Food Research International, Vol. 31, No. 2, pp. 111–117, 1998

PII: S0963-9969(98)00070-2
0963-9969/99/$—see front matter

Characterization of vacuum microwave, air and freeze dried carrot slices

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Vacuum microwave drying of carrot slices was compared to air drying and freeze drying on the basis of rehydration potential, color, density, nutritional value, and textural properties. Vacuum microwave dried (VMD) carrot slices had higher rehydration potential, higher α-carotene and vitamin C content, lower density, and softer texture than those prepared by air drying. Carrot slices that were air dried (AD) were darker, and had less red and yellow hues. Less color deterioration occurred when vacuum-microwave drying was applied. Although freeze drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the VMD carrot slices were rated as equal to or better than freeze dried (FD) samples by a sensory panel for color, texture, flavor and overall preference, in both the dry and rehydrated state.

Keywords: vacuum microwave, dehydration, carrot slices, nutritional properties, color, texture

INTRODUCTION

Dehydration is one of the oldest methods of food preservation and it represents a very important aspect of food processing. Thermal damage incurred by a product during drying is directly proportional to the temperature and time involved. The high temperature and long drying time associated with conventional hot-air drying often causes heat damage and adversely affects texture, color, flavor and nutritional value of products (Schadle *et al*., 1983; Yang and Atallah, 1985; Yongsawatdigul and Gunasekaran, 1996*b*). Although freeze drying can be applied to circumvent heat damage and produce products with excellent structural retention, it is a costly process and is only suitable for high-value products. Also, freeze drying usually causes large losses of flavor volatiles (Flink, 1975). Thus, freeze dried (FD) products are often described as tasteless.

Vacuum microwave drying offers an alternative way to improve the quality of dehydrated products. The low temperature and fast mass transfer conferred by vacuum (Yongsawatdigul and Gunasekaran, 1996*a*), combined with rapid energy transfer by microwave heating, generates very rapid, low temperature drying. Moreover, the absence of air during drying may inhibit oxidation, and therefore, color and nutrient content of products can be largely preserved. Yongsawatdigul and Gunasekaran (1996*b*) reported that vacuum microwave dried (VMD) cranberries had redder color and softer texture as compared to the hot air dried (AD) cranberries. Petrucci and Clary (1989) also indicated that the contents of vitamin A, vitamin C, thiamin, riboflavin, and niacin in dried grape were largely preserved during vacuum microwave drying. The texture of a food material may also be modified by vacuum microwave drying. The microwave power and pressure can be manipulated to expand the structure of some products, yielding

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structure and texture that are unobtainable by other techniques. In some cases, it may be possible to create a food texture which is similar to that produced by frying (Durance and Liu, 1996; Huxsoll and Morgan, 1968).

Carrots have the highest carotene content among human foods (Bao and Chang, 1994*a*; Bureau and Bushway, 1986). This unique property makes dried carrot slices an excellent candidate for developing an oil free, healthy snack food if the nutritional value can be well preserved and a puffed texture can be generated by the vacuum microwave drying process. The color, flavor, and rehydration ability of dried carrot that is currently used as an ingredient for instant soups or meals could also be improved by the rapid heating rate and low drying temperature provided by vacuum microwave. The objectives of this study were to investigate the effects of vacuum microwave drying on the physical properties, nutritional values, and sensory acceptability of carrot slices as compared to conventional hot air drying and freeze drying.

MATERIALS AND METHODS

Preparation of dried carrot slices

Carrots (*Daucus carota*) were washed, peeled, sliced (4 mm) and water blanched (90°C, 7 min) before drying. One kg of blanched carrot slices was prepared for each drying process. A 2450 MHz vacuum microwave drier (DRI Dehydration Research Inc., Vancouver, BC) of nominal 4 kW variable power was used in this research. The dryer employed four 1 kW magnetrons. Variable power was controlled with a computer program which turned on one to four magnetrons as needed for gross adjustments. Finer power graduations were achieved with on-off cycles of the magnetron, controlled with a commercial Triac system. Power settings are reported as measured with the IMPI 2-liter test (Buffler, 1993). To dry the samples to the final moisture content of 10%, microwave power was 3 kW for 19 min followed by 1.0 kW for 4 min and 0.5 kW for 10 min at a constant vacuum of 100 mm Hg. The microwave drying cavity was a cylinder of approximately 0.35 m radius and 0.50 m length. Chamber pressure was adjusted with an air flow valve which bled small amounts of air into the drying chamber in opposition to the vacuum pump. Hot air drying was at 70°C and freeze drying was set at 1.6 mm Hg with chamber temperature of 20°C and condenser temperature of −55°C. Prior to analysis, all dried samples were equilibrated over saturated potassium acetate ($a_w = 0.215$). All experiments were performed in duplicate.

