Carotenoid Content and Physicochemical and Sensory Characteristics of Carrot Chips Deep-Fried in Different Oils at Several Temperatures

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ABSTRACT: The influence of deep-frying using different oils and temperatures on carotenoid content and physicochemical and sensory characteristics of carrot chips was investigated. Sliced carrots were steam-blanched, cooled, soaked in 0.2% sodium metabisulfite, and deep-fried in canola, palm, or partially hydrogenated soybean oil (PHSO) at 165, 175, or 185 °C. Frying temperature, but not oil, significantly ($P < 0.05$) affected the α-carotene, β-carotene, and total carotenoid contents. Oil type significantly ($P < 0.05$) influenced all color values. Increasing temperature lowered the redness value, which correlated with decreased carotenoid content, color darkening, and decreased hardness value. Trained panelists detected no differences among oil types in crispness, sweetness, odor, and acceptability. The best carrot-chip product was that fried in PHSO at 165 °C.

Key Words: deep-frying, carotenoid, carrot chips, oil, frying temperature

Introduction

CAROTENOIDS ARE IMPORTANT MICRONUTRIENTS for human health (Castenmiller and West 1998). The biological function of carotenoids is primarily as vitamin-A precursors (Institute of Medicine 2000). In addition to their provitamin-A activity, carotenoids may have several other important biological functions in animals and man (Van Vliet 1996). Epidemiological studies have shown that high intakes of carotenoid-rich vegetables and fruits and high blood levels of β-carotene are associated with decreased incidence of some cancers (Törrönen and others 1996), age-related macular degeneration, cataracts, coronary heart disease or cardiovascular disease, and perhaps other diseases and pathological processes (Kohlmeier and Hasting 1995; Biesalski and others 1997; Kritchevsky 1999). Low concentrations of dietary carotenoids may also be needed to inhibit oxidative damage and decrease oxidation susceptibility (Jacob and Burri 1996).

Carotenoids are widely distributed among colored fruits and vegetables and are important sources of vitamin A, especially in those parts of the world where the intake of animal foods is relatively low (Van Vliet and others 1996; West 1998). However, the bioavailability of the provitamin-A carotenoids from plants is greatly influenced by many factors such as the structure of the carotenoids, the nature of the embedding matrix, levels of dietary fat, the amount and the type of carotenoids, nutritional status, the presence of antioxidants and fibers, and the extent of processing (Castenmiller and West 1998; Rock and others 1998; Riedl and others 1999).

Carrots, the most important source of dietary carotenoids in western countries including the United States (Block 1994; Törrönen and others 1996), contain the highest amount of β-carotene of the common fruits and vegetables (Desobry and others 1998). β-carotene constitutes 60% to 80% of the carotenoids in carrots, followed by α-carotene (10% to 40%), lutein (1% to 5%), and the other minor carotenoids (0.1% to 1.0%) (Chen and others 1995). Among the provitamin-A carotenoids, β-carotene showed the highest vitamin-A activity on a molar basis (Van Vliet 1996; Biesalski 1997). Other carotenoids are estimated to have only half of β-carotene's potency (Castenmiller and West 1998). Processing may convert some of these carotenoids into cis-isomers (Lessin and others 1997) and epoxy-carotenoids (Ball 1998) that may have lower vitamin-A activities (Johnson and others 1996; Ball 1998).

To maximize the use of carrots as a source of provitamin A as well as an antioxidant, it is important to find an appropriate processing method to manufacture products that are not just highly preferred by consumers but also are good nutritional sources of provitamin A. In recent years, researchers (Slinde and others 1993; Aukrust and others 1994, 1995; Baardseth and others 1995, 1996; Skrede and others 1997) have developed carrot chips from carrot slices, using lactic-acid fermentation to decrease reducing sugars, and deep-frying in palm oil. It has been reported that the carotenoid levels of carrots were well retained during the processing of carrot chips (Skrede and others 1997). In addition, due to deep-frying, the product contains lipids that may further improve the ability of carrot chips to serve as a source of provitamin A for humans. Nevertheless, research on carrot-chip production without lactic-acid fermentation using different oils and temperatures has not yet been reported.

Our objective was to evaluate the effect of deep-frying on carotenoid content and physicochemical and sensory characteristics of carrot chips fried in different frying oils (canola, palm, PHSO) at different temperatures (165, 175, 185 °C) without fermentation prior to deep-frying.

Materials and Methods

Materials

Fresh jumbo carrots (*Daucus carota* cv. Navajo) harvested in Bakersfield, Calif., U.S.A., were purchased from Grimmway Farms (Bakersfield, Calif., U.S.A.) and arrived packaged in linear low-density polyethylene bags (2.54 mil; Mercury Plastics, Inc., Industry, Calif., U.S.A.). The roots were stored in these

polyethylene bags in the dark at 0 to 2 °C (Suslow and others 1998) and 98% relative humidity (RH) for 1 to 2 mo prior to processing. At these temperatures and RH, mature carrot roots can be stored for 7 to 9 mo (Hardenburg and others 1990). The oils utilized were refined palm oil (Welch, Holme & Clark Co., Inc., Newark, N.J., U.S.A.), canola oil (Procter & Gamble, Cincinnati, Ohio, U.S.A.), and PHSO (Bunge Food, Bradley, Ill., U.S.A.). These oils did not contain detectable quantities of β-carotene and cis-9-β-carotene; however the α-carotene content was 0.075 μg/g refined palm oil, 0.36 μg/g canola oil, and 0.21 μg/g PHSO.

