Abstract: The effects of calcium pretreatment, vacuum level, and apple variety on the texture of apple chips, processed using a combination of air drying and vacuum microwave dehydration (VMD), were determined. Pretreatment of apple slices by immersion in 1-5% aqueous CaCl₂ significantly increased crispness of chips as determined by instrumental and sensory analysis; however above 1%, chips were perceived as bitter. Higher vacuum applied during VMD significantly lowered density and increased crispness of chips. This effect was mediated by the vaporization of water in the interior of the chip, which caused expansion of the tissue. Chips made from Fuji apples had higher calcium contents, and were crisper than Red and Golden Delicious apple chips. Microstructure of the chips evaluated by scanning electron microscopy indicated that chips with thicker cell walls and large internal voids were crisper.

Keywords: vacuum microwave dehydration, apple chips, calcium, texture, structure
All other chemicals were of reagent grade.

Sample Preparation

Part 1. Calcium Pretreatment. 1 kg of Golden Delicious apples was prepared for each drying process. Apples were washed, sliced to a thickness of 4 mm, steam blanched for 2 min and immediately dipped in 0, 1, 2, 3, 4, or 5% calcium chloride solutions at room temperature with constant stirring for 1 min. Excess solution was shaken from the slices. Apple slices were air dried on a Vers-a-belt dryer (Wal-Dor Industries Ltd., New Hamburg, Ontario) at 70 °C with an air flow rate of 1.1 m³/min for about 30 min to a moisture content of ~50% on a dry weight basis (db). Samples were then placed in the high-density polyethylene drying drum in a 2 kW maximum power microwave vacuum chamber (EnWave Corp., Port Coquitlam, B.C.). The drum was rotated at a rate of 5 revolutions per minute. After a vacuum of 28 inches of Hg was achieved, samples were vacuum microwaved dried at a microwave power of 1.5 kW for 4 minutes followed by an additional 1 min to 2 minutes, until a final moisture content of ~5% db was obtained. Vacuum was maintained in the chamber by a water-ring vacuum pump, model LEMC 60 (Sihi Pumps Ltd., Guelph, Ont., Canada). Dehydrated samples were packed in individual cheesecloth bags, which were then placed in an airtight bag. They were allowed to equilibrate at room temperature for 14 d to the same water activity prior to analysis. All experiments were performed in triplicate.

Part 2. Vacuum Level and Drying Technique. 1 kg of Golden Delicious apples were prepared as mentioned in Part 1, with the following change. Instead of a CaCl₂ solution, all Golden Delicious varieties were used to prepare VMD apple chips as described above in Part 1. Apple slices were air dried for approximately 30 min to ~50% db. The partially dried apple slices were then VMD at vacuum levels of 7, 14, 21, 24, and 28 inches of Hg with a constant microwave power of 1.5 kW to obtain apple chips with a moisture content of ~5% db. Drying times varied from approximately 10 min to 7 in of Hg, to 4 min at 28 in of Hg.

For the study of the effect of drying techniques, preparation of air-dried apple chips were carried out on a Vers-a-belt dryer (Wal-Dor Industries Ltd., New Hamburg, Ontario). Apple slices were air dried for approximately 3.5 h at 70 °C with an air flow rate of 1.1 m³/min to a moisture content of ~5% db. For the preparation of freeze-dried apple chips, apple slices were freeze-dried under vacuum (100 mic Hg) with a chamber temperature of 20 °C and a condenser temperature of ~55 °C for approximately 10.5 h.

Part 3. Apple Varieties. Red Delicious, Fuji, and Golden Delicious varieties were used to prepare VMD apple chips as described above in Part 1, except that blanched apple slices were dipped in 0 and 1% CaCl₂ solutions for 1 min.

Analysis

Moisture Content Determination. Samples, in triplicate, were weighed into pre-weighted, labeled aluminum weigh boats and then dried in vacuum oven at 70 °C and a vacuum level of 27 in of Hg for 16 h. Upon completion of the drying, weight boats were cooled in a desiccator and weighed. The moisture content of the sample on a dry weight basis (% db) was then calculated from the difference between the wet and dry weights divided by the dry weight of the sample.