Rehydration

The rehydration potential of dried carrot slices was evaluated by immersing 10 g samples in water at (1) 25°C and (2) 100°C. Samples were drained and weighed at 30, 60, 90, 120, 150, and 180 min for those at 25°C and at 1, 2, 4, 6, 8, and 10 min for those at 100°C. The water absorbed (g) divided by the dry sample weight (g) was expressed as the rehydration ratio. The slope of rehydration ratio vs. rehydration time was defined as the rehydration rate.

Density

The density of dried carrot slices was measured by immersing the samples in a 100 mL graduated cylinder prefilled with 50 mL of mineral oil. The data were expressed as the weight of sample (g) per volume (mL).

Texture

The puncture resistance of dried carrot slices and the shear resistance of rehydrated samples (100°C, 10 min) were measured with a TA-XT 2 Texture Analyzer (Texture Technologies Corp. 18 Fairview Rd., Scarsdale, NY). A 3.2 mm diameter rod was used to measure the force required to penetrate an individual dried carrot slice positioned over a plate with a 9.3 mm diameter hole. The force required to cut through an individual rehydrated carrot slice was measured using a Warner-Bratzler (WB) device with a gap of 4.2 mm between two shear bars. Both puncture and shear measurements were conducted at a crosshead speed of 0.5 mm/s. The values of punch and shear force reported were the mean of 30 measurements.

Color

Color of dried and rehydrated (100°C, 10 min) samples were evaluated by a Hunter LabScan II Spectrocolorimeter (Hunter Lab., Reston, VA). The instrument, equipped with a D_{65} illuminant and 2° observer optical position, was standardized using a black plate and a standard white plate (No. LS-13685, $X = 79.8$, $Y = 84.67$, $Z = 91.23$). The results were expressed as Hunter L (whiteness/darkness), a (red/green), and b (yellow/blue) values.

Carotenes

The α and β carotene contents of carrot slices were analyzed using high performance liquid chromatography (Bushway and Wilson, 1982; Bureau and Bushway, 1986). The wavelength of detector was set at 470 nm. A Vydac 5 μm 210TP54 column 250 cm × 4.6 cm (Anspec, Ann Arbor, MI) and a solvent system, methanol-BHT stabilized tetrahydrofuran (THF) 90/10 (v/v), were used for the reverse-phase separation of carotenes. The α and β-carotene content of carrot was calculated by comparison with carotene standards and expressed as micrograms of carotene per gram of sample on a dry weight basis.

Vitamin C

An AOAC (1984) microfluorometric method was used to determine the total amount of vitamin C in the carrot slices. The fluorescence intensity was measured by a Shimadzu RF 540 spectrofluorophotometer (Shimadzu Corp., Kyoto, Japan) with excitation wavelength at 350 nm and emission wavelength at 430 nm. Data were calculated on a dry weight basis and expressed as microgram of vitamin C per gram of solid.

Sensory evaluation

The sensory evaluation of dried and rehydrated (100°C, 10 min) samples was carried out by a taste panel of 12 untrained judges. The panelists were asked to indicate their preference for each sample, based on the quality attributes of color, appearance, texture, aroma/flavor, and overall acceptability. A balanced 9-point hedonic rating was employed for all the attributes evaluated where 9 denoted "like very much" and 1 indicated "dislike very much".

Statistical Analysis

Data were analyzed using ANOVA of MINITAB (Minitab Inc., 1994). Differences among mean values were established using Tukey's honestly significant difference (HSD) test (Petersen, 1985). Mean values were considered significantly different when $p \leqslant 0.05$.

