COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Carrots of Many Colors Provide Basic Nutrition and Bioavailable Phytochemicals Acting as a Functional Food

Sara A. Arscott and Sherry A. Tanumihardjo

ABSTRACT: Hippocrates, a philosopher who lived from 460 to 359 BC is often quoted as saying, "Let your food be thy medicine and your medicine be thy food." Having lived just shy of a century at a time when life expectancies were much less, he must have understood the importance of a healthy diet. A diet high in fruit and vegetables has been linked to optimal health in a variety of studies. One vegetable that has gained popularity is the carrot due in part to the introduction of "cut & peel" convenience packages. Although most people in the United States know carrots as an orange vegetable that can be eaten raw or in a variety of cooked dishes, original carrots were yellow and purple. These carrot varieties are currently undergoing phenotypic recurrent selection to improve the profile of compounds considered to be beneficial. This process is called biofortification, which has increased provitamin A content by >40% since 1970. The most novel carrot produced to date is an orange–purple–red variety that not only contains provitamin A activity as α- and β-carotene, but also contains anthocyanins and the nonprovitamin A carotenoid lycopene, of which both are potent antioxidants. A functional food is one that provides benefit beyond basic nutrition. Biofortified carrots of many colors not only provide vitamin A, but may contribute to optimal health. Because supplements have not been shown to be overly beneficial, except for correcting deficiencies, whole food-based approaches to enhance health by utilizing functional foods such as biofortified carrots should be considered.

Introduction

Carrots (*Daucus carota* L.) are more than a versatile orange vegetable. Original carrots were purple and yellow, initially described in the 10th century in Iran and northern Arabia (Simon 2000). These carrots spread east and west from this center to be known across the Middle East, North Africa, Europe, and China by the mid-15th century. Yellow carrots were preferred in northern Europe until the development of orange carrots in The Netherlands in the 18th century. White carrots were noted in Europe and red carrots are thought to have originated in China around this time. Orange carrots have mainly supplanted these other colors in the west, but purple and yellow carrots persist in some areas of Turkey, India, and China and red carrots in Japan. Thorough documentations of the domestication and historical development of carrots have been published (Rubatzky and others 1999; Simon 2000). This review describes the nutritional value of orange as well as that of other carrots, nutritional improvements researchers have made through biofortification, the bioavailability of pigments from carrots and their impact on vitamin A status, and, finally, the putative health benefits attributed to carrots. Whole food-based approaches to enhance health by utilizing functional foods like biofortified carrots are currently popular (Jacobs and Tapsell 2007).

MS 20091032 Submitted 10/16/2009, Accepted 11/23/2009. Authors are with Univ. of Wisconsin-Madison, Interdepartmental Graduate Program in Nutritional Sciences, 1415 Linden Drive, Madison, WI 53706, U.S.A. Direct inquiries to author Tanumihardjo (E-mail: sherry@nutrisci.wisc.edu).

Carrot nutritional importance

Carrot is an economically important horticultural crop that has gained popularity in recent decades due to increased awareness of its nutritional value. Orange carrots are highly revered as "good for the eyes" due to their high content of hydrocarbon carotenoids, a class of phytochemicals that are often precursors to vitamin A. α- and β-Carotene predominate in orange carrots (Figure 1). Dietary vitamin A is consumed either as preformed vitamin A from animal-based or fortified foods, or as provitamin A carotenoids supplied by plant-based foods. In 2004, vegetables contributed nearly 27% of the total vitamin A in the available U.S.

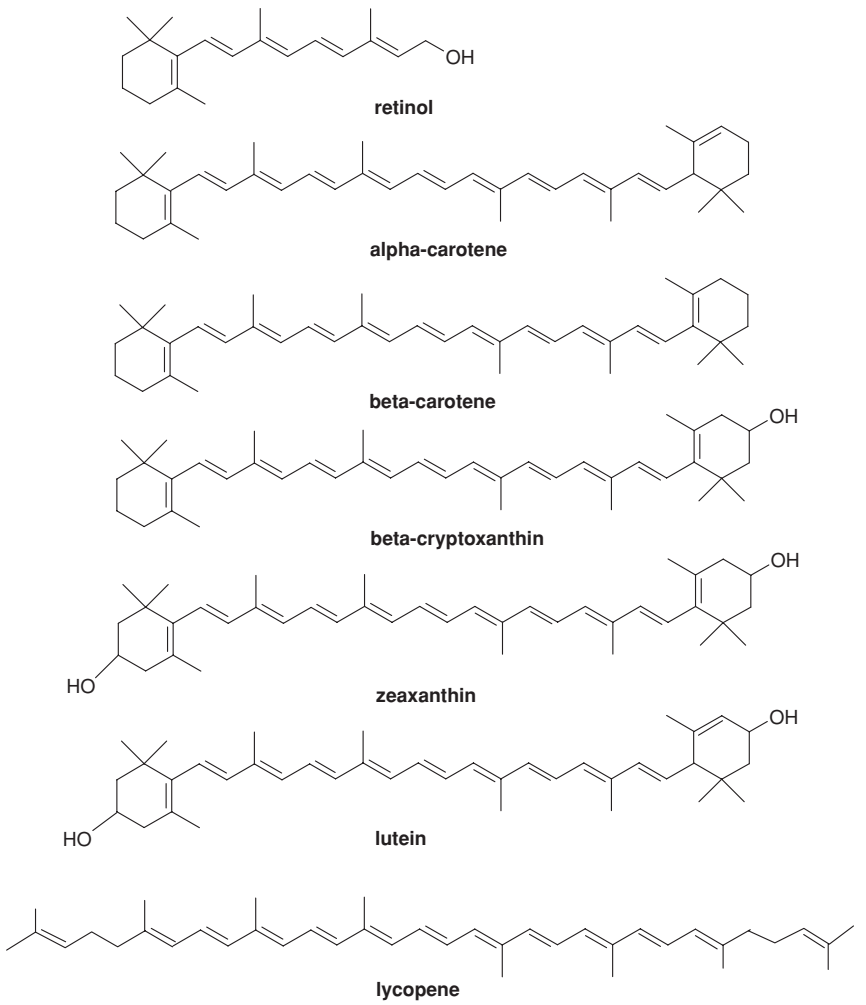

Figure 1 — The basic structures of common carotenoids found and quantified in human serum. Three of these are precursors to retinol (vitamin A). α- and β-Carotene are found in orange carrots and some varieties of red and purple carrots; lutein predominates in yellow and yellow–purple carrots; and lycopene is in red and the novel purple–orange–red carrot (Mills and others 2008).

food supply (Table 1), up from 18% in 1970 (USDA-ERS 2009). In 2007, carrots supplied an estimated 37% of the available fresh vegetable β-carotene, the major provitamin A carotenoid in the U.S. diet (Table 2).

