinetics and Some Quality Parameters of Osmotically Dehydrated Apple Slices

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This study compared mass transfer during osmotic dehydration (OD) and some quality indices of untreated apple slices to those of apple slices pretreated by either blanching, freezing, or applying high-intensity electric field pulses (HELP) or high pressure (HP). HP, HELP, and blanching increased water loss. Untreated and HELP-treated samples had comparable solids gains, which were lower ($P < 0.05$) than in the other samples. Apple slices turned brown after pretreatment but the L values of these samples increased with OD. The breaking force of dried samples increased with OD time, and pretreated samples had firmer dried texture than the untreated. Vitamin C content decreased with OD time, but HP- and HELP-treated apples had better retention of vitamin C.

Keywords: *Pretreatments; osmotic dehydration; water loss; solids gain; quality indices*

INTRODUCTION

Fruits and vegetables are an important part of the human diet, and the apple, being the most important temperate fruit of the world, is processed into a variety of products (*1*, *2*). Conventional dehydration of apple slices leads to a product of dark color, leathery texture, and poor flavor with a loss of nutritive values. Increasing consumer markets for minimally processed fruits and vegetables have prompted researchers to study "combined methods" as a preservation technique. In recent years, osmotic dehydration (OD) has received considerable attention due to the low temperature and energy requirements in addition to better retention of the initial nutritional values in the final product (*3*, *4*).

Mass transfer rates during osmotic dehydration depend on factors such as temperature, concentration of osmotic medium, size and geometry of the sample, sample to solution ratio, and degree of agitation of the solution (*1*, *3*, *5*−*7*). Recent studies have reported that mass transfer kinetics during osmotic dehydration can be enhanced by pretreating the fruit materials prior to osmotic dehydration. The influence of pretreatments such as high pressure (HP) application on pineapples, blanching and calcium infiltration on apples, high-intensity electric field pulses (HELP) application on carrots, and dehydrofreezing on apple and kiwi fruits on mass transfer kinetics have been reported (*5*, *8*−*11*).

During pretreatment, changes occur in the cell membranes which play a key role in the changes that occur within the tissue during further processing. The changes in the state of the cell membranes may vary between partial and total permeabilization depending on the treatment (*5*). The application of an external electrical field induces an electrical potential difference across the membrane, which leads to electrical breakdown and local structural changes of the cell membrane, thereby increasing its permeability (*12*). The application of high pressure has also been reported to increase the permeability of cell membranes of food materials, whereas freezing disrupts the cell membranes, resulting in a loss of tissue firmness (*10*, *13*). The extent of cell membrane permeabilization can be described using the cell disintegration index Z_p, which characterizes the proportion of damaged (permeabilized) cells within the cell system. Z_p is the impedance of cells with ruptured membranes and is determined on the basis of the changes in electrical conductivity of the cell system at different frequencies. For intact cells, $Z_p = 0$, and for total cell disintegration, $Z_p = 1$. The theory and determination of Z_p are described by Angersbach et al. (*14*). Further information on cellular integrity can be obtained by measuring the electrical conductivity of the solution in which the food materials is immersed. High conductivity is indicative of leakage of intracellular ions and, therefore, damage to membranes (*11*).

Texture, color, and vitamin C content are common quality indices of fruits and vegetables, and a major result of their processing is the loss of tissue firmness depending on the severity of the process. Freezing may cause severe damage to tissue, resulting in excessive softening, whereas low-temperature long-time blanching prior to freezing has been reported to improve the texture of frozen or dehydrated vegetables (*13*, *15*). Enzymatic browning occurs in fruits and vegetables after bruising or cutting or during storage, leading to the development of unpleasant colors, flavors, and loss of nutrients. Studies on different apple cultivars have shown that susceptibility to browning may depend on polyphenol oxidase (PPO) activity or degradation of phenolic content or both (*16*). The browning effect in apricot cubes was significantly lower in cubes pretreated in concentrated solutions of both sucrose and maltose (*2*). Ascorbic acid loss occurred in the convective air-drying of steam blanched apples and dehydrofrozen kiwi fruits with higher losses occurring with longer drying period (*1*, *8*).

The purpose of this work was to compare the influence of different pretreatments [blanching, freezing, high-

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intensity electric field pulse (HELP), and high pressure (HP), using optimal processing conditions for each pretreatment as recommended in the literature for fruits] on the mass transfer, cell membrane permeabilization, leaching of cellular constituents, texture, color, and vitamin C of osmotically dehydrated apple slices.

MATERIALS AND METHODS

Red Delicious apples purchased from a local supermarket were manually washed, peeled, and cut into circular disks of 38 mm diameter and 8 mm thickness using a knife and a core borer. Immediately after cutting, the apple disks were dipped into a 1% solution of ascorbic acid for 5 min to slow enzymatic browning (*17*). After removal from the solution, the slices were blotted with paper toweling, and initial weight before treatment was recorded. Fresh apple samples had the following initial characteristics: soluble solids, 13.2 ± 0.2%; titratable acid, 0.7 ± 0.08%; ascorbic acid content, 12.6 ± 1.3 mg/100 g of fruit; compressive force, 1540 ± 51 N; and moisture content, 85.3 ± 1.2%. Moisture content was determined by placing samples in a vacuum oven for 18 h at 70 °C. Soluble solids (percent, 25 °C) was measured on an RFM 80 digital refractometer.