All-trans-β-carotene was purchased from Sigma (St. Louis, Mo., U.S.A.); lutein was purchased from Fluka (Ronkonkoma, N.Y., U.S.A.); all-trans-β-cryptoxanthin was purchased from Indofine Chemical Co., Inc. (Belle Mead, N.J., U.S.A.); and all-trans-α-carotene was isolated and purified from fresh carrots in our laboratory. The α-carotene from fresh carrots was extracted according to Bushway and Wilson (1982) then isolated by repeated injection into a HPLC instrument with a Phenomenex Ultramex 3 C_{18} IP 3 μm 250 × 3.2-mm column (Phenomenex, Torrance, Calif., U.S.A.) and a mixture of acetonitrile:tetrahydrofuran (THF):methanol:1% ammonium acetate (65:25:6:4) as the mobile phase. The α-carotene peak identified utilizing the reports of Bushway and Wilson (1982) and Chandler and Schwartz (1987) was collected and dried using N_2 and dissolved in HPLC-grade hexane. The identities and concentrations of the α-carotene as well as other carotenoid working standards were confirmed spectrophotometrically (Beckman DU 640, Beckman Instruments Inc., Fullerton, Calif., U.S.A.) using previously reported absorptivities (Epler and others 1993). The purity of crystalline α-carotene from this carrot extract was estimated to be 96%. All HPLC-grade solvents (acetonitrile, THF, methanol, and hexane) were obtained from Fisher Scientific Co. (Fair Lawn, N.J., U.S.A.). The HPLC-grade solvents were degassed under vacuum and filtered through a 0.45-μm membrane filter (Pall Gelman Laboratory, Ann Arbor, Mich., U.S.A.) prior to use.

Carrot-chip production

The production of deep-fried carrot chips was conducted at the Univ. of Nebraska Food Processing Center Pilot Plant. A preliminary study was conducted to determine the required speed of the peeler machine and the duration of carrot peeling, the length and the thickness of carrot slices, the duration of blanching and cooling, the concentration of sodium metabisulfite solution and the duration of soaking, and the frying temperature and the duration of frying. Based on this preliminary study, carrots were trimmed and cut into 55-mm lengths and mechanically peeled using a Hobart Peeler Machine (Hobart Manufacturing Co., Troy, Ohio, U.S.A.) at the lowest speed for 1 min and sliced to a 1.5-mm thickness using a Dito Dean Slicer Model TR-22 (Dean Food Preparation, Los Angeles, Calif., U.S.A.). The carrot slices were then steamed blanched for 4 min, cooled under running tap water for 4 min, and soaked in sodium metabisulfite 0.2% (w/v) solution for 15 min (6 L for 2.75-kg carrot slices). Sulfite has been reported to function as an antioxidant in stabilizing carotenoids in dehydrated carrots (Zhao and Chang 1995). The soaked carrot slices were drained until the surface was nearly dry and then deep-fried in a Toastmaster Fryer Model 1427 (Elgin, Ill., U.S.A.) using 3 types of oils (canola, palm, and PHSO) and 3 different frying temperatures (165, 175, and 185 °C). The carrot slices were fried (0.45 kg per batch) for 3 to 5 min or until there were no visible bubbles due to residual water (Aukrust and others 1995). The fried carrot chips were drained on paper towels and shaken with flaked salt to a salt content of 1.0% (w/w) (Melton and others 1993). Each treatment was replicated 2 times. The resulting carrot chips were weighed, and the total yield of carrot chips (%) was calculated as percentage of weight of fresh sliced carrots before and after deep-frying. The carrot chips were then packed and flushed with nitrogen gas using a Multivac M855 (Multivac Inc., Kansas City, Mo., U.S.A.). Two kinds of film—plain nonformable (Curlam® Grade 2500-G) and plain formable (Curlon® Grade 9301-S) (Curwood Bemis Specialty Films, Oshkosh, Wis., U.S.A.)—were used for packaging the chips using this machine, with the nonformable film being on the top exterior layer and the formable being below. The Curlam® film (2.5-mil thick) was constructed of polyester, polyvinylidine chloride, adhesive, and Surlyn®. The Curlon® film (5.0-mil thick) was constructed of proprietary coextruded film with ethylene vinyl alcohol barrier, Surlyn® sealant, and nylon structural layers. The barrier properties of Curlam® were $O_2 < 0.00018$ to 0.00014 ml s^{-1} m^{-2} at 23 °C and 0% RH and moisture vapor transmission rate (MVTR) < 0.000054 g s^{-1} m^{-2} at 38 °C and 90% RH, while those of Curlon® were $O_2 < 0.000\,358$ ml s^{-1} m^{-2} at 23 °C and 0% RH, and MVTR < 0.0000896 g s^{-1} m^{-2} at 38 °C and 90% RH according to the manufacturer. The packaged products were stored at −50 °C until used for carotenoid, physicochemical, and sensory analyses.

HPLC analyses of carotenoids

The HPLC system consisted of the following Waters Associates, Inc. (Milford, Mass., U.S.A.) equipment: a 600E solvent delivery system, a U6K injector, 484 UV detector, and a 5200 printer-plotter. The separation was carried out using a reversed-phase Microsorb-MV (5 μm, 250 × 4.6 mm) C_{18} column (Rainin, Woburn, Mass., U.S.A.), which was protected with a guard column of C_{18} materials (3 cm length × 4.6 mm i.d.) packed with spheri-5-C_{18} (5-μm particle size).