The popularity of carrots has also been influenced by the introduction of the convenient prepackaged "cut & peel" or "baby carrots," making carrots a leading vegetable snack item (USDA/ERS 1997). Annual U.S. per capita consumption of carrots in 2005 was 11.6 pounds per person. Fresh-market carrots account for nearly three-fourths of all carrots consumed in the United States, and at $0.10 per serving, are second only to potato as the most affordable vegetable (USDA ERS 2004). U.S. carrot consumption, which rises with age and income, varies with race (USDA ERS 2007). In 2005, non-Hispanic Whites (10.7 pounds) and Asians (10.3 pounds) ate the most carrots at home, followed by Hispanics (6.8 pounds) and Blacks (4.9 pounds).

World production

While carrots are not a major staple food in any part of the world due to low energy density, they are considered a primary vegetable in many countries. China, Russia, and the United States are the top 3 producers of carrots globally, contributing almost 50% of the world carrot crop (Table 3). Production and availability of carrots, and nearly all horticultural commodities that contain carotene, are increasing worldwide (Simon 1990). Table 4 illustrates how carrot production in all major regions has outpaced population increases, although this does not necessarily reflect per capita availability or consumption because it does not reflect measurable uses, such as farm inputs, exports, ending stocks, and industry. The increase of world carrot production has also outpaced total world vegetable production (Rubatzky and others 1999). Carrots are a temperate region crop and production in tropical regions is more limited; however, advancements in subtropical carrots have contributed to increased production capacity in South America (Simon 2000). Carrot yields have remained steady in much of Africa, but production trends show increases (Table 4), and expanded production in these areas is desirable.

Nutritional Value

The storage root of the carrot is the most commonly consumed portion of the plant, although the tender young foliage is occasionally used as a stir-fried herb and in salads in China and Japan (Rubatzky and others 1999). The roots, however, are the sole focus of this review. Carrots do not supply a significant amount of calories to the human diet, but do supply nutrition in the form of phytochemicals, such as carotenoids, anthocyanins, and other

Table 1—Vitamin A and carotenoid contributions from major food groups to U.S. food supply, per capita per day in the United States.[a]

Food group	Vitamin A μg RAE[b] (%)	Carotene μg (%)
Meat, poultry, and fish	345.6 (32.0)	0.0 (0.0)
Dairy products	189.0 (17.5)	14.3 (2.1)
Eggs	69.1 (6.4)	0.0 (0.0)
Fats and oils	88.6 (8.2)	13.6 (2.0)
Fruits	25.9 (2.4)	51.0 (7.5)
Legumes, nuts, and soy	0.0 (0.0)	0.7 (0.1)
Vegetables	289.4 (26.8)	559.6 (82.3)
White potatoes	0.0 (0.0)	0.0 (0.0)
Dark green, deep yellow	239.8 (22.2)	474.6 (69.8)
Other vegetables	50.8 (4.7)	85.0 (12.5)
Grain products	54.0 (5.0)	4.8 (0.7)
Sugars and sweeteners	0.0 (0.0)	0.0 (0.0)
Miscellaneous	18.4 (1.7)	36.0 (5.3)

[a]2004 data from USDA/ERS Food Availability (per capita) Data System 2009. Represents disappearance of food into the marketing system and includes substantial quantities of nonedible food portions and food lost to human use through waste, trimming, cooking, and spoilage in the home and marketing system. Data typically overestimate amounts of food and nutrients people actually ingest.
[b]1 μg RAE (1 retinol activity equivalent) = 1 μg all-*trans*-retinol, 12 μg dietary all-*trans*-β-carotene, or 24 μg other dietary provitamin A carotenoid.

Table 2—Supply of β-carotene from selected vegetable crops to U.S. population.

Vegetable crop	Per capita availability[a] kg/yr	β-carotene[b] ppm	β-carotene availability per capita μg/d	β-carotene availability per capita %[c]
Bell peppers	2.8	2	15.5	0.6
Broccoli	2.5	8	54.5	2.1
Brussels sprouts	0.1	4	1.6	0.1
Cabbage	3.6	0.1	6.5	0.3
Carrots	3.9	88	968.0	37.1
Celery	2.7	1.5	11.2	0.4
Collard greens	0.2	33	20.9	0.8
Sweet corn	3.8	0.1	1.5	0.1
Cucumbers	2.6	1.4	10.1	0.4
Kale	0.2	92	39.3	1.5
Iceberg lettuce	8.6	2	45.6	1.8
Romaine and leaf lettuce	6.4	13	225.6	8.6
Onions	9.3	0	0	0.0
Potatoes	17.1	0.06	2.8	0.1
Pumpkin	2.1	70[d]	405.2	15.5
Snap beans	0.9	4	9.8	0.4
Spinach	0.8	56	126.5	4.9
Squash[e]	1.8	2[f]	11.2	0.4
Sweet potatoes	2.1	92	542.3	20.8
Tomatoes	7.8	4	85.5	3.3

