Processing Effects on Carrot Phytonutrients

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Plant components, primarily secondary metabolites that have health-promoting properties are called phytonutrients. In vitro studies indicate phytonutrients may play a significant role, in addition to vitamins, in protecting biological systems from the effects of oxidative stress (Kalt, 2005). Various molecular processes, as well as environmental, dietary and lifestyle factors can invoke the production of a variety of reactive oxygen, nitrogen and iron species that are responsible for the irreparable damage to molecules, such as DNA, lipids, and proteins. It is well accepted that oxidative damage plays an important role in the etiology of many chronic diseases and the process of aging (Ames et al., 1993). In addition to natural defense mechanisms, diet may play an important role in disease prevention through ingestion of antioxidant compounds that reduce the oxidative threat to the biological systems.

The prevention of chronic diseases by phytonutrients is not limited to direct antioxidant activity. Other proposed mechanisms include the induction of disease-preventive enzymes, inhibition of disease-promoting enzymes, and inhibition of various cancer-inducing signals (Lambert and Yang, 2003; Waladkhani and Clemens, 2001). It has also been demonstrated that phytonutrients may possess anti-inflammatory and estrogenic activities (Hou, 2003) and may provide health benefits through modulation of cell signaling pathways and gene expression (Williams et al., 2004).

Phenolics and carotenoids represent two major classes of phytonutrients found in fruits and vegetables. Phenolics are ubiquitous plant components that are primarily derived from phenylalanine via the phenylpropanoid metabolism (Dixon and Paiva, 1995). They serve a major role in protecting plants from biotic and abiotic stresses. The hydroxylated aromatic ring characteristic of phenolics is an excellent reducing agent, enabling compounds present in the plant to donate a hydrogen radical to reactive free radicals in biological environments. The aromatic ring is capable of stabilizing the unpaired electron by resonance and terminating the propagation of additional radicals or damaging species. The antioxidant potency of phenolics has been documented in many in vitro studies (Duthie et al., 2000).

Carotenoids are synthesized through the isoprenoid pathway in plant plastids and are stored in the chloroplasts with the function of protecting chlorophyll during photosynthesis (Cunningham and Gantt, 1998). The primary sources of dietary carotenoids include carrots (*Daucus carota* L.), tomatoes (*Lycopersicon esculentum* Mill.), sweet potatoes (*Ipomoea batatas*), spinach (*Spinacia oleracea* L.), and

other green leaf vegetables (Block, 1994). In addition to pro-vitamin A activity, carotenoids act as potent antioxidants in vivo. The conjugated double bond structure is capable of stabilizing an additional electron from a free radical or other reactive compound (Mortensen et al., 2001).

Processing can have a dramatic effect on the phytonutrient content of fruits and vegetables. In this paper, we review various processing factors that influence phytonutrient losses in carrots, a common vegetable and major source of β -carotene in the U.S. diet (Block, 1994; Simon and Wolff, 1987).

PREPROCESSING FACTORS INFLUENCING PHYTONUTRIENT CONTENT OF FRUITS AND VEGETABLES

Carrot phytonutrient content, as well as that of other fruits and vegetables is affected by a number of preprocessing factors including genetics, cultivation practices, environmental growing conditions, maturation, and post-harvest handling and storage conditions, and excellent reviews are available on these topics (Goldman et al., 1999; Kalt, 2005). Although growers and processors can control many of these factors, a wide variation in phytonutrient content among raw materials is inevitable due to differences in cultivar and environmental growing conditions, as well as storage time before processing. Fresh commercial carrots consist of a number of cultivars that are commonly grown throughout the U.S. and Mexico, with a wide variation in phytonutrient content. For example, Simon and Wolff (1987) reported that both total and individual carotenes in carrots varied significantly (up to 5-fold) due to differences in genotype, growing location and year. The effect of raw product quality on variation in total β -carotene and total phenolic content of processed carrot puree was apparent in a study by Talcott et al. (2001). Commercially processed samples representing 10 lots of product obtained from three processing locations over a one year period varied 2.5-fold in both total phenolics and total carotenoids, with the variation between each processing location being greater than variation within each location. Furthermore, root size is an important factor affecting the 6-methoxymellein (6-MM) content of carrots, with small roots having higher levels than large roots (Talcott and Howard, 1999; Kidmose et al., 2004). In contrast, root size did not affect carotenoid content (Kidmose et al., 2004).