RESULTS AND DISCUSSION

Dehydration rate and rehydration potential

As illustrated in Fig. 1, vacuum microwave drying was a much faster drying process than air or freeze drying. While it took only 33 min for the vacuum microwave to dry 1.0 kg of the blanched carrot (91.4% moisture) to a final moisture content of 10%, 8 and 72 h, respectively, were required to air dry and freeze dry the samples. Average dehydration rate over the drying periods was 0.013 kg water kg^{-1} dry matter h^{-1} for FD, 1.31 kg kg^{-1} h^{-1} for AD and 19.1 kg kg h^{-1} for VMD. Mass transfer within the food is rapid during microwave heating because heat is generated within the food, creating a large vapor pressure differential between the center and the surface of products. The high internal vapor pressure produced by microwave heating and the low chamber pressure provided by vacuum caused the structure of carrot slices to expand and puff. Due to this puffing effect, the density of VMD carrot slices (0.55 g/mL) was much lower than AD carrot slices (1.13 g/mL) (Fig. 2). FD carrot slices had the lowest density (0.17 g/mL) among the dried samples, since this process allows ice to sublime, leaving voids within the structure.

The rehydration curves of dried carrot slices at 25°C and 100°C are shown in Fig. 3. At both 25°C and 100°C, VMD carrot slices exhibited higher rehydration ratios as well as higher rehydration rates than AD carrot slices. FD carrot slices, due to their porous structure, had the highest rehydration ratio and rehydration rate. These results are in agreement with the density data (Fig. 2) showing that a less dense structure had higher capacity to absorb water when reconstituted. When water temperature was increased, less rehydration time was required for reconstitution. At either temperature (25°C or 100°C), higher rehydration rates occurred at the beginning of rehydration. This is especially noted with the FD samples.

Textural and color properties

Textural properties of dried and rehydrated carrot slices were measured as puncture force and shear strength, respectively (Fig. 4). The puncture force measures the hardness of a product's surface and is an indicator of the extent of case hardening that has occurred during drying (Kim and Toledo, 1987). The shear strength is an indicator of the toughness of the product when consumed in the rehydrated state. The puncture force

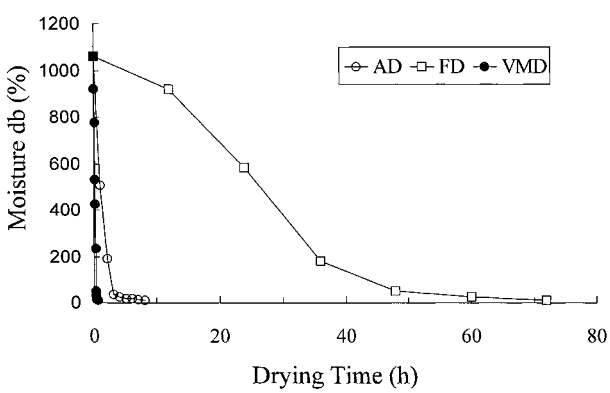

Fig. 1. Dehydration curves of air dried (AD), vacuum microwave dried (VMD), and freeze dried (FD) carrot slices.

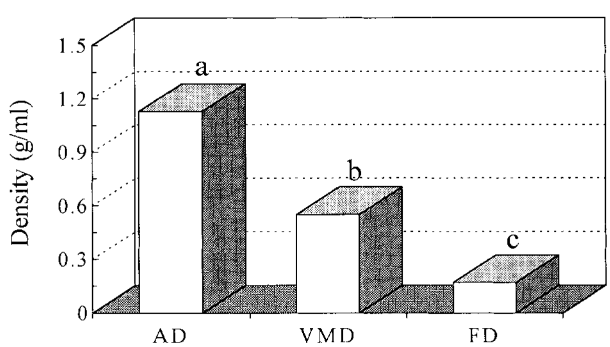

Fig. 2. Density of air dried (AD), vacuum microwave dried (VMD), and freeze dried (FD) carrot slices. Different letters indicate a significant difference ($p \leqslant 0.05$).