[a]Fresh vegetables, retail weight. From USDA Economic Research Service 2009, calculated as the residual of commodity's total annual available supply after subtracting measurable uses, such as farm inputs, exports, ending stocks, and industrial uses.
[b]From USDA-NCC Carotenoid Database for U.S. Foods – 1998. References raw vegetable concentrations except where noted.
[c]Reflects per capita fresh vegetable availability data which does not account for some vegetables such as fresh green peas; various Asian vegetables, such as bok choy, turnips, and rutabagas; fresh beets; parsnips; leeks; scallions (green onions); rhubarb; domestically-produced greenhouse vegetables; and other specialty and dehydrated vegetables.
[d]Canned.
[e]All squash varieties.
[f]Acorn winter squash only, raw. Squash β-carotene concentrations vary considerably based on variety.

phenolic compounds. The greatest nutritional interest in carrots stems from their phytochemical content, but research has also focused on carrots as a source of fiber. In Table 5, the nutrient composition of carrots is compared to other commonly consumed vegetables in the U.S. diet that contribute to total β-carotene intake based on the National Health and Nutrition Examination Survey (NHANES) 2003 to 2004, all age groups. Nutrient content of carrots can vary with cultivar (Nicolle and others 2004), season (Horvitz and others 2004), environmental conditions (Rosenfeld and others 1998), and maturity (Phan and Hsu 1973).

Macronutrients and micronutrients

Carrot root is approximately 88% water, 1% protein, 7% carbohydrate, 0.2% fat, and 3% fiber (USDA 2008). The carbohydrate fraction is almost exclusively simple sugars, predominantly sucrose, glucose, and fructose, with a small amount of starch (USDA 2008). Carrots contribute significantly to dietary vitamin A intake through α- and β-carotene and modestly to other nutrients. A 100-g serving of raw carrot (about 0.75 cup chopped carrot) contributes the following percentages of the Recommended Daily Allowance of a female aged 19 to 30 y: 120% vitamin A (as retinol activity equivalents), 4.5% vitamin E, 3% calcium, 4% magnesium, 7% potassium, and 11% fiber.

Carrots contain the B vitamins thiamin, riboflavin, and niacin in appreciable quantities when compared with other commonly consumed vegetables (Table 5). Nicolle and others (2004) found that potassium was the most abundant mineral in 20 cultivars of orange, yellow, white, and purple carrots, with a mean of 579 mg/100 g fresh weight (FW) and a range from 443 to 758 mg/100 g FW. Some minerals were less affected by cultivar, such as calcium, while minerals such as copper and zinc varied more by cultivar. Moreover, as calcium levels increased, iron content also increased. There was no correlation between color and mineral or trace element contents, but dark orange carrots (high β-carotene) had the highest mineral content.

Carrot fiber

Content of dietary fiber and digestible carbohydrate can vary between cultivars and also during processing and storage (Svanberg and others 1997). Food reference tables and reports in the literature vary considerably with regard to fiber values, likely due to different methods of fiber analysis (Marlett 1992). Reports of total dietary fiber values range from 2.42% (Rani and Kawatra 1994) to 6.4% (Da Silva and others 2007). Other published values include 2.5% (Marlett 1992), 2.8% (USDA 2008), 3.4% (Svanberg and others 1997), 3.63% (Souci and others 2008), and 4.4% (Ramulu and Udayasekhararao 2006). The insoluble fibers, cellulose and hemicellulose, constitute the greatest portion (50% to 92%) of the total dietary fiber with a very small amount of lignin (4%). The soluble fibers consist of fermentable hemicellulose and pectin (Marlett 1992) and constitute 8% to 50% of total fiber.

Carrot fiber has become of interest to food processers due to the large quantities of carrot waste created in the cut & peel carrot and carrot juice industries. Carrot pomace is the wet carrot shavings produced from carrot processing which is subsequently dried to form a powder. The fiber composition of carrot pomace can differ from whole carrot depending on the processing method. Carrot pomace made from carrot peels had a reduced insoluble to soluble dietary fiber ratio when blanched before drying (Chantaro and others 2007), increasing its perceived quality as a functional fiber for adding to other foods. The water retention and swelling capacities of carrot pomace were relatively high compared to other agricultural byproducts such as apple, pear, and orange pomace (Chantaro and others 2007). The relatively high soluble dietary

Table 3—Carrot production by country, top 20 producers.[a]

Rank	Country	Production (MT)
1	China	8395500
2	Russian Federation	1730000
3	United States of America	1601790
4	Poland	935000
5	Ukraine	706500
6	United Kingdom	677144
7	Italy	641558
8	Japan	630000
9	Germany	555000
10	Netherlands	430000
11	France	417800
12	Turkey	380000
13	Mexico	378517
14	India	350000
15	Belgium	320000
16	Indonesia	308675
17	Belarus	306000
18	Australia	302560
19	Canada	301450
20	Morocco	300000

[a]Source: FAO-ERS 2005.

fiber fraction, high pectic substances in the peels, or the blanching might account for this property. Nawirska and Uklánska (2008) found "Dolanka" carrot to have the highest percentage of soluble fiber when compared with apple, cabbage, strawberry, black currant, and chokeberry pomace. However, previously they found carrot pomace to have the lowest total dietary fiber as well as the lowest relative pectin and soluble hemicellulose compared with apple, cherry, black currant, and pear pomace (Nawirska and Kwasniewska 2003). Differences may be related to different industrial methods of pomace production as well as carrot variety.

The β-carotene content of carrot pomace was reduced approximately 19% by blanching and by drying, although low-temperature drying reduced the β-carotene more (57%) than the higher-temperature drying (46%) likely due to increased dry time (Chantaro and others 2007). Total phenolic content and total antioxidant activity of carrot pomace were both reduced by blanching and increased drying temperatures. These results suggest that the nutritional quality of a functional fiber obtained from carrot pomace is related to the processing method.