PHYTONUTRIENTS IN CARROTS

Carrots are a significant source of phytonutrients, including phenolics (Babic et al., 1993a), polyacetylenes (Hansen et al., 2003; Kidmose et al., 2004) and carotenoids (Block,

1994). Due to appreciable levels of a variety of different compounds, carrots are considered a functional food with significant health-promoting properties.

Carotenoids are distributed throughout the plant, but are most abundant in the root tissues of carrots, with phloem tissue having the highest levels, peels having intermediate levels and xylem having the lowest levels (Howard and Dewi, 1996). The predominant carotenoids, β -carotene and α -carotene, account for about 60% and 20%, respectively, of the total carotenoid content in mature orange carrots, with γ - and ζ -carotenes, β -zeacarotene, and lycopene present in very small levels (Heinonen, 1990; Simon and Wolff, 1987). Carotenoids and other lipophilic components may contribute up to 4.8% of the total antioxidant capacity of raw carrots (Wu et al., 2004).

Phenolics in carrots are present throughout the root, but are highly concentrated in the periderm tissue (Mercier et al., 1994). In carrots, the two major classes of phenolics are hydroxycinnamic acids (HCAs) and *para*-hydroxybenzoic acids (*p*-HBAs) (Babic et al., 1993a). Although HCAs and *p*-HBAs possess antioxidant activity, carrots generally rank low in antioxidant capacity compared to other fruits and vegetables due to their low phenolic content (Ou et al., 2002; Wu et al., 2004).

The demand for fresh and fresh-cut vegetables, including carrots, has increased significantly over the past decade (Higgins 2000), but they are not always readily available due to cost, growing season, and logistical issues. Hence, carrots are frequently stored for several months under refrigerated conditions or processed to extend storage life. They are currently available as raw, fresh-cut (including sticks, sliced, shredded, and mini-peeled), canned and frozen products. Due to the widespread and diverse availability of carrots, there is a need to understand the changes in phytonutrients that may result from processing and long-term storage.

EFFECTS OF STORAGE ON PHYTONUTRIENT CONTENT OF FRESH CARROTS

Phenolics. The changes in phenolic content and antioxidant capacity of raw, unprocessed carrots with storage has received little attention, but it is well known that several phenolic compounds including chlorogenic acid, isochlorogenic acid, and the bitter principle 6-MM can increase during storage if carrots are wounded or exposed to ethylene or microbial infection (Heatherbell and Wrolstad, 1971; Lafuente et al., 1996; Sarkar and Phan, 1974). Kidmose et al. (2004) determined that the levels of 6-MM did not change during 4 months of cold storage. The levels of 6-MM can be reduced by peeling, ultra-violet treatment or boiling (Mercier et al., 1994; Talcott

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and Howard, 1999). The total phenolic content of carrots stored at refrigerated temperatures for 3 months doubled, while storage at room temperature for 10 d, designed to simulate market conditions, increased phenolic content 2- to 3-fold (Zhang et al., 2005). In our studies, the HCA and *p*-HBA contents of raw carrots that were peeled before analysis remained relatively stable during 3 months of refrigerated storage (data not shown).

Carotenoids. The changes in raw carrot carotenoid levels during refrigerated storage are reported to be minimal (Gross, 1991; Kidmose et al., 2004). This was also observed in our studies of carrots stored at 4.4 °C for 3 months (Hager and Howard, unpublished data, Fig. 1). Howard et al. (1999) observed an increase in β -carotene in two carrot cultivars during the first two weeks of refrigerated storage, but observed no changes during subsequent storage.

EFFECTS OF MINIMAL PROCESSING ON PHYTONUTRIENT CONTENT OF FRESH CARROTS

Consumption of fresh-cut fruits and vegetables has greatly increased in the past decade as consumers demand more fresh-like foods and greater convenience (Higgins 2000). As a result, various fresh-cut carrot products, such as shredded, baby, mini-peeled, and sliced have become widespread. Changes in phytonutrient content of fresh-cut products is expected since there is no thermal treatment used to inactivate enzyme systems that can modulate (increase or decrease) levels of phytonutrients. The use of modified atmosphere packaging (MAP), designed to increase shelf life of fresh-cut carrots through suppression of respiratory activity, ethylene biosynthesis, and growth of spoilage microorganisms can also influence phytonutrient retention through modulation of enzyme systems.