The extraction of carotenoids was carried out using the modified method of Barua and Olson (1998) as follows: Carrot chips or fresh carrots (30 g) were crushed or pureed using a food processor (Black & Decker, Model HC 3000, Shelton, Conn., U.S.A.) and 2 g was weighed into a 20-mL vial. Three mL of THF was added to the vial, which was then covered with a Teflon-coated cap, and vortexed for 1 min. The mixture was homogenized (Biohomogenizer M133/1281-0, Biospec Products Inc., Bartlesville, Okla., U.S.A.) at low speed for 1 min and at high speed for 3 min. During the homogenization, the vial was immersed in ice, and light exposure was limited. The homogenizer was rinsed with THF (1 to 2 mL), more THF was added into the mixture until the volume reached 10 mL, and the vial contents were vortexed again for 1 min and then flushed with argon gas for 3 min to remove the air. The extract was kept in the freezer (−50 °C) overnight. The next day, the vial contents were vortexed for 1 min and put back into the freezer (−50 °C). On the 3rd day, the vial contents were vortexed again for 1 min and centrifuged at 3000 × g at 5 °C for 10 min. The supernatant fluid was collected into a 100-mL brown volumetric flask (or 50 mL depending upon the carotenoid content) by decantation. A 2nd extraction was done on the residue using 4 mL THF followed by centrifugation as described. A 3rd and 4th extraction with 4 mL THF followed by centrifugation was performed as described when needed to produce a white plant residue without any re-

maining orange color. The THF extract was pooled in the above flask and then was topped off with a mixture of acetonitrile, THF, methanol, and 1% ammonium acetate (65:25:6:4). Before injecting into the HPLC system, the extract was diluted with mobile phase 10 to 100 times. The carotenoids were separated using acetonitrile:THF:methanol:1% ammonium acetate (65:25:6:4) as the mobile phase under isocratic conditions (Nierenberg and Nann 1992; Sun and others 1997). Injections (50 μL) were made in duplicate for each sample. Proofs of identities and pre-extraction spiking were conducted. Percent recoveries of the congeners from pre-extraction spiking were 82 to 89 (lutein), 88 to 98 (α-carotene), and 95 to 100 (β-carotene).

Individual carotenoids were identified by comparison of retention times and absorbance spectra to those of carotenoid standards and comparison to previous carotenoid separation on C_{18} columns. Separation times using a flow rate of 1 mL/min were 3.82 min for lutein, 14.35 for α-carotene, 15.18 min for β-carotene, and 16.24 min for tentatively identified cis-9-β-carotene. Skrede and others (1997) and Sharpless and others (1996) identified this peak as cis-9-β-carotene using donated cis-9-β-carotene standard. The elution order of the tentatively identified cis-9-β-carotene was the same as reported by Skrede and others (1997), Sharpless and others (1996), and Sander and others (1994) who utilized donated cis-9-β-carotene standards. Other researchers (Nyambaka and Ryley 1996; Chen and Chen 1994; Craft and others 1990) also identified cis-9-β-carotene from various food products in a manner similar to that utilized in the present research. As no cis standards were commercially available, cis-9-β-carotene was quantified using the all-trans β-carotene standard (Chen and others 1995; Lessin and others 1997). Vitamin-A activity was calculated as retinol activity equivalents (RAE) using 12 μg per RAE for all-trans β-carotene and 24 μg per RAE for all-trans α-carotene (Institute of Medicine 2001). The retention values (%) of carotenoids in the carrot chips as the effect of carrot-chip processing were calculated as described by Murphy and others (1975).

Physicochemical analyses

Color. A Minolta CR300 Chromameter (Minolta Co., Ramsey, N.J., U.S.A.) was used to measure L, a, and b values of fresh carrots and carrot chips. In the CIE color system, "L" describes lightness (black = 0, white = 100); "a" intensity in red (a > 0); "b" intensity in yellow (b > 0); and "hue angle" (Hue° = $\tan^{-1}$ b/a) the hue of the color (red = 0, yellow = 90). The color analyses were performed on homogenized raw carrots and on crushed carrots chips (Slinde and others 1993).

Texture. The texture of carrot chips was measured using a TAXT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, N.Y., U.S.A.). This method measured the force needed to break a chip at a constant speed. The force and work required to rupture the chips can be correlated to hardness and crunchiness of the chips. The instrument was equipped with an aluminium guillotine or knife blade, 4 cm × 4 cm, 1 mm thick, and an acrylic fixture to hold the chip in position (TA-260 Hinge and Cantilever Fixture, Texture Technologies Corp.). Twelve chips from each treatment were used for the testing, and the results averaged.

Water activity. The water activity of the carrot chips before and after frying was determined by an AquaLab water activity analyzer (Decagon Devices, Inc., Model CX-1, Pullman, Wash., U.S.A.). Samples were crushed and analyzed in duplicate (Wagner and Warthesen 1995).

Moisture and dry-matter content. For moisture content and dry-matter determination of fresh carrots and carrot chips, the samples were crushed, and portions of 2 g weighed, dried at 105 °C for 20 to 22 h, cooled in a desiccator, and weighed again (Baardseth and others 1995).