Pretreatments. *Blanching.* Blanching was effected by direct immersion of samples in hot water at 60 °C in a water bath for 5 min (*15*).

Freezing. Samples were sealed in airtight polyethylene bags and placed in the freezer overnight at −28 °C. Thawing at room temperature was usually completed between 30 min and 1 h with the samples in the polyethylene bag. This allowed drip water to be reabsorbed by the samples (*8*).

HELP. High voltage from a generator (Pure Pulse Technologies Inc., San Diego, CA) was used to charge the capacitor, which was then discharged at 1 Hz through the samples placed between parallel stainless steel electrodes (spaced 5 cm apart) in tap water. The exponential decay pulses were monitored on line with an oscilloscope (Philips, model PM 3335), and 20 pulses were administered to the samples, each with a pulse duration of 800 μs. The specific energy input per pulse in apple tissue was 154 J/kg, having a field strength of 1.4 kV/cm (*5*, *14*).

HP. The pressure vessel (National Forge Europe) used had a working volume of 700 mL and a maximum recommended working pressure of 600 MPa. Temperature within the pressure vessel was controlled by an external heat exchanger. Samples were subjected to 400 MPa for 10 min at 25 °C (*10*). The pressure was built up in 2 min, and decompression time was ~10 s. A mixture of distilled water and press oil (97:3 v/v) was used as the medium for transmitting pressure.

OD. Weight after treatment was recorded, and the samples were placed in a glass beaker containing a 50 °Brix sugar solution immersed in an agitated water bath at 40 °C. Commercial food grade sucrose was used as the osmotic agent at a ratio 1:25 apple slice to syrup (w/w). OD times of 0−6 h were used (30 min interval for the first 2 h and, after that, readings were taken every hour). At the end of the OD process, samples were taken out of the sugar solution, rinsed in a stream of water to remove adhering osmotic solution, blotted dry (with a paper towel), and weighed. Samples were then dried in the air oven at 80 °C for 27 h to obtain total solids. Experiments were run in triplicates.

Computations of water loss and solute gain during OD were based on the assumption that there was no change in the total insoluble solid content of the samples during immersion (*18*). The following expressions were used in the computations of samples treated before OD:

$$\text{solids gain } (S_g, \text{g/g}) = (M_f - S_t)/S_t \quad (1)$$

$$\text{water loss (WL, g/g)} = [(M_t - S_t) - (M_{od} - M_f)]/S_t \quad (2)$$

$$\text{moisture content (MC, g/g)} = (M_{od} - M_f)/S_t \quad (3)$$

For untreated samples subjected to OD similar equations were used, but S_t and M_t were replaced by S_0 and M_0, respectively.

Examination of Cell Condition through Impedance Measurement. The extent of cell membrane permeabilization was determined using the cell disintegration index (Z_p) (*14*). Impedance measurement of fresh and treated samples at low and high frequencies within the frequency band of 3 kHz and 50 MHz using the impedance measurement equipment (Electronic Manufacture Co., Mahlsdorf, Germany) was carried out. Impedance measurements were conducted after pretreatment and after OD.

Electrical Conductivity of the Osmotic Solution. Electrolyte release during OD and the electrical conductivity of the osmotic solution were measured using a conductometer (model CG 858, Schott Geräte GmbH, Hofheim, Germany). For these tests, a ratio 1:5 (w/w) of apple to sugar solution was used so that the impact of diffused fluid could be detected. In another set of experiments, a total of 10 mL of juice was gradually added to 50 mL of distilled water or 50 °Brix sugar solution and mixed on a magnetic plate stirrer. Electrical conductivity was determined after every addition of 0.5 mL of juice. Apple juice was obtained from crushed samples that were pressed using a hand presser and then filtered through a metal sieve (test sieve DIN No. 24, mesh width 0.25 mm).

Quality Tests. *Color.* Measurements were conducted twice—after OD and after air-drying using a colorimeter (CR-200 Minolta, Minolta Camera Handels GmbH, Ahrensburg, Germany) to obtain the *L*, *a*, and *b* values.

Texture. Firmness of samples was measured using a texture analyzer (model TA-XT2, Stable Micro System, Surrey, U.K.). The maximum deformation force required to compress the sample to a depth of 5 mm on a nonlubricated flat platform using a cylindrical probe (5 mm diameter) was recorded by the texture analyzer and used as a measure of product firmness. The miniature three-point bend rig (HDP/3PB) located on the heavy-duty platform was used to measure the breaking strength (fracture) of the dried samples. The crosshead speed was 1 mm/s.

Vitamin C was determined using the procedure described by Rückemann (*19*).

Statistical Analysis. Statistical analyses were carried out using PlotIT software (*20*). Data were subjected to two-way analysis of variance (balanced design), and means were compared using the Duncan multiple-range test.