Phenolics. Phenolic levels in fresh-cut carrots can increase significantly during storage as a result of wounding and stimulation of the phenylpropanoid pathway. In fresh-cut carrot slices, HCAs, evaluated by HPLC at 325 nm and quantified as chlorogenic acid equivalents, increased about 6-fold during refrigerated storage in perforated packages for 21 d (Hager and Howard, unpublished data, Fig. 2). The *p*-HBA content, evaluated by HPLC at 280 nm and quantified as *p*-HBA equivalents, increased with storage between d 0 and 3, and then remained stable for the remainder of the 21-d storage.

Babic et al. (1993a) evaluated changes in phenolic content in shredded carrots during refrigerated storage under air and MAP conditions. For carrots stored in air, the levels of chlorogenic acid and dicaffeoylquinic acid increased 4-fold during storage for 7 d, but levels of *p*-HBAs increased only slightly with refrigerated storage for 7 d, with the largest increase occurring at the end of storage. Storage of shredded carrots under controlled atmospheres containing 30% CO₂ and/or 0% O₂, or in polypropylene film pouches significantly reduced the accumulation of phenolic compounds during 7 d of refrigerated storage.

Fig. 1. Total carotenoid and total α - and β -carotene isomer content of raw (a), frozen (b), and canned (c) carrot slices during 3 months storage at 4 °C (Hager and Howard, unpublished data). Bars represent $\pm$ standard error.

Fig. 2. Total hydroxycinnamic acid (HCA) and *p*-hydroxybenzoic acid (*p*-HBA) content in fresh-cut carrot slices during storage for 21 d at 4 °C (Hager and Howard, unpublished data). Bars represent $\pm$ standard error.

Table 1. Potential sites and processing variables influencing the phytonutrient content of thermally processed carrots.

Process unit operation	Variables influencing phytonutrient content
Washing	Spray vs. immersion
Blanching	Water vs. steam
	Time and temperature
Peeling and trimming	Depth of peeling
	Amount of crown and tip removed
Particle size reduction	Degree of exposed surface area
Brining	Carrot to brine ratio
	Brine composition
Retorting	Static vs. agitated
	Time and temperature

Babic et al. (1993b) also reported that chlorogenic acid content of shredded carrots prepared from four different cultivars and stored in oriented polypropylene film responded differently after 1 d storage at 4 °C, ranging from 0% to 50% of initial content. Alasalvar et al. (2005) reported that shredded purple and orange carrots accumulated total phenolics during 13 d refrigerated storage, but purple carrots did not synthesize additional anthocyanins during storage. They also found that that MAP treatments affected phenolic content, with a 95% O₂ + 5% CO₂ atmosphere promoting phenolic synthesis, and a 90% N₂ + 5% O₂ + 5% CO₂ atmosphere retarding phenolic synthesis. Other studies on carrot sticks (Howard et al., 1994) and carrot slices (Leja et al., 1997) also report an increase in total phenolics during refrigerated storage.

The changes in phenolic content during storage of fresh-cut carrots are associated with wound-induced stimulation of the enzyme phenylalanine ammonia lyase (PAL). Increased PAL activity with storage has been observed in carrots stored in air (Howard et al., 1994; Leja et al., 1997), but PAL activity is inhibited by low oxygen environments as observed in MAP storage (Alasalvar et al., 2005; Babic et al., 1993a) or by surface steam treatment (Howard et al., 1994).

Phenolics synthesized in response to wounding can markedly affect the antioxidant capacity of fresh-cut carrots. The hydrophilic antioxidant values of fresh-cut carrot slices measured by the ORAC assay increased 6-fold during storage, paralleling the increase in total phenolics of HCAs and *p*-HBAs (data not shown). The linear relationship observed between the two variables ($R^2 = 0.989$) demonstrated that wound-induced production of phenolics during storage can significantly boost antioxidant capacity. In contrast, Alasalvar et al. (2005) did not observe an increase in antioxidant capacity by the ORAC assay in shredded orange and purple carrots during 13-d storage, despite marked increases in total phenolics.