Fat content. Fat content of fresh carrots and carrot chips was determined according to AOAC International official method no. 960.39 (AOAC International 2000) using a Soxtec System HT6 (Tecator Soxtec System, Tecator Inc., Herndon, Va., U.S.A.) instrument.

Sensory analyses

The sensory portion of this research was approved by the university's Institutional Review Board for Research Involving Human Subjects. Fourteen potential panelists, all Americans from the Plains area, age 19 to 49 y, were recruited from faculty, staff, and graduate students at the Univ. of Nebraska, Lincoln to evaluate the color, crispness, odor, sweetness, flavor, and overall acceptability of these products. The panelists were trained and oriented in doing the scoring test (Lawless and Heymann 1998) employed for this product-oriented test (Watts and others 1989). Carrot chips were removed from the freezer 18 h before testing (Melton and others 1993), and the chips were at room temperature when tested. Each panelist received coded samples. Testing was conducted in individual booths equipped with white fluorescent lights. The panelists came to the sensory laboratory on 4 different occasions, and for each occasion, each panelist judged 6 samples from the 9 treatments utilizing a Balanced Incomplete Block Design.

Statistical analyses

Carotenoid and physicochemical data were tabulated and analyzed by 2-way analysis of variance (ANOVA) to determine the effect of oil, temperature, and oil:temperature interaction. A 2-way ANOVA with oil:temperature treatments and judges as sources of variation was carried out on sensory data to determine differences among the treatments (Shamaila and others 1996). Correlations between values were also determined (Steel and others 1997). For all analyses, differences were considered significant at $P < 0.05$. All statistical analyses were carried out with the General Linear Model (GLM) procedure of SAS version 6 (SAS Institute Inc., Cary, N.C., U.S.A.).

Results and Discussion

Carotenoid content of fresh and blanched carrot slices

The carotenoid contents of fresh and blanched carrot slices are presented in Table 1. Carotenoid concentrations of fresh carrots used in this study were higher than those reported by Skrede and others (1997) for carrot chips prepared using lactic-acid fermentation prior to the frying. Heinonen (1990) reported the carotenoid concentrations of 19 cultivars of carrots: (μg/100 g w/w) α-carotene ranged from 2200 to 4900; β-carotene, from 4600 to 10300; and lutein, from 110 to 560. The carrots used in our study contained carotenoids in these reported ranges. After blanching, no significant ($P \geq 0.05$) changes in the carotenoid content were observed. However, based on the dry-weight basis, the carotenoid concentrations were increased in the blanched carrot. This can be understood as blanching may cause the denaturation of the carotene-binding protein, which further releases the carotenoids so that they can be easily extracted (Dietz and Erdman 1989). Blanching produces a gradual breakdown in the protoplasmic

structure organization, with subsequent loss of turgor pressure, the release of pectic substances (Fuchigami and others 1995), and a final softening effect. Blanching also induces more disruption of the carrot cells (Prestamo and others 1998). Howard and others (1999) also found that steam-blanched carrots contained higher total carotenes than fresh carrots. In addition to the increased carotenoid content in the blanched carrots, blanching also resulted in isomerization of carotenoids (Desobry and others 1998). In the present study, we tentatively identified cis-9-β-carotene in blanched carrots that did not exist in the fresh carrot. The vitamin-A activities of fresh and blanched carrots in the present study were 851 and 775 μg RAE/100 g w/w, respectively, an amount high enough to satisfy the human daily need for vitamin A (Institute of Medicine 2001).

Yield, carotenoid content, and vitamin-A activity of carrot chips

The yields for carrot chips ranged from 15.9% to 16.5% (Table 2). The types of oil and frying temperatures did not significantly affect the yields of carrot chips. The yields of carrot chips in our study were higher than reported by Baardseth and others (1995) using lactic-acid fermentation (10.1% to 11.7%). Aukrust and others (1995), also using the fermentation technique, found the yield to be between 12.5% and 16%, depending on the initial concentration of NaCl in the brine used during fermentation. Differences in varieties as well as in the processing methods may be responsible for the differences in carrot-chip yield.

The carotenoid contents of deep-fried carrot chips in the present study were: (μg/100 g w/w) lutein, 1964 to 2480; α-carotene, 10832 to 15573; β-carotene, 28958 to 37156; and tentatively identified cis-9-β-carotene, 9468 to 17987 (Table 2). As mentioned earlier, the 3 oils did contain minute quantities of α-carotene but not β-carotene and cis-9-β-carotene. The existence of cis-9-β-carotene in the deep-fried carrot chips was also found by Skrede and others (1997). The total carotenoid and vitamin-A activity of the carrot chips (w/w) ranged from 51222 to 72456 μg/100 g chips and from 2866 to 3746 μg RAE/100 g chips, respectively. The carotenoid contents and vitamin-A activities of carrot chips reported in the present study were higher than those reported by Skrede and others (1997), but this may be due to the differences in carrot variety and processing method. The blanching and soaking of the carrot slices in 0.2% sodium metabisulfite before frying may have contributed to the relatively high retention of the carotenoid and vitamin-A activity (Table 3) in the carrot chips. As discussed earlier, the blanching treatment may have denatured the carotene-binding protein and softened the fiber matrix of the carrots, thus increasing carotenoid release during extraction. Zhao and Chang (1995) reported that sulfite and cornstarch can retard loss of redness and total α- and β-carotene breakdown during storage of dehydrated carrots and that sulfite acts as an antioxidant.