Calcium Content Analysis: Apple chip samples (~1 g) were ashed in a muffle furnace at 500 °C for 24 hours so that only white ash remained. The residues were cooled and dissolved in 5 ml of 6N HCl. The suspension was warmed to effect a complete solution. The samples were then diluted with 1% LaCl₃ solution (Fisher) and analyzed for calcium content with a Perkin Elmer Atomic Absorption Spectrophotometer (Woodbridge, Ont., Canada). All calcium values were reported on a dry weight basis.

Instrumental Textural Analysis: The TA XT2 Texture Analyzer (Stable Micro System Ltd., Surrey, England) was used to measure the slope (g/mm) of the first peak produced during the punch and die test. Each chip samples was centered on a metal base with a 1 cm hole, and a circular, flat ended punch (5 mm diameter), moving at 7.0 mm/sec was used to break the chip. The slope of the first peak recorded in the force/deformation curve was calculated from the baseline to the peak height, using the software, XT.RA Dimension (Version 3.7) (Stable Micro System Ltd., Surrey, England). The slope of the first peak was essentially linear from baseline to the peak height. 15 measurements were obtained from each of 3 replicate samples. Therefore, the slope values were the mean of 45 measurements.

Density: The density of apple chips was measured by immersing the weighed samples (~20 g) in a 500 ml graduated cylinder pre-filled with 200 ml of dried flax seed, followed by tapping the cylinder lightly against the counter top until no volume change was observed. Volumes were obtained by measurement of the flax seed displacement. The data were expressed as the weight of sample (g) per volume (ml). Measurements were performed in triplicate.

Scanning Electron Microscopy (SEM): The structure of the dehydrated apple chips was examined using scanning electron microscopy. Apple chips were first dipped in liquid nitrogen and then immediately fragmented into small pieces. Apple chip fragments were attached to SEM stubs and subsequently coated with gold (~25 nm), using the Nanotech SEMPREP II Sputter Gold Coater, and, finally, stored under desiccation (1 to 2 days) until examined by the scanning electron microscope (Stereoscan 250, Cambridge Instruments Ltd., Cambridge, UK). Polaroid pictures were taken and processed as specified by the manufacturer.

Sensory Evaluation of Crispness: Quantitative descriptive analysis (Stone and others 1974) was carried out to determine the effect of calcium pretreatment on bitterness, and calcium pretreatment and apple variety on the crispness of apple chips. Panelists with sensory evaluation experience were recruited from the staff and students of the University of British Columbia. Selected panelists were then trained in sensory descriptive evaluation. The sensory analysis was carried out in triplicate. Commercial deep fried Golden Delicious apple chips (Seneca Foods Corp., Marion, N.Y., U.S.A.) were provided as a reference standard for moderately crisp chips. Panels were conducted under red fluorescent light to minimize the effect of the apple chip color on the assessment of the texture attributes.

The panelists were asked to bite through the whole samples with their front teeth to evaluate the crispness. A 15 cm unstructured line scale, with anchor points at 1.5 cm from each end and at the midpoint was used to evaluate the sensory crispness. Panelists indicated the intensity of each attribute by making a vertical line across the unstructured line. Quantitation was made by measuring the distance from the left end point of the line to each point marked by the panelist.

Statistical Analysis: Data were analyzed using ANOVA (Minitab Inc., State College, Pa., U.S.A., 1994). Data for calcium levels of chips made from Fuji, Red Delicious, and Golden Delicious apples in Part 3 was log transformed prior to statistical analysis.
analysis due to non-homogeneity of the variance. Differences among mean values were established using Tukey’s multiple comparison test (Peterson 1985). Mean values were considered significantly different when $P \leq 0.05$. Pearson correlations were done on treatment means.