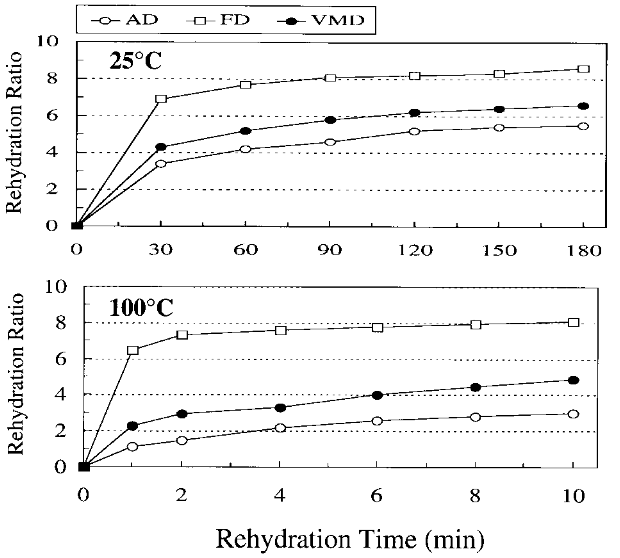

Fig. 3. Rehydration curves of air dried (AD), vacuum microwave dried (VMD), and freeze dried (FD) carrot slices at 25°C and 100°C.

required to break VMD and AD carrot slices were 11.0 and 18.1 N, respectively, indicating that less case hardening occurred with VMD carrot slices. FD carrot slices, on the other hand, required the least puncture force (5.5 N). During air drying, liquid diffuses to the surface of the carrot from the interior and carries solutes with it. As the surface moisture evaporates, solutes concentrate and precipitate, leaving a hard and dry skin. Less case hardening occurred with vacuum microwave processing as heat was generated within the product, resulting in *in situ* vaporization of water which was able to rapidly diffuse out of the tissue, without carrying dissolved solutes with it.

When rehydrated, the shear strength required to cut VMD samples was 10.9 N as compared to 12.7 N for AD samples and 5.6 N for FD samples. The texture of

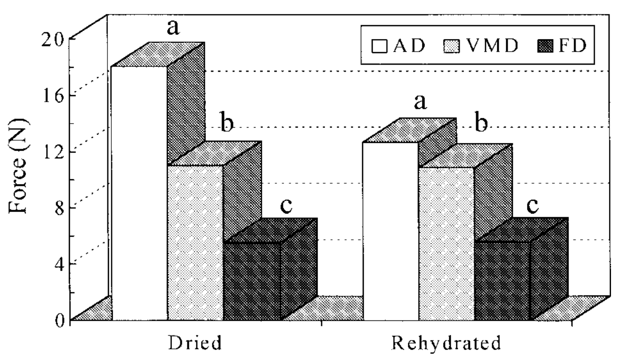

Fig. 4. Texture properties of dried (punch test) and rehydrated (single blade shear test) carrot slices. AD: air dried; VMD: vacuum microwave dried; FD: freeze dried. Different letters in the same group of bars indicate a significant difference ($p \leqslant 0.05$).

VMD carrot slices was softer than that of AD samples but harder than that of FD samples.

Carrot slices that were processed by the three drying methods were distinguishable based on both visual and instrumental assessment of color. Instrumentally, carrot slices that were AD were darker, with less red and yellow hues than the FD and VMD samples (Table 1). FD samples had the highest degree of lightness, with a slightly lower yellow hue than that of VMD samples. The darker appearance of the AD and VMD carrot slices compared to the FD samples may be due to the exposure to heat during drying. According to Howard *et al.* (1996), the lightness of carrot is affected by processing temperatures, with higher temperatures causing darker color. A similar observation was also reported by Abbatemarco and Ramaswamy (1995). It might also be expected that the AD and VMD carrots would appear darker since the density of these slices was greater than FD product, yielding a higher concentration of pigment per volume of tissue.

The yellow and red color of carrot slices is attributed to the presence of carotenes (Wagner and Warthesen, 1995). The decrease in *a* values or red color in the AD and VMD carrot slices compared to FD slices correlates with the loss of α- and β-carotenes (Fig. 5). However, this loss of pigment is not correlated with the *b* values recorded. There may be an interaction between carotenoid degradation and structural changes in the carrot tissue that occur during heating and drying. Work by Purcell *et al.* (1969) indicated that the bathochromic shift from red to yellow hues observed after heating high carotenoid containing vegetables was associated with the degradation of the chromoplasts and solubilization of carotenoids in other cellular lipids.

When reconstituted, the differences in color (Hunter *L*, *a*, and *b* values) among the AD, FD, and VMD carrot slices were smaller. All the samples appeared darker, with the largest decrease in the lightness noted for the FD samples. There was a large increase in the red hue of AD sample, and relatively minor changes in the other *a* and *b* values.