The frying temperature, but not the type of oil, significantly affected ($P < 0.05$) the carotenoid content of carrot chips. Increased frying temperature significantly decreased ($P < 0.05$) the carotenoid content and the vitamin activity of the carrot chips. This phenomenon was expected (Hagenimana and others 1998). Several chemical and physical changes occur during frying, including starch gelatinization, protein denaturation, water vaporization, and crust formation (Hagenimana and others 1998). In addition to heat transfer, mass transfer takes place and is characterized by the movement of oil into the product and movement of water in the form of vapor from the product into the oil (Saguy and Pinthus 1995; Pinthus and others 1993). So, factors like frying temperature, frying duration, and product size and shape influence the carotenoid content of the fried carrot chips.

The carotenoid levels of carrots were well retained during the processing of carrot chips in the current study (Table 3). There were no significant differences ($P \geq 0.05$) in the retention of α-carotene, β-carotene, total carotenoids, and vitamin-A activity among the chips fried in different types of oil. However, significant differences ($P < 0.05$) in the retention of these carotenoids and vita-

Table 1—Carotenoid content (μg/100 g w/w) and vitamin-A activity (μg RAE/100 g w/w) of fresh and blanched carrot slices

Carrot slice	Moisture content %	Lutein	α-carotene	β-carotene	Cis-9-β-carotene	Total carotenoids	Vitamin-A activity[a]
Fresh	88.0	394 (3270)	3160 (26224)	8626 (71585)	—	12180 (101079)	851 (7058)
Blanched	92.0	372 (4662)	2883 (36128)	7861 (98509)	106 (1328)	11222 (140627)	775 (9714)

Number in ( ) represents amount on dry-weight basis.
[a]μg Retinol Activity Equivalent (RAE) = $\frac{\mu g\ \alpha\text{-carotene}}{24} + \frac{\mu g\ \beta\text{-carotene.}}{12}$

Table 2—Effect of type of oil and frying temperature on yield (%), carotenoid content (μg/100 g w/w), and vitamin-A activity (μg RAE/100 g w/w) of carrot chips

Type of oil	Frying temp °C	Yield	Lutein	α-carotene	β-carotene	Cis-9-β-carotene	Total carotenoids	Vitamin-A activity[a]
Canola	165	15.9	2275	13022^{d}	36447^{bc}	13948^{bcd}	65692^{bcde}	3580^{bcd}
	175	16.1	2131	14750^{cd}	36655^{b}	14870^{bc}	68406^{bcd}	3669^{bc}
	185	16.1	2161	12870de	31659^{bcd}	12854^{cd}	59544de	3175de
Palm	165	16.2	2438	15321^{bc}	36529^{bc}	17987^{b}	72275^{b}	3683^{bc}
	175	16.1	2480	15301^{bc}	37000^{b}	15749^{bc}	70530^{bc}	3721^{b}
	185	16.3	1964	10832^{f}	28958^{d}	9468^{d}	51222^{e}	2866^{e}
PHSO[g]	165	16.5	2426	15573^{b}	37156^{b}	17301^{bc}	72456^{b}	3746^{b}
	175	16.1	2285	13187^{cd}	32728^{bcd}	13090^{cd}	61290^{c}	3277^{cde}
	185	16.4	2042	11766^{def}	30564^{c}	10208^{d}	54580^{e}	3038^{e}

[a]μg Retinol Activity Equivalent (RAE) = $\frac{\mu g\ \alpha\text{-carotene}}{24} + \frac{\mu g\ \beta\text{-carotene}}{12}$
[b-f]values within a column with the same letters are not significantly different ($P \leq 0.05$).
[g]PHSO: partially hydrogenated soybean oil

min-A activity were observed among chips fried at different temperatures, with those fried at 185 °C having the lowest retention. On the average, for all temperatures and oil types, about 85% of the initial carotene content of the carrots was retained in the carrot chips, either as all-trans α- or β-carotene or as cis-9-β-carotene.

Color value, texture, water activity, moisture content, and fat content of carrot chips

The color of the carrots was reported to be largely due to the presence of carotenes (Bao and Chang 1994). The orange color of carrots and carrot chips was described by the lightness (L), redness (a), yellowness (b), and Hue° parameters. The color values of carrot chips ranged from 32.3 to 46.1 (L), 14.7 to 20.4 (a), 13.4 to 26.5 (b), and 42.1 to 53.5 (Hue°). Deep-frying seemed to decrease the L, a, and b values of the fresh carrots, while blanching had little effect. The type of oil significantly influenced ($P < 0.05$) the carrot-chip color in L, a, b, and Hue° values (Table 4). Palm oil seemed to produce carrot chips that were higher in lightness (L), redness (a), yellowness (b), and Hue° values than PHSO and canola oil. However, the redness (a) value of carrot chips fried in PHSO was not significantly different ($P \geq 0.05$) from those fried in palm oil. Frying temperature also significantly affected ($P < 0.05$) the carrot chip color in L, a, and b values but not the Hue° value. Increasing the frying temperature significantly decreased ($P < 0.05$) the color attributes of carrot chips in L, a, and b.