Carotenoids. Studies evaluating carotenoid changes in fresh-cut carrots during storage have produced contradictions. According to Howard and Dewi (1996), the removal of peel resulted in significant losses of β -carotene, α -carotene, and total carotenoids in mini-peeled carrots. In our studies, levels of all-*trans*- β - and α -carotenes in peeled fresh-cut carrot slices increased 53% and 29%, respectively, with 21-d storage at 4 °C (data not shown). In contrast to these results, Li and Barth (1998)

reported that mini-peeled carrots stored under refrigeration for 4 weeks retained only 30% of their original α - and β -carotene contents, whereas Howard and Dewi (1996) reported a 19% loss in total carotenoids in mini-peeled carrots during refrigerated storage. Shredded orange carrots, in a study by Alasalvar et al. (2005), lost small quantities of carotenoids with 13-d storage, although a MAP atmosphere of 90% N₂ + 5% O₂ + 5% CO₂ resulted in greater retention than a 90% O₂ + 5% CO₂ atmosphere. It has been proposed that exposure of sliced carrots to oxygen may induce auto-oxidation as well as enhance carotene-degrading enzymes. Since many enzymes are stimulated upon wounding, it is possible that synthesis of carotenoids may occur during storage of fresh-cut carrots, especially if they are stored in air. Another potential factor influencing conflicting results for carotene degradation in fresh-cut carrots is extraction efficiency. The complete extraction of carotenoids may be difficult after storage due to the accumulation of lignin on the abraded carrot surface (Howard and Griffin, 1993). There have been no reports on changes in carotene isomers in response to minimal processing and storage, but our results indicate that levels of *cis* isomers do not change during refrigerated storage. Since *cis* isomers are formed primarily as a result of direct light and heat exposure (Gross, 1991), no changes in isomer content are expected under refrigerated (4 °C) and dark storage conditions. The application of cellulose-based edible coatings has been shown to reduce carotene losses during storage of mini-peeled carrots (Li and Barth, 1998; Chen et al., 1996).

EFFECTS OF PHYTONUTRIENT STRUCTURE AND CELLULAR LOCALIZATION ON LOSSES DURING PROCESSING

The retention of phytonutrients during processing is influenced by chemical structure, which determines solubility, and cellular localization. Water-soluble phytonutrients including various classes of phenolics, such as phenolic acids, hydroxycinnamates and flavonoids (primarily anthocyanins, flavonols, flavones, procyanidins), readily leach into the water during blanching and into the brine during canning. In contrast, carotenoids are well-retained during blanching and canning due to their nonpolar nature, although losses can occur due to thermal degradation and oxidation. Localization of phytonutrients within plant cells can also influence losses during processing.

Phenolics compartmentalized in the vacuole and apoplast are readily lost due to membrane disruption following thermal treatments, while cell wall-bound phenolics resist leaching and may be more easily extracted or bioavailable after processing due to tissue softening. Carotenoids are contained within chloroplasts or chromoplasts in membrane-protein complexes. Thermal processing causes tissue softening and destruction of the membrane-protein complex, facilitating carotenoid extractability. This is commonly cited as one of the reasons why many processed vegetables are reported to have higher levels of carotenoids than their fresh counterparts (Dewanto et al., 2002; Lessin et al., 1997; Shi and Le Maguer, 2000). Factors such as leaching of soluble solids into the liquid canning medium and inactivation of carotene oxidizing enzymes are also reported to increase amounts of carotenoids caused by thermal processing (de Sa and Rodriguez-Amaya, 2004; Edwards and Lee, 1986).

PROCESSING FACTORS INFLUENCING PHYTONUTRIENT LOSSES DURING PROCESSING

Preparation and processing steps contain many potential areas for loss of carrot phytonutrients during canning operations (Table 1). Raw carrots must be washed thoroughly to remove dirt and debris before blanching and minor losses of water-soluble phytonutrients may occur if epidermal tissues have been damaged. After washing, carrots are commonly blanched by immersion in hot water or exposure to steam before freezing or canning in order to remove intercellular gases, inactivate enzymes, facilitate peeling, slicing and dicing, and clean the root. Blanching is essential for the inactivation of enzymes that can cause loss of quality in frozen vegetables during storage, but significant losses of water-soluble phytonutrients can occur due to leaching into the blanch water. In regard to phytonutrient retention, steam blanching is preferable to water blanching due to reduced leaching of water-soluble components. Furthermore, removal of tissues such as skins during processing can have a marked effect on phytonutrient retention. In most produce, carotenoids and flavonoids, located predominantly in epidermal tissue, are removed by peeling operations (manual, steam or lye assisted) before processing, which can greatly reduce the concentration of compounds in processed products. In juice processing, significant amounts of phytonutrients are retained in the press cake residue after pressing. Hence, by-products of fruit and vegetable processing represent promising sources of compounds with bioactive properties that could be exploited in the development of novel food ingredients and dietary supplements (Moure et al., 2001; Schieber et al., 2001).