Z-Score Transformation of Data from Sensory Analysis: The significant panelist effect was observed when statistical analysis of the sensory results was carried by ANOVA. It was observed that the panelists were using different parts of the scale during the sensory trials. Therefore, in order to standardize the sensory scores from different panelists, z transformation using Equation (2) was then performed on the sensory data, as described by Reid and Durance (1992).

$$z = \frac{(x - X)}{s.d.} \quad (2)$$

where $z$ is the transformed score, $x$ is the actual scores from a panelist for a sensory attribute, $X$ and s.d. are the mean and the standard deviation of all the sensory scores for that sensory attribute from the same panelist, respectively. The transformed scores (that is, $z$ scores) were calculated and analyzed statistically using ANOVA to assess the effect of different treatments on the sensory crispness of the apple chip products.

Results and Discussion

The Effects of Calcium Pretreatment

Dipping the apple slices in solutions with increasing calcium chloride ($\text{CaCl}_2$) concentration resulted in apple chip samples with higher calcium (Ca) content (Figure 1). At the lower (0 to 2%) $\text{CaCl}_2$ concentrations, a linear increase in Ca content of chips was observed. At the higher $\text{CaCl}_2$ concentrations (3 to 5% $\text{CaCl}_2$), the increase in sample Ca content was still linear but with a much lower slope than in the lower $\text{CaCl}_2$ concentration range. This was probably due to the saturation of available Ca binding sites in the samples.

Increasing the Ca content of the VMD apple chips resulted in significantly higher slope readings of the force/deformation curve in instrumental analysis and crispness ratings by sensory analysis (Figure 2). It has long been known that Ca confers rigidity to cell walls and appears to serve as an intermolecular binding agent that stabilizes pectin-protein complexes of the middle lamella in plant tissue (Demarty and others 1984; Dey and Brinson 1984; Fry 1986; Grant and others 1973). In previous studies, it was observed that infiltration of calcium into apples resulted in the immediate deposition of calcium at the cell wall site (Glenn and Poovaiah 1990; Monsalve and others 1993; Siddiqui and Bangerth 1996) and promoted cross-linking of pectic polymers.

ANOVA of the raw sensory crispness scores indicated a significant panelist effect and a Ca pretreatment by panelist effect. It was noted that despite training and use of references samples, panelists tended to use different portions of the line scale; therefore $z$ transformation was used to force all panelist scores into the same scale. The sample Ca content was observed to be highly correlated to both the $z$ scores of sensory crispness ($r = 0.954$, $p = 0.001$) and the instrumental compression slope ($r = 0.976$, $p = 0.000$). The extensive cross-linking of pectic polymers by Ca facilitated the formation of a cell wall network with increased mechanical strength. However, increasing sample Ca content above 22800 $\mu$g/g db did not result in an appreciable increase in either the sensory crispness rating or the instrumental slope readings. Further, while chips dipped in 0 or 1% $\text{CaCl}_2$ were not perceived as having a bitter taste, the 2% or higher $\text{CaCl}_2$ treatments resulted in a significant ($p < 0.05$) increase in bitter perception in the chips (Figure 3). Therefore, the application of a 1% $\text{CaCl}_2$ pretreatment to the apple slices was selected to produce apple chips with a significant increase in crispness but without a detrimental effect on the taste.

Crispness is a desired textural characteristic of chips. It has been reported that crispness is characterized by resistance to deformation under load up to the point of sudden fracture, and that this characteristic can be best measured by the slope of the force/deformation curve (Bourne and others 1966). This was in agreement with what was observed in this experiment where the instrumental slope of the

![Figure 1](image1.png)

**Figure 1**—Calcium content of Golden Delicious apple chips vs %$\text{CaCl}_2$ in pre-drying dip. $n = 3$. Error bars represent the standard error of the mean.

![Figure 2](image2.png)

**Figure 2**—Mean slope of the force deformation curve ($\bullet$) and mean crispness $z$ scores ($\square$) of VMD apple chips with different calcium content. For each attribute, any 2 values not followed by the same letter are significantly different at $p 0.05$. Error bars represent the standard error of the mean. $n = 45$ for instrumental texture. $n = 21$ for crispness. Mean, raw crispness scores are recorded in brackets.
force/deformation curve was found to be highly correlated ($r = 0.997$, $p = 0.000$) to the sensory crispness of the apple chips. Therefore, the slope of the force/deformation curve was used as a measure of sensory crispness of apple chips in other experiments.