The color values of carrot chips in the current study prepared without fermentation were similar to chips produced using lactic-acid fermentation, though the redness (a) values were higher. The L, a, and b values reported by previous researchers using lactic-acid fermentation were : 44.9 to 51.3 (L), 10.1 to 12.6 (a), 15.8 to 26.5 (b) (Slinde and others 1993); 49.0 to 52.4 (L), 15.1 to 16.3 (a), 26.2 to 29.0 (b) (Baardseth and others 1995) and 15.9 to 20.4 (b) (Aukrust and others 1995); values observed in the current study are given in Table 4. The purpose of lactic-acid fermentation prior to frying in the previous studies was to decrease the reducing sugars that are responsible for the browning reaction during the frying of the carrot slices. The blanching treatment followed with rinsing the blanched carrots under running tap water and then soaking in 0.2% sodium metabisulfite may contribute to the decreased reducing sugars in the carrot slices, or the sulfite may also block the formation of pigments in the Maillard reaction pathway, resulting in deep-fried carrot chips with good color in the present study. Marquez and Anon (1986) reported that blanching can result in the removal of sugars and might be an effective way to control color development during frying since the reducing-sugar content is normally the primary compositional factor that influences darkening.

The redness (a) value of carrots reflects the carotenoids in carrots (Baardseth and others 1995). Our data indicated that there were positive correlations between the redness (a) values and the following carotenoid contents: lutein ($r = 0.77$, $P < 0.05$), α-carotene ($r = 0.79$, $P < 0.05$), β-carotene ($r = 0.76$, $P < 0.05$), cis-9-β-carotene ($r = 0.73$, $P < 0.05$), total carotenoid ($r = 0.77$, $P < 0.05$), and vitamin-A activity ($r = 0.77$, $P < 0.05$). The decrease in a values in the carrot chips fried at the higher temperature correlated with the loss of α- and β-carotenes (Table 2). Skrede and others (1997) reported a significant correlation ($r = -0.72$, $P < 0.05$) between Hue° value and the total carotenoid content. However, our data indicated no significant correlation ($P \geq 0.05$) between Hue value and the total carotenoid content.

Frying temperature and the interaction of type of oil and temperature significantly affected ($P < 0.05$) the texture value (that is, the hardness) of carrot chips in the current study. The type of oil alone did not affect the hardness of the chips. There was no certain pattern

Table 3—Effect of type of oil and frying temperature on retention of carotenoid and vitamin-A activity in carrot chips (%)

Type of oil	Frying temp °C	α-carotene	β-carotene	Total carotenoids	Vitamin-A activity
Canola	165	65.6^{bc}	67.2^{abc}	85.9^{abcd}	67.0^{abc}
	175	75.2^{ab}	68.5^{ab}	90.5^{abc}	69.5^{ab}
	185	65.5^{bc}	58.9^{bc}	78.4^{bcd}	59.9^{bc}
Palm	165	78.4^{ab}	69.1^{ab}	95.9^{a}	70.0^{ab}
	175	78.1^{ab}	69.1^{ab}	93.3^{ab}	70.5^{ab}
	185	56.6^{c}	54.7^{c}	68.6^{d}	54.9^{c}
PHSO[e]	165	81.2^{a}	70.9^{ab}	98.3^{a}	72.5^{a}
	175	67.1^{bc}	61.0^{bc}	81.0^{bcd}	62.0^{abc}
	185	61.2^{c}	58.3^{bc}	73.7^{cd}	58.6^{bc}

[a-d]values within a column with the same letters are not significantly different ($P \leq 0.05$).
[e]PHSO: partially hydrogenated soybean oil

Table 4—Effect of type of oil and frying temperature on L, a, b, and Hue° values, texture, water activity (a_w), moisture content, and fat content of carrot chips

Carrot slice	Frying temp °C	L	a	b	Hue^0	Texture g force	Water activity	Moisture content %	Fat content %
Fresh	—	45.1	25.5	24.1	43.4	—	—	88.0	nd
Blanched	—	47.2	25.8	25.2	44.3	—	—	92.0	nd
Fried in Canola	165	33.7^{ef}	17.3^{b}	16.5^{d}	43.6^{cd}	494.3^{a}	0.44^{a}	2.1^{b}	59.2^{b}
	175	34.0^{ef}	16.1^{bc}	14.6^{e}	42.1^{d}	437.8^{ab}	0.44^{a}	2.6^{ab}	60.1^{ab}
	185	32.3^{f}	14.7^{c}	13.4^{e}	42.4^{cd}	334.5^{d}	0.44^{a}	2.9^{a}	58.8^{b}
Fried in Palm	165	46.1^{a}	20.4^{a}	26.5^{a}	52.4^{a}	412.6^{bc}	0.41^{cde}	2.2^{b}	61.2^{ab}
	175	42.2^{b}	17.9^{b}	23.3^{b}	52.6^{a}	426.6^{bc}	0.42^{bc}	2.7^{ab}	61.4^{ab}
	185	43.2^{b}	17.6^{b}	23.8^{b}	53.5^{a}	457.1^{ab}	0.42^{b}	2.7^{ab}	61.5^{ab}
Fried in PHSO[g]	165	38.3^{c}	19.9^{a}	19.5^{c}	44.4^{c}	429.4^{bc}	0.40^{e}	2.0^{b}	60.6^{ab}
	175	36.4^{d}	17.2^{bc}	17.5^{d}	45.5^{bc}	408.6^{bc}	0.40^{de}	2.3^{ab}	62.0^{a}
	185	34.6^{de}	15.5^{c}	16.5^{d}	46.9^{b}	390.4^{bcd}	0.41^{bcd}	2.8^{ab}	61.1^{ab}

nd = not detectable
[a-f]values within a column for fried products with the same letters are not significantly different ($P \leq 0.05$).
[g]PHSO: partially hydrogenated soybean oil

as to how temperature affected the hardness, however, the trend was that the higher the temperature, the lower the hardness. That there were no significant differences in the hardness of carrot chips fried in different types of oils may be an indicator that the chips had similar crispness as discussed later in the sensory characteristics findings.