Pigments and Other Compounds

Carotenoids are responsible for the yellow, orange, and red colors of carrots, while anthocyanins, a class of polyphenolic compounds, are responsible for the color of purple carrots. All of these pigments have been studied for their health benefits, including protection from certain cancers and cardiovascular disease, and consumer interest in natural whole foods rich in these compounds, often referred to as "functional foods," is growing (Hasler and Brown 2009). Modern vegetable breeders have initiated development of some colored carrot breeding lines (Simon and others 1997; Lazcano and others 2001) to increase the nutritional quality and visual appeal of the food supply.

Carotenoids

Carotenoids are a group of phytochemicals that comprise a family of over 700 compounds in nature (Britton and others 2004) and are responsible for the pigmentation in many fruits and vegetables. Those that predominate and are often quantified in human serum include lutein, zeaxanthin, β-cryptoxanthin, lycopene, and α- and β-carotene (Figure 1). They are synthesized exclusively in plants and serve as the source for all animal carotenoids. Carotenoids are accessory light-harvesting pigments to chlorophyll in the chloroplasts of photosynthetic tissues and in the chromoplasts of nonphotosynthetic tissues such as fruits, flowers, and the roots of carrots. Other functions of carotenoids in plants include photoprotection by quenching the excess energy of excited chlorophyll or singlet oxygen (Gross 1991), and also as an attractant to pollinators such as in flowers. The carotenoids in carrot roots may likely serve none of the previously mentioned purposes and may be the result of mutation (Gross 1991; Simon and others 2008). Carrot root carotenoids occur as pure-pigment crystals in chromoplasts. Each crystal is surrounded by a membrane to form a carotene body (Ben-Shaul and others 1968). The crystalline nature of the carotene in carrots negatively impacts bioavailability (Zhou and others 1996). For comparison, in peppers, pumpkin, and fruit, carotenoids are found in carotenoid-carrying lipid droplets of globulous chromoplasts. In green leaves, the carotenoids are located in the photosystems of the inner chloroplast membranes and are directly associated with lipoproteins and lipids.

Carrot roots are rich in carotenoids. Six carotenes (α-, β-, γ-, and ζ-carotenes, β-zeacarotene, and lycopene) can be routinely separated and quantified in typical and dark orange carrots (Simon and Wolff 1987). The predominant carotenoids are the provitamin A carotenes, that is, α- and β-carotene, accounting for 13% to 40% and 45% to 80% of the carotenoids in orange carrots, respectively (Simon and Wolff 1987; Gross 1991). Early

Table 4—World carrot production 1970–2003.[a]

Year[b]	World	Africa	North and Central America	South America	Asia	Europe	Oceania
1970	7908	214	1099	281	1776	3049	117
1980	10499	383	1328	465	2677	3591	141
1990	13696	558	1773	630	4003	4304	193
2000[c]	20489	913	2619	950	8163	7494	350
2003[c]	23321	1054	2674	982	10801	7484	327
Production change[d]	+195	+392	+143	+249	+508	+145	+179
Population change[e]	+40	+55	+34	+45	+42	+10	+37

[a]FAO Production Yearbook Statistics. Production values = 1000 Mt. China and Asia USSR not included in 1983 estimate; Nigeria not included before 1985.
[b]Production values are average of the preceding 3 y.
[c]Former USSR republics included in appropriate European or Asian grouping.
[d]Change in carrot production from 1970 to 2003, percent.
[e]Change in region population from 1970 to 2003, percent. Source: UN 2009.

Table 5 – Nutrient composition of several common fruits and vegetables that contribute to intake of total β-carotene for comparison to carrot.

Vegetable	Water %	kcal 100 g	g/100 g fresh weight					Vit A μg RAE[a]	mg/100 g fresh weight										
			CHO	Protein	Fat	Fiber	Ash		Vit C	Vit B_1	Vit B_2	Niacin	Vit E	Ca	P	K	Na	Mg	Fe
Carrot	88	41	9.6	1.0	0.2	2.8	1.0	835	5.9	0.07	0.06	0.98	0.66	33	35	320	69	12	0.3
Sweet potato	77	86	20.1	1.6	0.1	3.0	1.0	709	2.4	0.08	0.06	0.56	0.26	30	47	337	55	25	0.6
Cantaloupe	90	34	8.2	0.8	0.2	0.9	0.6	169	37	0.04	0.02	0.73	0.05	9	15	267	16	12	0.2
Tomatoes	94	18	3.9	0.9	0.2	1.2	0.5	42	13	0.04	0.02	0.59	0.54	10	24	237	5	11	0.3
Spinach	91	23	3.6	2.9	0.4	2.2	1.7	469	28	0.08	0.19	0.72	2.03	99	49	558	79	79	2.7
Lettuce, iceberg	96	14	3.0	0.9	0.1	1.2	0.4	25	2.8	0.04	0.25	0.12	0.18	18	20	141	10	7	0.4
Broccoli	91	28	5.2	3.0	0.3	3.3	0.9	150	93	0.06	0.12	0.64	1.45	48	66	325	27	25	0.9
Lettuce, romaine	95	17	3.3	1.2	0.3	2.1	0.6	436	24	0.07	0.07	0.31	0.13	33	30	247	8	14	1.0
Collards	90	30	5.7	2.4	0.4	3.6	0.9	333	35	0.05	0.13	0.74	2.26	145	10	169	20	9	0.2
Watermelon	91	30	7.5	0.6	0.1	0.4	0.2	28	8.1	0.03	0.02	0.18	0.00	7	11	112	1	10	0.2

Source: USDA Natl. Nutrient Database for Standard Reference: http://www.ars.usda.gov/nutrientdata.
[a]1 μg RAE (1 retinol activity equivalent) = 1 μg all-*trans*-retinol, 12 μg dietary all-*trans*-β-carotene, or 24 μg other dietary provitamin A carotenoid.

varieties of orange carrots in the United States had carotene contents in the range of 70 ppm, but breeding efforts, through phenotypic recurrent selection of roots with a darker orange color, increased that value to 90 ppm by the 1970s (Simon and others 2009). Modern spectrophotometric detection of high levels of root carotenes has allowed breeders to push the concentration above 130 ppm in typical orange and dark orange carrots, that is, high-carotene mass, can reach 500 ppm (Simon and others 1989).