RESULTS AND DISCUSSION

Effect of Pretreatments on Percent Moisture and Solid Contents of Samples. MC of samples deviated from initial values after pretreatment (Table 1). Generally, sample solid content decreased after pretreatment with a corresponding increase in the MC. HP-treated samples had the highest solid loss (32.8 ± 3.7% of the initial solids), whereas application of HELP resulted in the lowest loss of solids (13.4 ± 0.4%). The high solid loss associated with the application of HP may be due to the release of fluid, air, and other cellular substances into the environment (polyethylene bag), but some of these were reabsorbed when the pressure was removed. Thawing frozen samples in the polyethylene bags allowed the reabsorption of leached fluid, which increased the MC and reduced the loss due to pretreatment. When leached fluid was allowed to drain during thawing, weight losses were as high as 40%, hence, the adoption of thawing in polyethylene bags. Application of HELP and blanching pretreatments were conducted by direct immersion in water, but the losses are higher in the blanched samples, probably due to heat-induced chemical reactions leading to degradation of cell constituents (*1*, *9*). Apples from the same batch were used for experimentation with the average MC determined, but for mass transfer calculations it was necessary to determine the actual MC of the samples as this would

Table 1. Average Moisture and Solid Contents of Apple Slices before and after Pretreatments before Osmotic Dehydration

	pretreatment			
parameter	blanching (60 °C, 5 min)	freezing (−28 °C overnight)	HELP (20 pulses, pulse width = 800 μs, specific energy input per pulse = 154 J/kg)	HP (400 MPa, 10 min at 25 °C)
initial moisture content, %	85.6 ± 0.1[a]	86.3 ± 0.6	85.7± 0.5	85.3 ± 1.1
initial solid content, %	14.4 ± 0.7	13.7 ± 0.5	14.3 ± 0.6	14.5 ± 1.2
moisture content after treatment, %	88.3 ± 0.9	86.9 ± 0.7	87.2 ± 0.7	89.1 ± 1.2
solid content after treatment, %	11.7 ± 1.2	13.0 ± 0.7	12.8 ± 0.7	10.9 ± 1.4
% initial solids lost due to treatment	20.9 ± 1.5	22.1 ± 2.2	13.6 ± 2.3	32.9 ± 3.7

[a] Mean of three readings ± standard deviation.

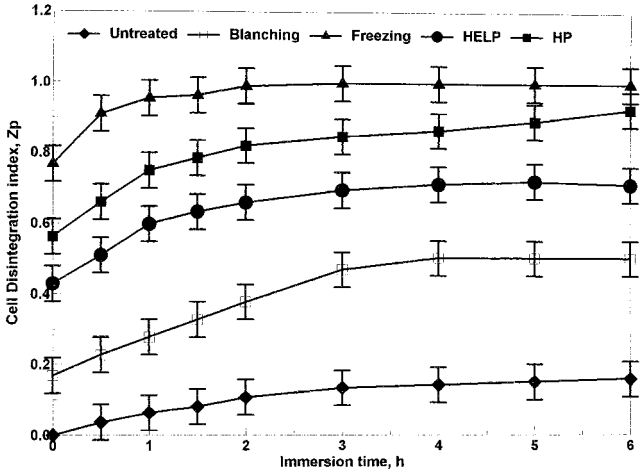

Figure 1. Cell disintegration index (Z_p) of apple slices as affected by pretreatments (blanching, 60 °C, 5 min; freezing, −28 °C overnight; HP, 400 MPa for 10 min at 25 °C; HELP, 20 pulses, pulse width = 800 μs, specific energy input per pulse = 154 J/kg) and osmotic dehydration time.

influence the results, hence, the different initial MC values reported in Table 1.

Extent of Cell Membrane Permeabilization. A Z_p of 0.7 had been reached by prefrozen samples before OD was initiated (Figure 1). Application of HELP and HP induced a $Z_p > 0.4$ and 0.5 in the samples, respectively, whereas a Z_p of only 0.1 had been achieved in blanched samples. Data on the extent of cell membrane permeabilization after pretreatment (at 0 h OD time) confirm earlier reports of cell permeabilization by the various pretreatments studied (*7*, *9*, *10*, *14*). OD time was significant on extent of cell membrane permeabilization only in the first 3 h. There was a small increase in Z_p values (0.1−0.2) with OD time, but the extent of increase was influenced by the pretreatment, suggesting that the osmotic process resulted in only a small proportion of the permeabilized membranes. The increase in permeabilized cell membranes may be a result of the two processes taking place simultaneously during OD, that is, WL (resulting in shrinkage) and solids gain (leading to porosity). Shrinkage and porosity are known to affect the diffusional properties of foods and, thus, may influence cell membrane permeabilization (*1*, *20*, *21*).

WL. Samples subjected to HP lost a greater ($P < 0.0.5$) amount of water than the other pretreated samples up to the fifth hour of OD, whereas prefrozen samples had less ($P < 0.05$) WL than the others (Figure 2a). The prefrozen samples were expected to contain more free water, which should readily diffuse into the osmotic solution, but this was not the case and probable reasons are discussed under solids gain. The higher WL