The water activity (a_w) and moisture content of carrot chips in the present study ranged 0.40% to 0.44% and 2.0% to 2.9% (Table 4), respectively. This lower water activity may help the carrot chips maintain carotenoid content during storage. Arya and others (1982) reported that carotenoids were relatively stable when water activity ranged from 0.32 to 0.57, equivalent to a moisture content of 8% to 12% in freeze-dried carrots. There was a significant difference ($P < 0.05$) in water activity in the present study, but not in moisture content of carrot chips, among the types of oil with canola oil resulting in the highest water activity. Frying temperature significantly affected ($P < 0.05$) the moisture content of carrot chips: the higher the temperature, the higher the moisture content. Perhaps at higher temperatures, the crust forms more quickly and blocks water release from the carrot slice matrix. As indicated by the lower lightness (L) value, the higher temperature also caused the browning reaction to occur faster and that may have affected the color development. In deep-fried onion slices, Hansen (1998) found that the moisture content after frying and color development of the fried product, expressed as hue angle (Hue°), showed a strong correlation at each temperature. There was a significant difference in the relationship between moisture content and color at the different frying temperatures. Our data indicated a negative correlation ($r = -0.74$, $P < 0.05$) between moisture content and the redness (a) value of the chips. The issue of frying temperature is rather complex as temperature influences not only color development (darkening), which influences the carotenoid changes, but also moisture loss, both of which are important in the evaluation of the quality of the fried product (Hansen 1998).

The fat content of carrot chips in the current study was high (58.8% to 62.0%) (Table 4). There was no significant difference ($P \geq 0.05$) in the fat content of carrot chips among the chips fried in different frying oils and frying temperatures. Similar results were observed by Baardseth and others (1995) on carrot chips prepared using lactic-acid fermentation. Hagenimana and others (1998) reported that the oil content of fried sweet-potato chips was linearly related to the dry-matter content of storage roots. The fat content of the carrot chips is also dependent on the variety of carrots (Baardseth and others 1995). The high-fat content of carrot chips could be either an advantage or disadvantage, depending on one's viewpoint. It could be disadvantageous since the high-fat content may contribute to high-calorie intake. But, the high-fat content of carrot chips could be an advantage to people in developing countries who still need to increase their calorie intakes. Moreover, the high-fat content in the carrot chips may help in increasing the absorption and utilization of carotenoids as vitamin-A precursors, which is very important for people in developing countries. Provitamin-A carotenoids are better retained by humans when consumed together with fat (Dimitrov and others 1988; Jalal and others 1998; Takyi 1999).

Sensory characteristics

The sensory characteristics of carrot chips are presented in Table 5. There were no significant differences ($P \geq 0.05$) in odor and sweetness of carrot chips fried in different types of oil and at different temperatures. However, the crispness appears to be significantly affected ($P < 0.05$) by frying temperatures. The oil types appeared to significantly ($P < 0.05$) affect the flavor. Frying temperature also significantly affected ($P < 0.05$) the color score of carrot chips. With increasing frying temperature, the color score of the chips was increased, which means the chips were darker. The lightness (L), redness (a), and yellowness (b) values were significantly ($P < 0.05$) negatively correlated ($r_L = -0.85$, $r_a = -0.90$, $r_b = -0.85$) with the color scores from sensory analyses, which means that higher L, a, and b values were associated with lower color scores and lighter colored chips. There was no significant difference ($P \geq 0.05$) in crispness scores as an effect of oil types observed by panelists. This agrees with the hardness value discussed above (Table 4). All of the chips were perceived to have similar crispness by the panelists. Although there were no significant differences ($P \geq 0.05$) in the sweetness scores of the chips fried in different types of oil and at different temperatures, there was a trend indicating that the increasing temperature seemed to decrease the sweetness score of the chips.

The overall acceptabilities of carrot chips are given in Figure 1, with 9 being the highest score (like extremely) and 1 the lowest score (dislike extremely). Basically, the carrot-chip product was acceptable to the panelists. There were no significant differences ($P \geq 0.05$) in overall acceptability among the carrot chips fried in different types of oil. However, the frying temperature significantly affected ($P < 0.05$) the overall acceptability of the chips, with the highest acceptability scores being for carrot chips fried at 165 °C. There were positive correlations between the scores of crispness ($r = 0.92$, $P < 0.05$) and sweetness ($r = 0.73$, $P < 0.05$) with the overall acceptability of carrot chips. The higher the score on crispness and sweetness, the higher the acceptability of the carrot chips. Therefore, we can conclude that the crispness and the sweetness of

Table 5—Effect of type of oil and frying temperature on sensory characteristics of carrot chips