The effect of Ca on apple chip structure was observed under the scanning electron microscope. The untreated (0% CaCl₂) apple chip tissue had a honeycomb structure constructed of closely connected cells (Figure 4a). In contrast to the thin and smooth cell wall structure observed in the untreated apple tissue, that of the Ca-pretreated tissues was thicker, and result in a more irregular network (Figure 4b). Instead of a net-like pattern, cell wall breakage resulted in large open structures in the Ca-pretreated tissues and yielded chips with a crisper texture. In the Ca-pretreated apple tissues, the rigidity of cell wall structure conferred by the cross-linking of Ca ions to pectin resulted in an increase in the strength and a decrease in the flexibility of cell walls. Therefore, with the same amount of expansion force provided by water vapor generated during VMD, a greater loss of the original apple structure was observed in the Ca-pretreated apple chips. Also, the increase in cell wall rigidity may have prevented the collapse of sample structures during de-hydration.

### Effects of Vacuum Levels and Drying Techniques

An inverse linear relationship ($r = -0.910$, $p = 0.04$) was found when apple chip density was regressed against vacuum level (Figure 5). When a higher vacuum level was employed during vacuum microwave drying, a larger puffing effect was obtained, thus leading to a less dense apple chip product. Previous studies demonstrated that the structure of carrot slices (Lin and others 1998) and potato slices (Durance and Liu 1996) could be puffed and expanded by vacuum microwave drying, and the extent of puffing was dependent on the vacuum level employed (Durance 1997). During vacuum microwave heating, the absorption of microwave energy by water molecules results in vaporization of water within the chip at a higher rate than diffusion to the surface. As a result, a large vapor pressure differential between the center and surface of products is obtained. The lower the pressure in the chamber during the VMD process, the higher the pressure differential, resulting in a greater outward force causing the apple chips to expand. Vickers and Bourne (1976) demonstrated that a crisp food product probably consists of cells or cavities which are usually filled with air and a structural phase or cell walls that are formed by a brittle matrix. Materials with these characteristics will produce crisp sounds that arise from collective breaking of individual cells. Therefore, it seems that puffing is an important component contributing to crisp texture in a dried food product (Torreggiani and others 1995).

A positive and significant linear relationship was found between the slope of the force/deformation curve and the vacuum level employed during VMD ($r = 0.911$, $p = 0.04$) (Figure 5). This indicated that a crisper texture was obtained when higher levels of vacuum were employed. Also, the slope of the force/deformation curve obtained by apple chips was found to be highly correlated to the chips’ densities ($r = -0.986$, $p = 0.002$). Hence, with the application of higher vacuum levels, crisper apple chips were obtained as a result of a greater degree of puffing.

In evaluation of the effect of drying techniques on texture of apple chips, only chips produced from the highest level of vacuum, 28 in Hg (that is, VMD chips with highest crispness) were used for comparison to the air and freeze-dried ones (Table 1). Due to the puffing effect provided by vacuum microwave drying at 28 in Hg, the density of vacuum microwave dried (VMD) apple chips was significantly lower than that of air-dried (AD) apple chips. Freeze-dried (FD) apple chips had the lowest mean density among the dried samples, but this was not significantly different from VMD chips ($p > 0.05$). During air drying, as the total water content is reduced, the liquid interface passes through the surface and creates very high surface tension forces that caused progressive contraction of the samples, and eventually shrinkage of tissue structures (Stanley and Tung 1976). Apples do not have the solid matrix to resist this collapse. However, during freeze-drying, the frozen apple slices remain rigid and moisture is sublimed directly from a solid state to a vapor state. This rigidity to a large extent prevents the collapse of the solid matrix after drying (Liapis 1987), leaving numerous voids within the structure. However, FD apple chips, with their very porous structure, were spongy and not crisp. The smallest slope among the dried samples was obtained by the FD chips samples in the instrumental test indicating that these chips were the least crisp (Table 1). The peak slope obtained by VMD apple chips was significantly higher than that of AD apple chips. Apart from tissue shrinkage, the diffusion of solutes during air drying may have an effect on the chip texture. In the early stages of drying as moisture is removed from the surface of the sample, removed moisture is replaced by the