Total root carotenoid content can vary significantly between cultivars (Simon and Wolff 1987; Heinonen 1990; Nicolle and others 2004; Grassmann and others 2007) and is the major source of variation in reported carrot carotenoid concentrations. Additionally, the growing season, soil, maturity, and genetic factors also influence carotenoid content of carrots (Hart and Scott 1995; Rosenfeld and others 1997, 1998). β-Carotene is heterogeneously distributed across the carrot root section, and in all yellow, orange, red, and purple carrot classes is generally highest in the outer root, or phloem, and much lower in the xylem (core) (Baranska and others 2006). Carrot roots of the high-carotene mass line, however, exhibit high concentrations of β-carotene in the xylem (Baranska and others 2005). Specific and sensitive HPLC techniques have greatly improved carotenoid analysis of plant tissues; however, different sample preparation and extraction techniques contribute variability to reported vegetable carotenoid concentrations (Scott and others 1996; Kimura and Rodriguez-Amaya 1999). Table 6 lists some current reported carotenoid concentrations of orange and dark orange carrots, as well as other colored carrots.

In addition to α- and β-carotene, some typical orange carrots have detectable levels of lutein, although modern breeding efforts have attempted to eliminate the yellow core, which was perceived as a defect (Simon and others 2009). Lutein has no provitamin A activity, but is found localized in the macular region of the eye in humans and may have importance in eye health and protection from age-related macular degeneration (Tanumihardjo and Yang 2005). Lutein is an important pigment in yellow carrots and they can contain from 1 to 5 ppm lutein, but only very low levels of carotenes (2 to 4 ppm) compared to orange carrots (95 to 311 ppm) (Table 6). Sun and others (2009) reported that white and yellow carrots contained the lowest total carotenoids (2 and 6 ppm FW, respectively) compared with dark orange (160 ppm FW) > orange (98 ppm, FW) > purple–yellow (92 ppm FW) > red (73 ppm FW) and > purple–orange (40 ppm FW) carrots. Nonetheless, lutein and β-carotene from yellow carrots are bioavailable when fed to humans in processed forms (Molldrem and others 2004).

Lycopene is the carotenoid primarily responsible for the color of red carrots. While lycopene also has no provitamin A activity, even though it is a hydrocarbon, it is the most potent antioxidant *in vitro* of all the carotenoids found in appreciable amounts in humans (Di Mascio and others 1989) and has been implicated in protection from certain cancers (Giovannucci 2002). Investigations of the lycopene content of red carrots are much fewer than for the carotenoid content of typical orange carrots, in spite of the fact that red carrots are commonly consumed in India (Tanumihardjo and others 2008). Reported lycopene content of red carrots ranges from 50 to 100 ppm (Table 6), which is similar to or greater than typical tomato concentrations. The year-round average of red, ripe, raw tomatoes is 30 ppm with a range of 9 to 42 ppm (USDA Carotenoid Database 1998). Red carrot cultivars also contain α-carotene, β-carotene, and lutein, the amounts varying by type of red carrot.

A group of polyphenolic pigments called anthocyanins are responsible for the color of purple carrots. Current cultivars of purple varieties include solid purple carrots, often referred to

Table 6—Carotenoid content of raw carrots of different colors.[a]

Carrot color	Total (ppm)			
	α-Carotene	β-Carotene	Lutein	Lycopene
Orange				
A[b]	22	128	2.6	nd[c]
B	27	69	0.4	0.6
C	40	69	nm	nm
D	13 to 31	32 to 66	0.6 to 1.8	nm
E	47.1	47.5	nd	nd
H	10 to 22	18 to 38	nm	nm
I	57 to 70	45 to 52	4 to 5	nd
Dark orange				
A	31	185	4.4	17
B	45	113	0.7	0.9
D	75.8	172	1.0	nm
F	96 to 192	215 to 311	NR	NR
Yellow				
A	0.5	1.8	5.1	nd
B	0.2	3.6	2.4	0.04
C	tr	tr	nm	nm
D	nd	3.3	1.4 to 2.3	nm
I	Tr	Tr	5 to 10	nd
Red				
A	1.1	3.4	3.2	61
B	0.2	22	0.2	50
I	nd to 4	35 to 40	Tr-3	85 to 100
Purple–white				
I	2 to 3	2 to 3	9 to 10	nd
Purple–orange				
A	4	123	11	nd
B	10	28	1.1	0.2
C	87	161	nm	nm
I	62 to 100	65	8 to 10	nd
Purple–yellow				
B	2	15	3	0.4
D	nd	3.1 to 3.8	1.8 to 2.2	nm
White				
A	nd	0.06	0.09	nd
B	0.05	0.34	1.7	0.04
C	nd	nd	nm	nm
I	nd	nd	tr	nd

[a]Carotenoid concentrations of raw carrot, ppm.
[b]References: A = Surles and others (2004); B = Sun and others (2009); C = Alasalvar and others (2001); D = Nicolle and others (2004); E = EL-Qudah (2009); F = Simon and others (1989); H = Rodriguez-Amaya and others (2008); I = Grassmann and others (2007).
[c]nd = not detected; nm = not measured; NR = not reported.