The size and type of carrot product (whole, halved, quartered, diced, sliced, julienne, puree) may influence phytonutrient retention due to variation in the surface area exposure. Although a study has not been conducted comparing phytonutrient retention in different types of carrot products that vary in piece size,

it is likely that the higher amount of disrupted cells and exposed surface-area to volume ratio of small pieces would promote greater leaching of water-soluble phytonutrients. Carrot purees are distinctly different from other canned carrot products in that only a small amount of water is added to control product consistency. Greater retention of water-soluble phytonutrients in purees, in comparison to products canned in water, would be expected since compounds are trapped within the product matrix, whereas extensive leaching of phytonutrients can occur in products canned in aqueous media.

The type of retort used for sterilization can also impact the phytonutrient content of canned carrots. In a static system, cans or jars remain stationary throughout the sterilization process resulting in slow heat penetration, lengthy process times, and lack of uniform heating. In other rotary processing systems, the cans or jars may be rotated end-over-end or allowed to rotate on their axes during the sterilization process. The agitation produced by rotary processing improves heat distribution and uniformity throughout the can and greatly reduces process time, enabling greater color and texture retention (Abbatemarco and Ramaswamy, 1994). However, Brownmiller (2000) found that rotary- and still-processed sliced carrots had similar color and provitamin A activity, but rotary-processed carrots had lower levels of total phenolics and ORAC values than still-processed carrots. Sterilization time and temperature can also influence retention of phytonutrients. Degradation of carotenoids follows first-order kinetics; therefore, high-temperature short-time processing treatments have been used successfully to retard degradation of carotenoids in processed carrots (Chen et al., 1994; Chen et al., 1995). Although losses of naturally occurring antioxidant phytonutrients in fruits and vegetables occur during sterilization, especially if they are processed in brine, the formation of Maillard reaction products during high temperature processing can result in elevated antioxidant capacity (Nicolini et al., 1999). The antioxidant activity of Maillard reaction products has been attributed to the accumulation of high molecular weight compounds, called melanoidins, formed in the advanced stages of the reaction that also contribute brown coloring to the product (Manzocco et al., 2001).

THERMAL PROCESSING EFFECTS ON PHYTONUTRIENT CONTENT OF CARROTS

Blanching, freezing, and frozen storage

Phenolics. Thermal treatments used in blanching and canning can significantly impact the phenolic content of carrots, especially if water is used as the heating medium. Another factor influencing phenolic content during thermal treatments is tissue softening associated with cell wall structural changes. Degradation of cell wall pectic substances can loosen the cell wall-middle lamella complex and enhance the extraction of phenolics esterified to cell wall polymers (Beveridge et al., 2000). Several studies have reported on phenolic

losses in blanched and frozen carrots. Carrot cubes blanched in water retained only 52% of chlorogenic acid, the major phenolic found in carrots (De Maria et al., 1998). In our studies we found that the phenolic content (HCAs and *p*-HBAs) of fresh carrots was 31% and 28% higher than that of canned and frozen carrots, respectively; however, the *p*-HBAs, primarily esters, were retained to a greater extent in frozen and canned samples due to their lower water solubility (data not shown). Ninfali and Bacchiocca (2003) reported that frozen carrots analyzed immediately after freezing retained only 40% of the original total phenolics in raw carrots, whereas, in our studies, frozen carrots, as compared to raw carrots, retained 6% and 71% of HCAs and *p*-HBAs, respectively. However, we found that the phenolic content remained relatively stable from 0 to 3 months frozen storage. In contrast to these reports, Puupponen-Pimia et al. (2003) reported no loss in total phenolics or antioxidant capacity measured by the 2,2-diphenyl picrylhydrazyl (DPPH) assay in carrots after blanching or during long term frozen storage.

Carotenoids. Several studies report an increase in total carotenoids after steam blanching (Howard et al., 1999; Puupponen-Pimia et al., 2003; Sulaeman et al., 2001). Blanching has also been reported to result in isomerization of carotenoids (Desobry et al., 1998).