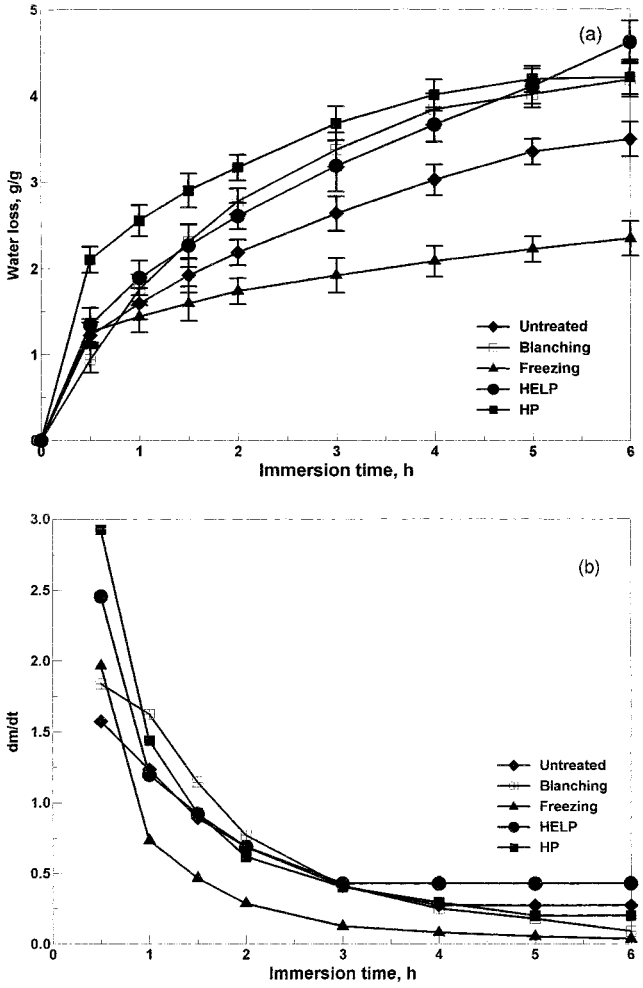

Figure 2. Effect of pretreatments on (a) water loss and (b) rate of change of moisture dm/dt with osmotic dehydration time.

values observed for HP- and HELP-treated and blanched samples agree with earlier reports (*10*, *18*). High WL values by blanched samples were attributed to loss of material associated with damage of cellular tissue caused during blanching, whereas application of HP was reported to have damaged the cell wall structure of pineapple tissue, leaving the cells more permeable, which enhanced solute transfer (*10*, *18*). For all treatments studied, WL increased with OD time (Figure 2a). After 3 h of OD, the rate of change in MC, dm/dt (Figure 2b), had stabilized to ∼0.43 in HELP-treated samples, whereas the rate of change in others continued to decrease, and in some dm/dt tended to zero. By the third hour of OD, ∼54.9% (HELP), 63.4% (HP), 33.1% (freezing), 58.2% (blanching), and 45.4% (untreated) of the initial moisture had been released by the samples;

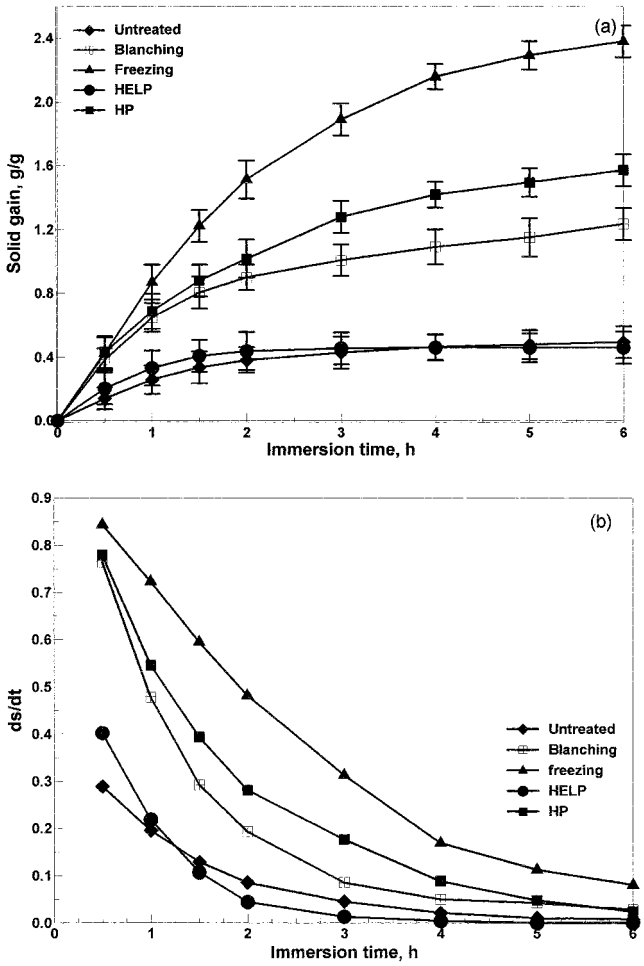

Figure 3. Effect of pretreatments on (a) solid gain and (b) rate of change of solid gain ds/d*t* with osmotic dehydration time.

however, by the sixth hour, the amount of WL had increased by about 7.4 and 24.8%, such that 79.7% (HELP), 72.6% (HP), 40.5% (freezing), 72.2% (blanching), and 60.3% (untreated) of the initial water had been released. The low rate of change in prefrozen sample after the third hour of OD may account for high moisture retention by these samples. These results confirm that pretreatments such as blanching, HP, and HELP increase WL during OD, but the optimal OD time is influenced by pretreatment. Influence of pretreatment was distinct on d*m*/d*t* within the first hour of OD (Figure 2b), after which there was no difference in the rate of moisture loss. The initial difference may be attributed to differences in the extent of cell membrane permeabilized due to pretreatment (Figure 1), but as OD progresses, accumulation of sugar on the product surface minimizes the impact of cell membrane permeabilization.