### Table 1—Density and compression slope of dried apple chips

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Density 1,2</th>
<th>Compression Slope 1,3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Microwave Dried</td>
<td>0.19 (0.02)</td>
<td>989 (79)</td>
</tr>
<tr>
<td>(28 inches Hg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeze Dried</td>
<td>0.14 (0.02)</td>
<td>367 (21)</td>
</tr>
<tr>
<td>Air Dried</td>
<td>0.43 (0.06)</td>
<td>824 (64)</td>
</tr>
</tbody>
</table>

1 All measurements are recorded as mean (standard error). Any two values not followed by the same letter were significantly different at $p < 0.05$.
2 $n = 3$
3 $n = 45$
migrating liquid water from the interior of the sample. A layer of soluble solids is then left and builds up on or near the external surface of the product. This would then increase the resistance to further escape of water from the product’s interior, and eventually causes the formation of a tough, leathery skin described as ‘case hardening’ (Hanson 1976). Effects of different drying methods and vacuum levels on apple chip structure were observed under the scanning elec-

Figure 4—Scanning electron micrographs of apple chips. A. Golden Delicious vacuum (28mm Hg) microwave dried apple chips with 0% CaCl₂ pretreatment. B. Golden Delicious vacuum (28mm Hg) microwave dried apple chips with 1% CaCl₂ pretreatment. C. Golden Delicious air dried apple chips with 0% CaCl₂ pretreatment. D. Golden Delicious low vacuum (7mm Hg) vacuum microwave dried apple chips with 0% CaCl₂ pretreatment. E. Golden Delicious freeze dried apple chips with 0% CaCl₂ pretreatment. F. Red Delicious vacuum (28 mm Hg) microwave dried apple chips with 0% CaCl₂ pretreatment.
tron microscope. After air-drying, apple chips exhibited severe tissue shrinkage and collapse, with almost no open structures (Figure 4c). The structure of the VMD apple chips at 7-mm Hg vacuum level was similar to that of the air-dried ones, except that a small amount of open structure could still be observed (Figure 4d). The less severe shrinkage in the VMD (7-mm Hg) apple tissue compared to that of the AD sample may be due to the shorter drying time, lower drying temperature (maintained at less than 60 °C), and some tissue expansion from internal water vapor. In contrast, with the application of full vacuum, the VMD (28-mm Hg) apple chip tissue exhibited less shrinkage (Figure 4a); a honeycomb network structure of closely connected, and puffed cells were observed. A similar honeycomb network was observed in the freeze-dried sample, which exhibited the least amount of tissue shrinkage or cell collapse (Figure 4e). The cell walls of freeze-dried samples looked comparatively smoother and thinner than those of the VMD samples, explaining the non-crisp and spongy texture obtained by the freeze-dried apple chips.

The Effect of Apple Variety

Instrumental tests were carried out for the textural analysis of Golden Delicious, Red Delicious, and Fuji VMD chips. Calcium treatments (0 & 1% CaCl₂) were performed on each apple variety. The 1% CaCl₂ treatment was chosen in order to give a significant increase in crispness without a significant increase in bitterness of the chips. The 1% CaCl₂-pretreated apple chips of all apple varieties were significantly crispier, as indicated by a higher compression slope than their non Ca-pretreated (0% CaCl₂) ones (Table 2). This is consistent with results presented in Part 1.