Type of oil	Frying temp °C	Color[a]	Crispness[b]	Odor[c]	Sweetness[d]	Flavor[e]
Canola	165	5.0^{hij}	6.7^{f}	4.5^{fg}	4.8^{f}	6.1^{f}
	175	5.3^{hi}	5.5^{g}	5.3^{f}	4.6^{fg}	5.6^{fg}
	185	6.0^{fg}	4.4^{h}	4.5^{fg}	4.6^{fg}	5.6^{fg}
Palm	165	3.7^{l}	6.3^{fg}	4.4^{g}	4.4^{fg}	4.7^{h}
	175	4.7^{ijk}	4.3^{h}	4.0^{g}	4.0^{g}	4.4^{h}
	185	4.3^{kl}	4.7^{h}	4.2^{g}	3.9^{g}	4.5^{h}
PHSO[m]	165	4.4^{jk}	6.8^{f}	4.3^{g}	4.6^{fg}	5.6^{fg}
	175	5.5^{gh}	6.0^{fg}	4.0^{g}	4.4^{fg}	5.5^{fg}
	185	6.3^{f}	4.6^{h}	4.3^{g}	4.3^{fg}	5.0^{fg}

[a]1 = very light, 9 = very dark
[b]1 = very tough, 9 = very crispy
[c]1 = very bland, 9 = very intense
[d]1 = not sweet at all, 9 = very sweet
[e]1 = very bland, 9 = very intense
[f-l]Values within a column with the same letters are not significantly different ($P \geq 0.05$).
[m]PHSO: partially hydrogenated soybean oil

carrot chips seemed to be more important to the panelists in evaluating the acceptability of the carrot chips, although the flavor, color, and odor were still important.

The study reported here is part of a project aimed at developing the best method to produce carrot chips that are highly acceptable, have good sensory characteristics, and have high carotenoid content. We expect that this product or the processing method can be introduced both in developed and developing countries to alleviate nutrition and health problems related with carotenoid intake through a food-based approach.

Our study indicated that deep-fried carrot chips were high in α-carotene and β-carotene with the estimated vitamin-A potency ranging from 2866 to 3746 μg RAE per 100 g w/w chips. The consumption of 1 serving of carrot chips (30 g) is likely to meet the vitamin-A requirement of an adult (Institute of Medicine 2001). This means that this product is a rich source of carotenoids, either as a vitamin-A precursor or antioxidant. The fat content of the chips may increase the bioavailability of carotenoids, as consistent results obtained in animal models and humans suggest that dietary fat is a key factor in carotene absorption. The good sensory characteristics of deep-fried carrot chips could be an indicator of consumer acceptance of this product. Moreover, because chips are so popular around the world, it can be expected that this product will also be accepted worldwide.

Conclusions

THE FRYING TEMPERATURE, BUT NOT the type of oil, significantly affected the carotenoid content and vitamin-A activity of deep-fried carrot chips prepared without lactic-acid fermentation. Increasing frying temperature lowered the redness (a) value, decreased the carotenoid contents, darkened the color, and lowered the hardness value. No differences among oil types were found in chip crispness, sweetness, and odor scores by trained panelists. Negative correlations between L, a, and b values and the color score of the carrot chips and positive correlations between the crispness and the sweetness scores and the overall acceptability of carrot chips were observed. The frying temperature significantly affected ($P < 0.05$) the overall acceptability of the chips, with the highest acceptability score being for carrot chips fried at 165 °C in PHSO.

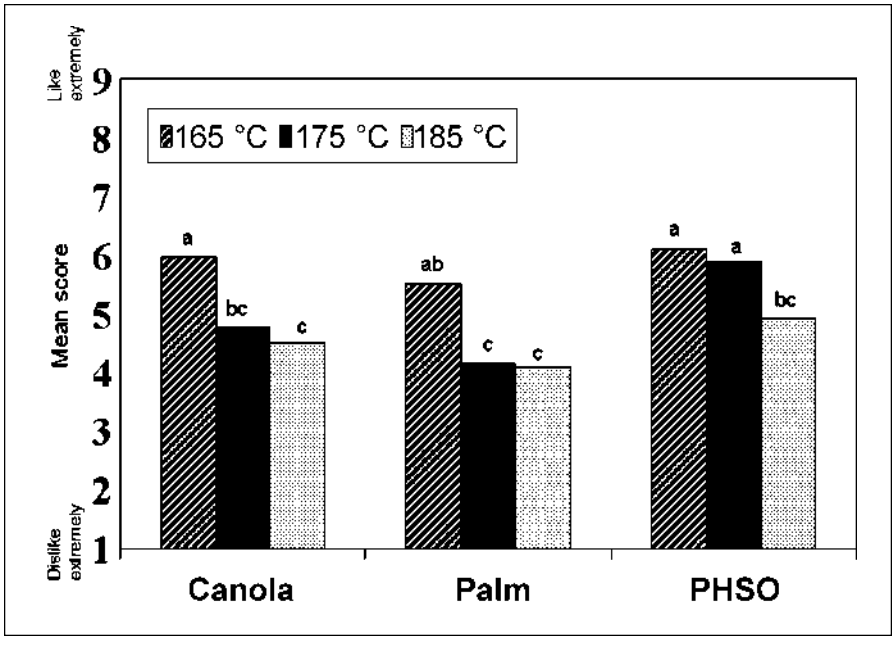

Figure 1—Effect of oil type and frying temperature on overall acceptability of deep-fried carrot chips (1 = dislike extremely, 9 = like extremely). [abc]values with the same letters are not significantly different (P ≥ 0.05). PHSO = partially hydrogenated soybean oil.

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