Solids Gain (S_g). HELP-treated samples had similar gains in solids as the untreated samples, and both of these were lower ($P < 0.05$) than those of HP, frozen, and blanched samples (Figure 3a). It has been reported that these pretreatments increase the permeability of cell membranes, which increases diffusivity of solutes (*8*, *10*, *20*). Application of HELP also increases permeabilization of the cell membrane, but its effect on solids gain is very minimal. This result suggests that solids uptake during OD may not necessarily be a function of permeabilized cells only but may also depend on the type of chemical and structural changes caused by the pretreatments. Sharma et al. (*1*) reported that more sugar penetrated into blanched apple rings than into nonblanched samples. They suggested that cell wall membranes of fruits being living biological units stretch and expand under turgor pressure generated inside the cells. When blanching is done, the semipermeability of the membrane is disturbed, which results in a higher intake of solute from the osmotic solution. The application of HELP causes electrophysical changes in the cells resulting in separate permeabilization of the plasma membrane or the tonoplast (*14*). It appears that this selective permeabilization may cause structural changes that favor the transfer of water across the membranes while limiting solid uptake.

The amount of solids gained increased with OD (Figure 3a), but the rate of solids uptake (Figure 3b) reduced with time. At the end of the third hour of OD, percent sugar in the samples was about 31.2% (HELP), 56.1% (HP), 65.4% (prefrozen), 30.0% (untreated), and 50.1% (blanched). By the sixth hour, percent sugar in HELP-treated samples was unchanged, whereas these values of other samples increased by 2−5%. This suggests that optimal sugar uptake is within the first 3 h of OD. For HELP-treated and untreated samples, solids gain was minimal after the third hour of OD (Figure 3), but there was continued WL to the system. The reverse was observed for frozen samples, for which WL after the third hour was minimal (Figure 2 and the rate of change approached zero), but solids uptake continued as OD progressed. Some authors have reported the formation of a dense superficial layer of solute from the soaking solution, which could block the escape of fluids contained in the fruit. The sugar accumulates on the sample periphery, upsetting the osmotic gradient process and decreasing the driving force for water removal. In addition, the sugar poses an additional resistance to mass exchange (*21*−*23*). The high sugar uptake by prefrozen samples during OD (Figure 3a) may account for the low WL by these samples, which agrees with the low rate of change d*m*/d*t* (Figure 2b). The solids uptake during OD has been reported to accumulate in the intercellular spaces and does not diffuse to the inner core of the samples (*7*). This may explain the lack of impact of permeabilized cell membranes. It is probable therefore that continued sugar uptake by prefrozen samples accumulated at the surface of the samples, and as solids uptake increased with OD time, the thickness of the solid layer increased, which affects the diffusion of water to the osmotic solution, hence resulting in high water retention by prefrozen samples (Figure 2a) and the low rate of change (Figure 2b).

Leaching of Cell Constituents into the Osmotic Medium. Leaching of cell constituents (electrolytes) into the osmotic medium was monitored by measuring the electrical conductivity (σ) of the medium. Conductivity of the osmotic medium increased with OD (Figure 4). Solutions of pretreated samples had higher σ values than the solution containing untreated samples, with HP-treated and prefrozen samples releasing the highest concentration of electrolytes into the osmotic solution. Electrical conductivity has been described as an index of cellular integrity indicative of leakage of intracellular ions and, therefore, damage to cell membranes (*11*), and this is confirmed by results in Figure 4. As more cells are permeabilized, the amount of electrolytes and ions leached into the osmotic solution increased. Untreated samples had the lowest proportion of permeabilized cell

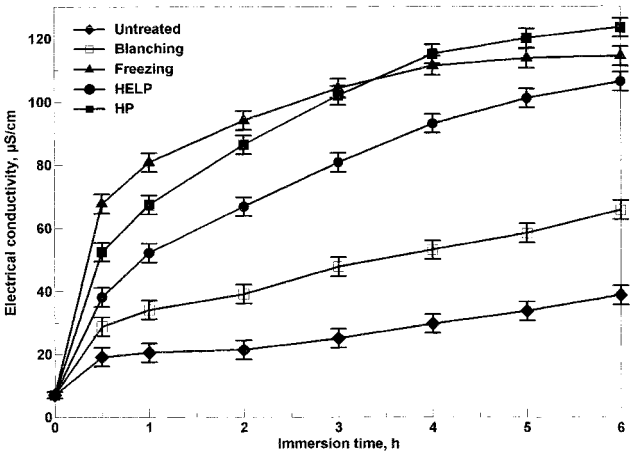

Figure 4. Influence of pretreatments on the electrical conductivity (σ) of the osmotic solution of apple slices with osmotic dehydration time.

membrane (Figure 1), and they show a corresponding low σ value in Figure 4.