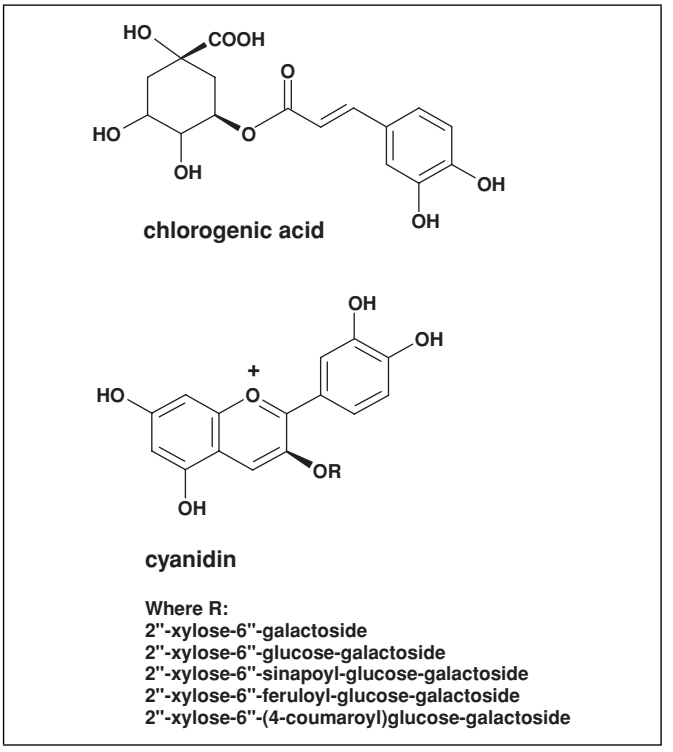

Figure 2—The main phenolic compounds found in carrots are chlorogenic acids. Polyphenols that are commonly quantified in purple carrots include 5 anthocyanins. The basic anthocyanin backbone is called cyanidin. The R groups are various glycosides.

as "black carrots," and carrots with purple phloem and white, yellow, or orange xylem (core). Purple carrots with a white core contain very low levels of carotene (4 to 6 ppm), whereas purple–orange carrots (38 to 130 ppm) can contain as much or more total carotene as typical orange carrots (Grassmann and others 2007) (Table 6). The continued research in carrot cultivar development has produced a novel purple–orange–red cultivar that contains approximately 40 ppm carotenes and 62 ppm lycopene (Mills and others 2008). While these colorful carrots are still a novelty for modern consumers, they share the flavor attributes of their orange counter-parts (Alasalvar and others 2001) and are generally well-liked by consumers (Surles and others 2004). Colorful carrots with a variety of pigments have the potential to contribute to the diet, not only the provitamin A carotenes, but also the beneficial health effects of their respective pigments.

Phenolic compounds

Carrots contain phenolic compounds with a single aromatic ring known as phenolic acids. The main phenolic compounds found in carrots are chlorogenic acids, which are hydroxycinnamic acid derivatives formed by the esterification of cinnamic acids, such as caffeic, ferulic, and p-coumaric acids, with (-)-quinic acid. These compounds contribute to the organoleptic properties of fresh and processed carrots (Rubatzky and others 1999). Recently, consumption of chlorogenic acids in coffee has been associated with reductions in several chronic diseases (Higdon and Frei 2006). Studies estimate approximately 30% intestinal absorption of chlorogenic acids (Farah and others 2008) and extensive metabolism of the remainder by colonic microflora (Olthof and others 2003).

Alasalvar and others (2001) identified 11 different phenolic acids in orange, purple, yellow, and white carrots. Chlorogenic acid (Figure 2) predominated in every color carrot, its concentration being 54.1, 8.5, 4.5, and 4.4 mg/100 g in purple, orange, white, and yellow carrots, respectively. Total concentration of all the identified phenolic acids was greatest in the purple carrots and followed the same color order as chlorogenic acid concentration. Grassmann and others (2007) found a similar ranking by color of total phenolics and included red carrots, which had a slightly higher concentration than yellow, orange, and white. Total phenolic content in carrots are often expressed in gallic acid equivalents as measured using the global Folin–Ciocalteu method

(Singleton and Rossi 1965), which also reacts with flavonoids such as the anthocyanins in purple carrots. Therefore, purple carrots are the most concentrated in total phenolics by this method when compared with the other varieties.

According to Caetano and Leal (2006), carrots were classified as a "low phenolic content" vegetable (<100 mg catechin equivalents/100 g FW), having just 12.9 mg, but were joined in that grouping by tomato (30.8 mg), green bean (36.8 mg), red onion (73.9 mg), and spinach (82.1 mg). In comparison, collard greens (348.3 mg) and red cabbage (213.1 mg) were in the "high phenolic content" group. Chu and others (2002) distinguished free, or soluble, phenolics from bound phenolics by submitting vegetable extract residues to additional base digestion. They found that broccoli had the highest total phenolics, followed by spinach, onion, red pepper, carrot, cabbage, potato, lettuce, celery, and cucumber. On average, the free-phenolic content was 76% of the total phenolics. Carrots had 37.6% as bound phenolics, second only to potato with the highest bound-phenolic content. Bound phenolics are found mostly in ester form and are associated with cell-wall components (Kang and others 2008). They lend cross-linking ability to confer structural stability in the cell-wall matrix. These bound phenolics may survive upper gastrointestinal digestion and be released in the colon where they may have positive health effects. Chu and others (2002) estimate that carrots and potatoes could release approximately one-half of their phenolics in the colon, compared with one-fourth in many other vegetables.

Phenolic compounds and antioxidant capacity

Gajewski and others (2007) found purple carrots, rich in anthocyanins, to have greater *in vitro* antioxidant capacity than orange and yellow carrots as measured from methanolic extract, which may more efficiently extract hydrophilic (phenolics), rather than hydrophobic (carotenoids) compounds. *In vitro* antioxidant capacity, as measured by oxygen radical absorbance capacity (ORAC), showed little difference between different colored carrots, including orange, yellow, purple, and white, which may be due to an extraction method optimized for hydrophobic, therefore carotenoid, extraction (Nicolle and others 2004). Both phenolic compounds and carotenoids are strong *in vitro* antioxidants. Phenolic fractions from red wine are potent free radical scavengers (Ghiselli and others 1998) and β-carotene is considered a strong quencher of singlet oxygen (Schafer and others 2002). Sun and others (2009) evaluated different colored carrots for their relative antioxidant capacity index (RACI) by assessing both hydrophilic and hydrophobic extracts. They found that chlorogenic acid was a major *in vitro* antioxidant in different colored carrots and that the phenolics (phenolic acids and flavonoids) made greater contribution to the total antioxidant capacity than carotenoids. Carotenoids were the major antioxidants in the hydrophobic extracts. Grassmann and others (2007) also found that antioxidant capacity of the hydrophilic extract correlated with total phenolics, and that of the hydrophobic extract correlated with carotenoids. These studies demonstrate that different methods and extraction procedures measure different compounds and that studies that explicitly measure both hydrophilic and hydrophobic extracts may provide greater information. It is important to keep in mind that *in vitro* studies do not necessarily reflect *in vivo* activity of many of these compounds. Research is beginning to uncover the numerous metabolites formed from many ingested parent compounds (Kay and others 2005) and emerging evidence is pointing towards mechanisms of action that go beyond the modulation of oxidative stress and may involve cell modulation through intracellular signaling cascades (Crozier and others 2009).