Despite slight variations, our results indicate that negligible changes in carotenoids occurred during 3 months frozen storage (Hager and Howard, unpublished data, Fig. 1). These results are consistent with other studies reporting that carotenoids in carrots are relatively stable during long-term frozen storage (Howard et al., 1999; Kidmose and Martens, 1999; Puupponen-Pimia et al., 2003). In contrast to these studies, Desobry et al. (1998) reported a 60% loss of carotenoids in sliced carrots stored for 12 months at -20 °C. In comparing carotenoid losses over two processing seasons, Puupponen-Pimia et al. (2003) reported losses in total carotenoids from 6 to 12 months frozen storage for one year, but found no losses the following year, when the total carotenoid content of the raw material was much lower.

Canned

Phenolics. A variety of canned (whole, sliced, quartered, diced, julienne) and jarred (purees) carrot products are commonly consumed in the U.S. All of these products are pressure sterilized (retorted) to achieve commercial sterility. The unit operations involved in processing, especially those involving elevated processing temperatures, can significantly alter the phenolic content of carrots. In a study conducted in a commercial setting, the effects of processing line location and batch tank holding temperature, as well as retorting temperature on the total phenolic content of carrot puree was studied (Howard et al., 1996). Increasing batch tank temperatures from 82.2 to 93.3 °C decreased the total phenolic content of carrot puree by 13%, but retorting the samples increased the total phenolic content by >40% at all batch temperatures. Retort temperature

also impacted total phenolic content, with puree retorted at 123.9 °C having higher levels of total phenolics than purees retorted at 118.3 and 121.1 °C. These results demonstrated that retorted puree had much higher levels of total phenolics than blanched puree, which was attributed to degradation of large molecular weight phenolics during retorting, release of cell wall-bound phenolics, and enhanced extraction of phenolics. In another study, carrot puree was retorted with and without periderm tissue after a long and short blanch time (Talcott et al., 2000). Processed puree was shown to have higher levels of phenolics and antioxidant capacity than fresh carrots, and samples with periderm had higher levels of total phenolics and antioxidant capacity than samples without periderm. The increase in phenolics observed after processing and one week storage at 40 °C was attributed to the oxidation and hydrolysis of cell wall phenolics, primarily benzoic and cinnamic acid derivatives. In contrast to the studies on carrot puree, the HCA and *p*-HBA contents of retorted carrot slices decreased by 75% and 30%, respectively, but the levels of both phenolic classes remained relatively stable from 0 to 3 months storage (data not shown). The discrepancies between results obtained for carrot puree and carrot slices can be explained by the different methods used to process the products.

Carotenoids. The two primary causes of losses of α - and β -carotenes in carrots during processing are oxidation and isomerization. Heat, ultraviolet/visible light, oxygen, and acids are capable of isomerizing and oxidizing the active all-*trans* form of carotenoids (Chen et al., 1994). Geometric isomerization of all-*trans* α - and β -carotenes to the *cis* α - and β -carotene forms can occur during processing, due to the high temperature conditions (Zechmeister, 1944; Chandler and Schwartz, 1988). The primary *cis* isomers formed during thermal processing are 9-*cis*, 13-*cis*, 15-*cis*- β -carotenes, and 15-*cis*- α -carotenes, although light exposure is the primary cause of 9-*cis* isomers of β -carotene (Chen et al., 1994).

Although isomerization and oxidation occur during processing, analysis of high carotenoid-containing fruit and vegetables has shown that processing increases carotenoid levels, even after accounting for the loss of water-soluble nutrients in water or steam used for blanching or aqueous brine used for canning (Chandler and Schwartz, 1988; Dietz et al., 1988). The greater quantity of carotenoids observed in processed fruits and vegetables may be associated with increased extractability of the carotenoids due to tissue softening and/or disruption of the caroteno-protein complex. In carrots 3.5% of β -carotene and 2.3% of α -carotene are part of the yellow carotene-protein complex (Milicua et al., 1991). Enhanced extractability of processed fruits and vegetables may also be associated with increased bioavailability of carotenoids in vivo. The human plasma content of *trans* carotenoids was greater in women that consumed processed rather than raw carrots despite losses due to isomerization (Rock et al., 1998).

In our study canned samples had significantly higher levels of *cis* isomers than fresh

carrots, with minimal changes in carotenoids observed during storage (Howard and Hager, unpublished data, Fig. 1). The 13-*cis*- β -carotene was the major isomer formed during canning (data not shown), which confirmed findings by Lessin et al. (1997). Canned samples contained lower levels of lutein than frozen and fresh carrots (data not shown); however, an increase in total carotenoids was observed with canning (data not shown). Although *cis* isomers of carotenoids formed during canning have reduced provitamin A activity, many of the isomers retain free radical scavenging capacity (Bohm et al., 2002).