Linear regression showed a better relationship between WL and σ values (r^2 of 0.940−0.995) than between σ and solids gain (r^2 of 0.837−0.987). This is not unexpected because the leached electrolytes are transported in the water being released. After 6 h of OD, the samples were crushed (using a pestle and mortar) for complete disruption of the cell membranes, representing 100% electrolyte leakage (*11*), and the final readings in the osmotic solution were taken. The results obtained (data not shown) showed that prefrozen and HP-treated samples had released most of the available/free electrolytes in the sample by the sixth hour of OD, whereas solutions of untreated, HELP, and blanched samples had higher σ values. By the sixth hour of OD, untreated samples still retained 75%, blanched 49%, and HELP-treated samples 25% of the possible electrolytes that could have been released into the osmotic medium. Juice from the untreated sample had a σ value of 2100 ± 25 μS/cm. Comparing this value to those in Figure 4 reveals that <8% of the available electrolytes in the juice is actually leached during OD. This agrees with the report that solid loss from sample during OD is negligible (*18*). Distilled water had a σ value of 7 μS/cm, and a 50 ° Brix sugar solution had a σ value of 5 μS/cm. Gradual addition of distilled water (0.5−10 mL) to a 50 °Brix sugar solution changed the σ value from 5 to 7 μS/cm. Addition of apple juice to a sugar solution increased its σ from 5 to 124 μS/cm at 40 °C, whereas the σ value of a water−juice mixture changed from 7 to 544 μS/cm (Table 2). Electrical conductivity of a sugar solution is influenced by the concentration and composition of ions and also the viscosity of the solution (*25*). The mixture of juice and water had a low σ value probably because of the diluting effect of water, but as the volume of juice increased in the mixture, σ increased. It has been reported that sugar molecules in solution interact with the ions, thereby limiting the amount of ions in solution that could be detected during measurement (*25*, *26*). This may account for the low σ values of sugar−juice mixtures compared to those of water−juice mixtures. The purpose of the above exercise was to investigate the possibility of a relationship between the volume of water released during OD and the corresponding σ value and to determine if this was comparable to that of a juice−sugar mixture. The results (Figure 4 and Table 2) agree with those of Schneider

Table 2. Influence of Systematic Addition of Apple Juice to Distilled Water or Sugar Solution on the Electrical Conductivity Value of the Resulting Mixture

	electrical conductivity, σ, μS/cm at 40 °C	
vol of apple juice in mixture, mL	apple juice in water[a]	apple juice in 50° Brix sugar solution[a]
0.0	7	5
0.5	62	15
1.0	103	21
1.5	143	27
2.0	183	34
2.5	220	39
3.0	254	44
3.5	281	51
4.0	303	56
4.5	331	61
5.0	355	67
5.5	376	74
6.0	394	79
6.5	416	85
7.0	432	89
7.5	449	96
8.0	476	102
8.5	497	106
9.0	513	112
9.5	530	119
10.0	544	124

[a] Initial volume = 50 mL.

(*25*) that the electrical conductivity of a solution is a function of viscosity (WL), composition, and concentration of ions in solution. Heat-induced enzymatic reactions during blanching lead to production of free carboxyl groups, which can bind Ca^{2+} and Mg^{2+} ions in the tissue (*4*, *26*, *27*). The binding of these ions prevents their release into the osmotic solution and may contribute to the low σ values observed for solutions containing blanched samples (*27*−*29*).

Texture. The maximum compressive force of pretreated samples (without OD) was lower than that of fresh apple, but the extent of reduction depended on the treatment (Figure 5a). Similar results have been reported for kiwi and apple (*4*, *8*). A significant decrease of the maximum force values after freezing indicated damaged fruit tissues, partly due to formation of ice crystals during freezing. When water is frozen at atmospheric pressure, ice is formed and the volume increases during phase transition, which is a cause of histological damage in tissues (*8*, *30*).

Within the first 3 h of OD, the influence of pretreatment was significant; when OD was extended beyond this period, there was no difference ($P > 0.05$), but the values reduced with time. Monslave-Gonzalez et al. (*4*) reported a similar observation that softening occurred during the first 2 h of treatment, after which the force ratio remained practically unchanged (*4*). Untreated and blanched samples had higher maximum force than those of other treatments, which agrees with the results of other studies which reported that blanched apple and carrot samples showed decreased texture compared to the control (*4*, *9*, *30*, *31*).

Prefrozen samples showed an initial decrease ($P < 0.05$) in the maximum force and then increased with further OD. The initial decrease may be related to the phase in which the free water in the frozen sample is released. However, higher maximum force with longer OD time may be attributed to the effect of sugar uptake. At higher OD time for prefrozen samples, the rate of water loss reduced while sugar uptake increased (Figure 3). This agrees with the report that the presence of