Despite the different intrinsic calcium levels, there was no difference in the crispness of chips of different varieties given the 0% CaCl₂ treatment. For Ca-pretreated samples, Fuji apples yielded chips with significantly higher slope, and therefore crispness, than the Ca-pretreated Golden Delicious, and the Red Delicious apples. Further, the calcium content of the Fuji apple chip before the calcium pretreatment was found to be higher than that of the Golden Delicious and the Red Delicious chips. The same trend was observed for apple chips after the calcium pretreatment. This may be due to Fuji apples containing higher amounts of pectin, and therefore more calcium binding sites, than the other two varieties. As found in Part 1, calcium content was highly correlated to the instrumental slope (r = 0.857, p = 0.03) of the chips.

The microstructure of the chips of different apple varieties was also studied. The Ca-pretreated (1% CaCl₂) chip samples made from Red Delicious and Fuji varieties were observed to have thicker cell walls and larger empty regions than the nontreated ones, similar to results obtained with Golden Delicious apples in Part 1 of this study. Also, a more obvious puffing effect was observed in the Ca-pretreated samples. Among the three varieties, similar structures were obtained for Fuji and Golden Delicious apple chips, while Red Delicious chips looked comparatively less puffy than the other two (Figure 4f). A slightly greater amount of cell collapse was observed in both the Ca-pretreated and the nontreated chips made with Red Delicious apples.

Conditions Required to Obtain Crisp Apple Chips Using Vacuum Microwave Dehydration (VMD) were determined. A 1% CaCl₂-pretreatment of apple slices before VMD enhanced the crispness of apple chip products, without having a negative effect on taste. Crispness was enhanced when the highest level of vacuum was applied, which may have resulted from the greater puffing effect. This correlated with irregular cellular structure and voids, caused by vapor pressure generated during the VMD process. Fuji apple chips were found to have a crispier texture than either Golden Delicious and Red Delicious chips, which may be related to higher endogenous levels of calcium binding components. By manipulation of sample and VMD conditions, textural parameters of products such as apple chips can be modified. Vacuum microwave drying is a technology capable of producing high quality apple chips.

Conditions Required to Obtain Crisp Apple Chips Using Vacuum Microwave Dehydration

Vacuum microwave dehydration (VMD) was used to dry apple slices and obtain apple chips. The effects of calcium pretreatment and vacuum levels on the textural quality of apple chips were studied. Calcium treatments (0 & 1% CaCl₂) were performed on each apple variety. The 1% CaCl₂ treatment was chosen in order to give a significant increase in crispness without a significant increase in bitterness of the chips. The 1% CaCl₂-pretreated apple chips of all apple varieties were significantly crispier, as indicated by a higher compression slope than their non Ca-pretreated (0% CaCl₂) ones (Table 2). This is consistent with results presented in Part 1.

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Conclusions

Vacuum Microwave Dried Apple Chips . . .

Table 2—Calcium content and compression slope of different apple varieties with and without calcium pretreatment.

<table>
<thead>
<tr>
<th>Variety</th>
<th>CaCl₂ %</th>
<th>Ca content (µg/g dry basis)</th>
<th>Compression slope (g/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Delicious</td>
<td>0</td>
<td>540 (6)</td>
<td>866 (34)</td>
</tr>
<tr>
<td>Red Delicious</td>
<td>1</td>
<td>11900 (50)</td>
<td>1180 (43)</td>
</tr>
<tr>
<td>Fuji</td>
<td>0</td>
<td>690 (4)</td>
<td>1035 (50)</td>
</tr>
<tr>
<td>Fuji</td>
<td>1</td>
<td>13100 (80)</td>
<td>1630 (71)</td>
</tr>
<tr>
<td>Golden</td>
<td>0</td>
<td>620 (4)</td>
<td>874 (72)</td>
</tr>
<tr>
<td>Golden</td>
<td>1</td>
<td>12500 (70)</td>
<td>1275 (52)</td>
</tr>
</tbody>
</table>

1 All measurements recorded as mean (standard error). Any values not followed by the same letter are significantly different at p < 0.05. 2 n = 3. Statistical analysis was log transformed data.
Vacuum Microwave Dried Apple Chips . . .

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