Retention of carotenes and vitamin C

The majority (85–97%) of vitamin A activity in foods is attributed to the α and β-carotene content (Sweeney and Marsh, 1971). Beside their pro-vitamin A activity, the antioxidant activity of α and β-carotene may have important effects in cancer prevention (Riboli *et al.*, 1996; Santos *et al.*, 1996). The amount of carotene may be diminished during drying. Therefore, it was of interest to establish the effects of the different drying processes on the stability of α and β-carotene. Fresh carrot was found to contain 434 μg α-carotene/g solid and 1153 μg β-carotene/g solid (Fig. 5). When subjected to blanching, α-carotene content decreased slightly, while β-carotene content did not significantly change. Air

Table 1. Hunter color values of dried and rehydrated carrot slices

	L	*a*	*b*
Dried			
AD	43.7 ± 2.9[a,d]	22.8 ± 1.5[a]	19.3 ± 1.3[a]
FD	63.9 ± 3.5[b]	28.2 ± 2.2[b]	23.6 ± 0.6[b]
VMD	49.7 ± 1.3[c]	27.8 ± 1.6[b]	25.7 ± 0.9[c]
Rehydrated			
AD	39.6 ± 1.6[a]	29.2 ± 2.2[a]	21.8 ± 1.0[a]
FD	47.8 ± 1.7[b]	26.6 ± 3.9[b]	25.0 ± 1.1[b]
VMD	42.2 ± 1.7[c]	28.9 ± 3.6[a]	23.4 ± 1.2[c]

[abc]Different letters in the same column within the same section (i.e., dried or rehydrated) indicate a significant difference ($p \leqslant 0.05$).
AD: air dried; FD: freeze dried; VMD: vacuum microwave dried.
[d]Values are mean ± standard deviation.

drying caused a decrease in both α and β-carotene content while less depletion of α-carotene occurred with vacuum microwave drying. The total losses of α and β-carotene during drying was 19.2% for the AD samples and 3.2% for the VMD samples. No significant change in α and β-carotene content was observed upon freeze drying. The loss of carotenes during drying can be attributed to a limited amount of oxidation (Schadle *et al.*, 1983). The rapid heating rate and depletion of oxygen offered by vacuum microwave reduced the loss of α-carotene during drying. These results agree with previous reports (Bao and Chang, 1994*a*,*b*; Schadle *et al.*, 1983) showing that α and β-carotenes in carrot are relatively heat stable during drying processes. This is probably due to the presence of α-tocopherol which functions as a natural antioxidant (Panalaks and Murry, 1970). The amount of α-tocopherol in carrot, as reported in literature, is about 0.11–0.50 mg/100 g (Booth and Bradford, 1963; Bunnell *et al.*, 1965).

Because vitamin C is relatively unstable to heat, oxygen, and light, the retention of this nutrient can be used as an indicator for the quality of dried carrot slices. If

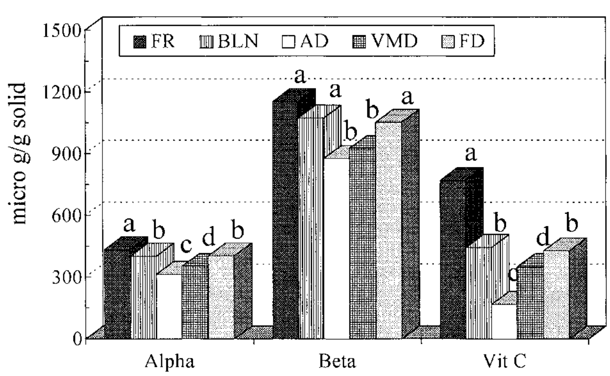

Fig. 5. Alpha/beta carotenes and vitamin C contents of fresh (FR), blanched (BLN), air dried (AD), vacuum microwave dried (VMD), and freeze dried (FD) carrot slices. Different letters in the same group of bars indicate a significant difference ($p \leqslant 0.05$).

vitamin C is retained well, other nutrients are also likely to be preserved. Prior to drying, carrot slices were blanched to inactivate ascorbic acid oxidase and to prevent enzymatic degradation of vitamin C in the subsequent processes. However, a substantial loss of vitamin C content, from 770 µg/g solid to 443 µg/g solid, occurred during the blanching process (Fig. 5). This was probably due to leaching of the vitamin C into the blanch water. Replacing water with steam might have reduced this loss.