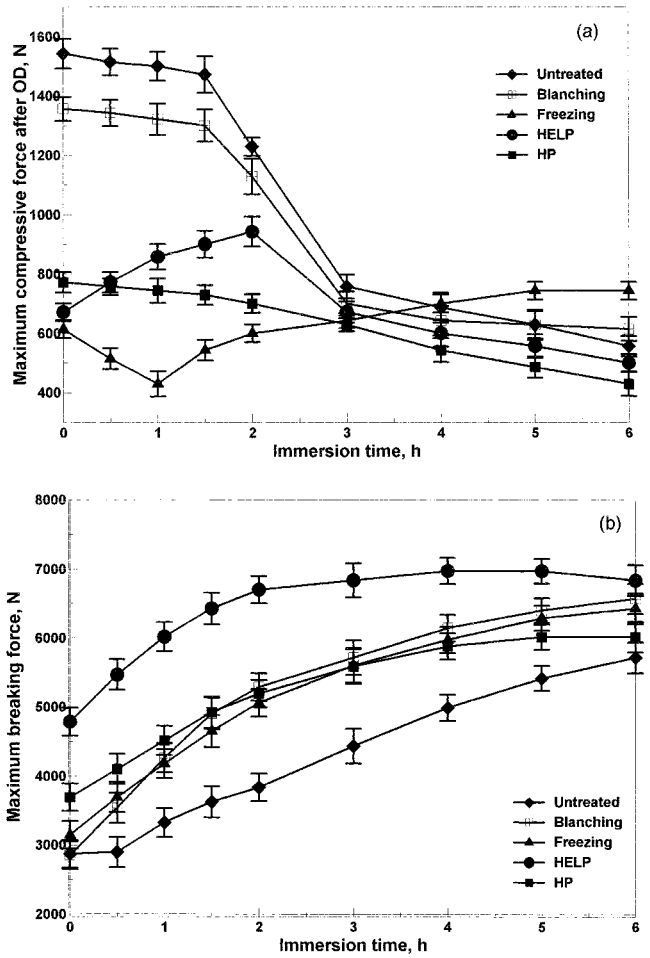

Figure 5. Maximum force of (a) nondried and (b) dried apple slices subjected to different pretreatments and different osmotic dehydration times.

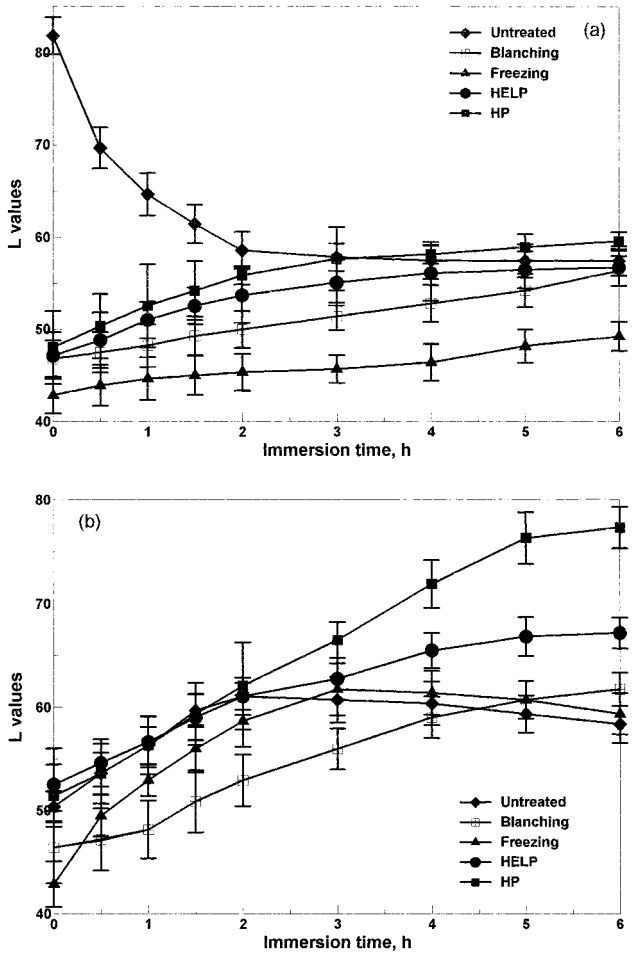

Figure 6. Values of (a) nondried and (b) dried osmotically dehydrated apple slices as influenced by different pretreatments and different osmotic dehydration times.

sugars increased firmness of thawed apple samples (*11*), and Monsalve-Gonzalez et al. (*4*) reported that softening correlated significantly with sugar uptake. SEM revealed that cells protected by sugars exhibited less damage to the middle lamella and less severe shrinking of the cell content (*2*).

Rastogi and Niranjan (1998) reported that the application of HP on pineapples damaged cell wall structure, leaving the cells more permeable with a reduction in intercellular material. This reduction in cellular materials, as confirmed in Table 1, may account for the difference in texture between treated and the untreated samples (Figure 5a), but it may be observed that the effect of prolonged OD on texture of these samples was not significant compared to those of blanched or untreated samples. HELP-pretreated samples, after the initial decrease in maximum force due to treatment, showed an increase in maximum force with OD time up to 2 h, after which it decreased. This trend corresponds to the sugar uptake pattern, which increased in the first 2 h of soaking and then leveled off while water continued to be released from the sample.

The maximum force required to fracture the dried samples (Figure 5b) was influenced by both the pretreatment applied and OD time. For all pretreatments, the maximum force increased with increasing OD time, but the rate of increase decreased after 3 h. This increase in maximum force with OD time may be attributed to higher sugar uptake. The pretreated samples had higher maximum force than the untreated. HELP-treated samples had the highest maximum force, whereas there was no difference in those of HP-treated, blanched, or frozen samples. Linear regression analysis showed a good relationship between solids gained and breaking force for the dried samples. The r^2 values ranged between 0.969 and 0.995 for pretreated samples, whereas untreated samples had an r^2 value of 0.794. This result indicates that combining pretreatment with OD will result in dried products of hard texture that can withstand further handling and processing. The force values for dried samples (Figure 5b) are much higher than those of the osmotically dehydrated samples (Figure 5a), which agrees with the report that air-drying results in higher maximum forces (*8*).