Other processed products

Carrot juices, dehydrated products, and fried carrot chips are currently available to consumers, but limited information is available on their phytonutrient content.

Phenolics. Ninfali and Bacchiocca (2003) reported total phenolic contents of fresh and frozen carrot juices as 0.26 and 0.20 mg·g⁻¹ juice, respectively. The total phenolic contents of the extracted pulps from fresh and frozen carrots were 0.14 and 0.10 mg·g⁻¹ wet pulp, indicating significant losses of phenolics occurred during juice extraction. With significant levels of phenolics embedded in the cell wall matrix (Parr et al., 1997), removal of carrot pulp was a likely source of phenolic losses.

Two commercial carrot juices analyzed by the total oxidant scavenging capacity (TOSC) assay indicate that the carrot juices are capable of scavenging peroxy, peroxynitrite, and hydroxyl radicals (Lichtenthaler and Marx 2005). Despite phenolic losses observed in juices, a study by Indrawati et al. (2004) on the kinetics of water-soluble antioxidants indicated that higher temperature processing increased antioxidant activity measured by the Trolox equivalent antioxidant capacity (TEAC) assay, a change attributed to the formation of Maillard reaction products.

Carotenoids. As a low acid food, carrot juice must be retorted to achieve commercial sterility. An alternative approach is to acidify and then sterilize the juice using a mild pasteurization process. Chen et al. (1995) determined how four different processing treatments affected the vitamin A content of carrot juice, and found that conventional canning (121 °C for 30 min) resulted in the highest destruction of carotenoids followed by high temperature short time heating at 120 °C for 30 s, 110 °C for 30 s, and acidification plus 105 °C heating for 25 s. Acidification to reduce thermal processing reduced the isomerization of carotenoids compared to the other more heat intensive processes (Chen et al., 1995).

The β -carotene content of dehydrated carrots (chopped, shredded, and powdered) was evaluated in a study by Suman and Krishna-Kumari (2002) and it was determined that the powder retained the most β -carotene during 3 months storage. Type of drying method also affected carotenoid retention, with sun-drying resulting in greater retention of β -carotene than solar or hot air cabinet drying. Negi and Roy (2001) reported that blanching of carrots before dehydration resulted in greater reten-

tion of β -carotene. Dried carotenoid powder, extracted from carrot waste, was evaluated under different light and temperature conditions during storage by Chen and Tang (1998). They determined that isomerization of carotenoids occurred readily under high storage temperatures (45 °C) or extended exposure to light. Sulaeman et al. (2001) evaluated how different frying oils and temperatures affected the carotenoid content of carrot chips, and found that frying temperature, but not oil type, influenced retention of total carotenoids. The results indicated that frying at 165 or 175 °C, as opposed to 185 °C, reduced the level of carotenoid losses. Across all temperatures and oil types, about 85% of the initial carotene content of the carrots was retained in the carrot chips.

CONCLUSIONS

Changes in phytonutrients during processing and storage of most fruits and vegetables have received little attention, but there are known to be some significant effects in carrots. Minimally processed, or fresh-cut carrots, may have additional health benefits under nonMAP conditions due to the accumulation of phenolics, but this must be balanced with potential losses in sensory quality and shelf-life. There is strong evidence that carotenoid losses may occur during storage of fresh-cut carrots, but the degradative mechanisms are not clear and have led to conflicting results.

There is evidence that thermal processing in aqueous media results in a significant loss in water-soluble components, such as phenolics, but it increases the availability of carotenoids. Storage of canned, frozen, or dehydrated carrots appears to have marginal effects on phenolic and carotenoid contents. A significant loss of phenolics occurs during processing of carrot juice, but the content of carotenoids and phenolics in juices are stable during storage. Carotenoids also appear to be well-retained during frying, but the effects on phenolics are unknown.

The conflicting results obtained in many studies involving processed carrots are perplexing, but most likely reflect variation in raw materials, processing conditions, storage conditions, extraction techniques and analytical methodologies. It is clear that further studies are needed to accurately determine phytonutrient losses in fruits and vegetables. These studies should be designed to simulate commercial processing operations, and should include mass balance studies throughout the processing unit operations in order to assess the true retention of phytonutrients. There also is a need to utilize standardized methods for the extraction and analysis of carotenoids, phenolics and antioxidant capacity.

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