Phenolic compounds as phytoalexins

Phenolic compounds may have a role in plant resistance to fungal and bacterial agents. They accumulate in carrots in response to cold, injury, or ethylene exposure (Rubatzky and others 1999). Total phenolics (Alasalvar and others 2004), chlorogenic acid, isochlorogenic acid (Hager and Howard 2006), trans 5′-caffeoylquinic acid, and para-hydroxybenzoic acid and its esters (Babic and others 1993) increase during storage if the flesh is wounded, after processing such as shredding, or under exposure to ethylene. The increases in phenolic content of fresh-cut carrots during storage are associated with increased phenylalanine ammonia lyase, a wound-induced enzyme. Compounds produced by plants in response to pathogen infection or wounding are referred to as phytoalexins because their production may be a defense mechanism. The bitter coumarin compound 6-methoxymellein, a phenolic oxidation product, preferentially accumulates in the tips of whole, unwounded carrots in response to ethylene (Talcott and Howard 1999) and may be due to a higher proportion of periderm to xylem/phloem at the tip, where respiration, and thus phytoalexin production, would be expected to be greatest. Additionally, the tip is the leading growth tissue and would be expected to have greater phytoalexin production.

Anthocyanins

Anthocyanins are water-soluble pigments that comprise a group of over 600 compounds that provide the red, purple, and blue colors of many fruits, vegetables, flowers, and grains. They are often used in industry as natural colorants in foods and beverages. In plants, anthocyanins function to provide photoprotection, scavenge free radicals, and attract animals for pollination (Neill and Gould 2003; Gould 2004). Dietary anthocyanins may play a role in health promotion and protection from cardiovascular disease (Reed 2002; Mazza 2007) and cancer (Hou 2003; Wang and Stoner 2008) by acting as dietary antioxidants, reducing inflammation and lipid oxidation, causing induction of anti-inflammatory and vasoprotective effects, phase II enzymes, and apoptosis. For example, anthocyanin-rich extracts from chokeberry and bilberry were shown to relax coronary artery rings isolated from pig hearts (Bell and Gochenaur 2006). Anthocyanins have also been implicated in improved brain and memory functions (Shih and others 2009).

Anthocyanins are polyphenolic compounds that are comprised of an anthocyanidin backbone, 2-phenylbenzopyrylium, also referred to as the flavylium cation. The 6 common anthocyanidin backbones are cyanidin, malvidin, delphinidin, peonidin, petunidin, and pelargonidin. These backbones can vary in the number and position of hydroxyl groups, methoxyl groups, and type, position, and number of attached sugar molecules which may also be acylated by various aromatic or aliphatic acids. The primary anthocyanins found in purple carrots (sometimes referred to as black carrots), are derivatives of cyanidin (Figure 2), but pelargondin and peonidin glycosides have also been identified (Kammerer and others 2003). The anthocyanins of purple carrots have no direct effect on flavor (Simon 2000; Surles and others 2004). Analysis of purple carrots has identified 5 main anthocyanin derivatives: cyanidin-3-(2″-xylose-6-glucose-galactoside) (Cy3XGG), cyanidin-3-(2″-xylose-galactoside) (Cy3XG), cyanidin-3-(2″-xylose-6″-sinapoyl-glucose-galactoside) (Cy3XSGG), cyanidin-3-(2″-xylose-6″-feruloyl-glucose-galactoside) (Cy3XFGG), and cyanidin-3-(2″-xylose-6″-(4-coumaroyl)glucose-galactoside) (Cy3XCGG) (Glabgen and others 1992).

Total anthocyanin concentration in the roots of purple carrots can vary widely between cultivars and even within a cultivar based on the degree of root coloring (Lazcano and others

2001; Kammerer and others 2004). Reports of total anthocyanin content range from 0 mg/100 g FW in orange carrots to 350 mg/100 g FW in dark purple carrots (Kammerer and others 2004; Simon and others 2008; Sun and others 2009). For comparison, total anthocyanin concentration is approximately 113 mg/100 g in blueberries, 117 mg/100 g in cherries, and 48 mg/100 g in raspberries (USDA 2003). The daily intake of anthocyanins in the U.S. diet is estimated to be 12.5 mg/day (Wu and others 2006). The anthocyanins in purple carrots contributed significantly to their *in vitro* antioxidant capacity (Sun and others 2009).

Dietary anthocyanins appear to have low bioavailability, recoveries in urine ranging from 0.004% to 0.1% of intake (Manach and others 2005; McGhie and Walton 2007). Studies with whole raw and cooked purple carrots and carrot juice in humans demonstrated that purple carrot anthocyanins are bioavailable and are absorbed intact, but with low efficiency (Kurilich and others 2005; Charron and others 2009). These feeding studies suggest that saturation of absorption of the cyanidin-based anthocyanins from purple carrots occurs between intakes of 250 and 350 μmol (equivalent to 150 to 250 g carrot). The percentage recovery of nonacylated anthocyanins was greater than acylated anthocyanins in studies with both whole carrots and carrot juice, suggesting that acylation, and not the plant matrix, influences bioavailability.