Further depletion of vitamin C content occurred during air drying. Only 167 µg/g solid, which represents 38% of the vitamin C in the blanched carrot, was retained in the AD carrot slices. This was apparently due to oxidation of ascorbic acid in the presence of hot air. The relatively long drying time associated with the air drying method also contributed to the severe loss of vitamin C (Schadle *et al.*, 1983). Vitamin C in the dried carrot slices was better retained (350 µg/g solid) when subjected to vacuum microwave drying. About 79% of the vitamin C in the blanched carrot was retained in the VMD carrot slices. No significant loss of vitamin C occurred during freeze drying because the temperature was very low during the drying process. The above data indicate that vacuum microwave drying can better retain vitamins, especially those sensitive to thermal damage and oxidation, than hot air drying.

Sensory evaluation

Sensory evaluation of the dried and rehydrated carrot slices was carried out to obtain preliminary information on consumer preference. When consumed in the dried state, VMD carrot slices received significantly higher ratings for texture and overall acceptability, and were rated as highly as FD samples for color and aroma/flavor (Table 2.). AD carrot slices, on the other hand, received the lowest rating for all the attributes evaluated. FD carrot slices possessed a preferable appearance according to the sensory panelists, which may be due to the excellent structural retention.

Table 2. Sensory evaluation of air dried (AD), freeze dried (FD), and vacuum microwave dried (VMD) carrot slices

	Color	Appearance	Texture	Aroma/Flavor	Overall
AD	4.9^{a}	4.3^{a}	2.7^{a}	4.5^{a}	4.2^{a}
FD	7.2^{b}	7.9^{b}	5.8^{b}	6.8^{b}	6.6^{b}
VMD	7.6^{b}	6.1^{c}	8.0^{c}	7.4^{b}	7.8^{c}

^{abc}Different letters in the same column indicate a significant difference ($p \leqslant 0.05$: $n=24$).

Table 3. Sensory evaluation of rehydrated air dried (AD), freeze dried (FD), and vacuum microwave dried (VMD) carrot slices

	Color	Appearance	Texture	Aroma/Flavor	Overall
AD	6.3^{a}	5.3^{a}	6.1^{a}	5.9^{ab}	6.1^{a}
FD	7.8^{b}	7.9^{b}	6.8^{a}	5.1^{a}	6.5^{a}
VMD	7.3^{ab}	6.5^{c}	6.3^{a}	6.4^{b}	6.2^{a}

^{abc} Different letters in the same column indicate a significant difference ($p \leqslant 0.05$: $n=24$).

When rehydrated, FD carrot slices retained the highest score for appearance; however the aroma/flavor of VMD carrot slices was preferred over those of FD samples (Table 3). This may indicate that there is preferential retention of flavor volatiles in product treated by VMD compared to FD. An evaluation of the effect of VMD on volatile retention in food matrices is the subject of on-going research. Color, appearance, texture, aroma/flavor, and overall acceptability of AD carrot slices were greatly improved when rehydrated. No significant differences were found in texture and overall acceptability among the rehydrated VMD, AD, and FD samples.

Reliable cost estimates of VMD are difficult to arrive at because very few commercial VMD systems are in commercial use. VMD uses electricity rather than the fossil fuels typically used for hot-air convection dryers. In Canada, electricity costs are about four times that of natural gas, the cheapest fossil fuel available. On the other hand, VMD is typical two or three times as efficient as convection food dryers in terms of water evaporated per unit energy. One study of energy, labor and capital costs conducted by Durance and Liu (1996) on a commercial pilot-scale drying operation indicated VMD costs about 15% greater than convection drying. By comparison, freeze drying costs have been reported up to 400% that of conventional drying (Fellows, 1988). These figures will of course vary widely depending upon local energy, labor and fixed costs.

CONCLUSIONS

Vacuum microwave drying is a very rapid drying process and requires only minutes instead of hours or days of drying time. Rehydration potential, nutritional value, color, and textural properties of VMD carrot slices are greatly improved as compared to AD carrot slices. Furthermore, in the dry state, VMD carrot slices possess a unique puffed texture which was preferred by sensory panelists and could be a desirable property for developing a snack type product.

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(Received 16 February 1998; accepted 31 July 1998)