Color. Browning in apple samples occurred after pretreatment on exposure to air (Figure 6a). Tregunno and Goff (*11*) reported a similar observation: frozen or blanched apple samples had low *L* values due to severe enzymatic browning before the OD process. The brightness of untreated samples decreased with OD time up to 2 h, after which the color remained stable. Pretreated samples, on the other hand, had higher *L* values as OD time increased. Browning could be enzymatic or nonenzymatic. Enzymatic browning occurs in fruits and vegetables after cutting as a result of oxidation of phenolic compounds by PPO in the presence of oxygen into quinones (*16*). The *o*-quinones of various phenolic compounds have great differences in stability and undergo subsequent reactions (i.e., oxidation and polymerization) leading to dark pigments. Two steps have

Table 3. Vitamin C Content of Pretreated Apples Osmotically Dehydrated for Different Durations

	vitamin C content, mg/100 g of fresh fruit, after osmotic dehydration time of			
pretreatment	0 h	2 h	4 h	6 h
untreated	10.8 ± 0.5[a]	5.4 ± 0.4	2.8 ± 0.4	1.2 ± 0.4
blanching				
freezing	4.1 ± 0.2	1.5 ± 0.4	0.8 ± 0.2	0.3 ± 0.2
HELP	10.3 ± 0.8	4.7 ± 0.5	1.1 ± 0.5	0.5 ± 0.4
HP	7.4 ± 0.3	4.3 ± 0.5	2.6 ± 0.5	1.5 ± 0.3

[a] Mean of three readings ± standard deviation.

been suggested in the nonenzymatic browning of processed foods: the first consists of browned polymeric compound formation, and the second is decomposition of these brown pigments to give colorless compounds (*32*). These authors reported that the activation energies for colorless browning intermediate formation increased as glucose concentration and temperature increased, and the higher the activation energy, the higher the degradation of the brown pigments to the colorless compounds. This phenomenon may account for the higher L values at longer OD time, which implies more sugar uptake. This agrees with the results of Torreggiani and Bertolo (*2*), who found that the browning effect was significantly lower in apricot cubes pretreated in concentrated solutions of sucrose and maltose than in untreated samples.

Figure 6b compares the L values (brightness) of the dried samples. For all of the treatments studied, L values increased with OD up to 3 h. The L values of dried blanched and untreated samples osmotically dehydrated for >3 h leveled off while those of HP, HELP, and frozen samples continued to increase. Air-drying improved the brightness of the pretreated osmotically dehydrated samples. Samples (treated and untreated) not osmotically dehydrated darkened upon drying, which is similar to the report that kiwi fruits not subjected to OD darkened upon air-drying (*8*).

Vitamin C. Fresh apple had an average vitamin C content of 12.6 ± 1.2 mg/100 g of fresh fruit, and Table 3 shows the vitamin C content of apple samples subjected to different operating conditions. Dried untreated (and no OD) samples had lower vitamin C content compared to the fresh sample. This agrees with the report that ascorbic acid loss occurred during air-drying process (*8*, *33*). The effect of OD time was similar for all of the pretreatments: the longer the OD time, the lower the vitamin C content, similar to the result of Jayaraman et al. (*33*). HELP-treated samples had vitamin C contents similar to those of untreated samples in the absence of OD. The order of magnitude of the effect of pretreatment on vitamin C is untreated > HELP > HP > freezing > blanching. The vitamin C content of blanched samples was not discernible, which may be attributed to thermal degradation during blanching. It should be noted that between 4 and 6 h of OD, the vitamin C content of HP-treated samples was higher than that of HELP-treated samples. This may be due to the fact that HP samples had higher sugar uptake in this time range of OD, whereas sugar uptake by HELP-treated samples had leveled off (Figure 3a), and it has been reported that the presence of sugar stabilized vitamin C in samples (*2*). Hence, the higher sugar uptake in this time range may be responsible for vitamin C retention.

Conclusion. HP and HELP facilitated more water loss during OD, but the influence of pretreatment was more distinct on rate and extent of sugar uptake during OD. Application of HELP is advantageous when moisture reduction and minimal alteration in product taste are desired due to minimal sugar uptake, whereas HP may be considered when product formulation through sugar uptake is desired. Although browning occurred after pretreatment, color improved with OD, especially in HP- and HELP-treated samples, which had brighter color than the untreated. Thus, application of HP and HELP as pretreatments may be considered in the production of dehydrated apple products as they yielded good-quality products having firmer texture, brighter color, and better retention of vitamin C compared to samples that were either blanched or prefrozen.

ABBREVIATIONS USED

S_g, solids gain; σ, electrical conductivity, μS/cm; WL, water loss; Z_p, cell disintegration index; MC, moisture content; HELP, high-intensity electric field pulse; HP, high pressure; OD, osmotic dehydration; M_0, sample weight before pretreatment, g; M_t, sample weight after treatment, g; M_{od}, sample weight after osmotic dehydration at time t, g; M_f, final weight of dried sample, g; S_0, initial solid content, g; S_t, solid content of sample after pretreatment, g.

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