Other relevant compounds

Many compounds contribute to carrot flavor and some of these may contribute to effects on human physiology. The characteristic "fresh carrot" flavor has been attributed to the volatile compounds mono- and sesquiterpenes, and also to sugars (Simon and others 1980). Terpenes generally impart a harsh or bitter flavor and these flavor attributes were seen to increase directly with terpene content in different carrot genotypes (Simon and others 1980; Kreutzmann and others 2008). Terpinolene (Figure 3) appears to be the most abundant volatile and the content of total volatiles varies greatly between genotypes (Simon and others 1980; Alasalvar and others 1999, 2001; Habegger and Schnitzler 2005; Kreutzmann and others 2008). While purple carrot cultivars in one study (Alasalvar and others 2001) are reported to have relatively low terpinolene content, the amounts in other colors vary widely. Cooking carrots can reduce volatile content by 70% to 95% (Simon and Lindsay 1983; Alasalvar and others 1999).

A group of compounds called polyacetylenes is responsible for the bitter off-flavor of carrots (Czepa and Hofmann 2004). These compounds are widely distributed in the Apiaceae family of plants that includes carrot, celeriac, parsnip, and parsley, and have been identified as phytoalexins, toxic compounds produced by plants in response to attack by pathogens or other stresses (Christensen and Brandt 2006). They are potent skin sensitizers, irritants, and also neurotoxic at high concentrations, and have traditionally been viewed as toxicants. More recently, polyacetylenes have been implicated as bioactive compounds with potential effects on human physiology and disease (Hansen and others 2003; Christensen and Brandt 2006).

Four polyacetylenes have been identified in carrot root, the most abundant are falcarinol, falcarindiol, and falcarindiol 3-acetate (Figure 3) (Christensen and Brandt 2006). Fresh weight concentrations of polyacetylenes range from 20 to 100 mg/kg (Czepa and Hofmann 2004; Zidorn and others 2005; Christensen and Kreutzmann 2007). Concentrations of carrot polyacetylenes vary by cultivar and appear to be localized to the carrot root phloem (Czepa and Hofmann 2004; Baranska and others 2005). Higher polyacetylene concentrations were found in carrots with higher carotenoid levels, and yellow carrots, with lower levels of carotenoids, had lower levels of polyacetylenes than orange carrots (Baranska and others 2005). Boiling carrots for 12 min reduced the falcarinol content by 70% compared with raw carrots (Hansen and others 2003).

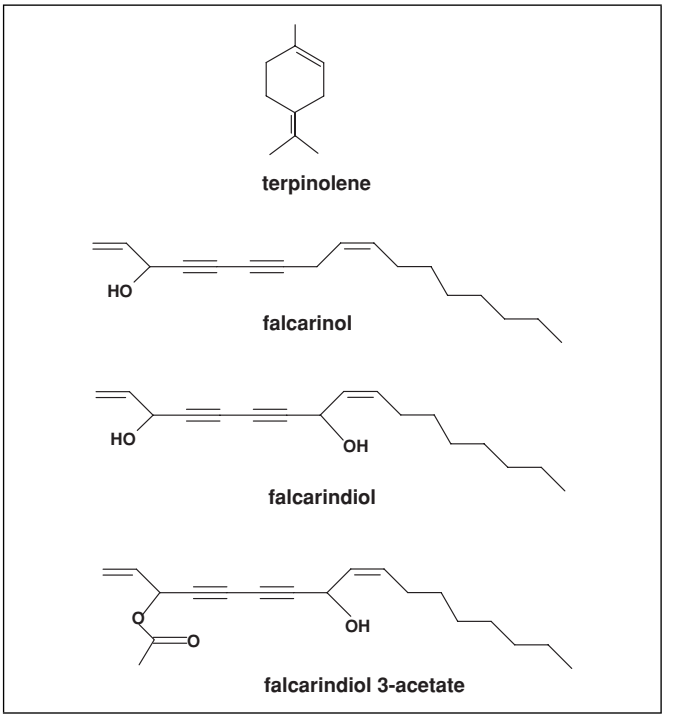

Figure 3—Chemical structures of terpinolene, falcarinol, falcarindiol, and falcarindiol 3-acetate. These compounds are in part responsible for the characteristic carrot flavor.

In vitro studies suggest that carrot polyacetylenes have antiinflammatory activity in macrophages (Metzger and others 2008), biphasic stimulatory and cytotoxic effects on primary mammary epithelial cells (Hansen and others 2003), and cytotoxic activity against a number of cell lines (Zidorn and others 2005). Rats fed 10% freeze-dried carrot powder with 35 μg falcarinol/g feed or falcarindiol extract had reduced numbers of larger class colonic aberrant crypt foci (Kobæk-Larsen and others 2005). To test bioavailability in humans, a study was conducted in male subjects with 300, 600, and 900 mL carrot juice that contained 16, 33, and 49 μmol falcarinol, respectively (Brandt and others 2004). All 3 treatments resulted in a rapid increase in plasma falcarinol within 30 min of the test-meal and peak concentrations at 2 h. The maximum concentrations in plasma were within the range that *in vitro* data indicate potential stimulatory effects (Hansen and others 2003); however, plasma concentrations were below the levels reported to elicit *in vitro* effects on cytotoxicity (Hansen and others 2003; Zidorn and others 2005), antioxidant or phase 2 enzyme induction (Ohnuma and others 2009), and antiinflammatory effects (Metzger and others 2008). While some researchers have suggested that epidemiologic data linking reduced lung cancer incidence with carrots could be related to falcarinol (Brandt and others 2004), more research on *in vivo* effects of this compound, which traditionally was considered a toxicant, is warranted.

Many other compounds contribute to the unique flavor of carrots; and consumers generally prefer carrots with high sugar and low volatile terpenoid contents (Rubatzky and others 1999). Carotenoids and phenolic compounds are the predominant

phytochemicals in all varieties and colors of carrots; however, other minor compounds and texture influence taste and possibly the health properties of this popular and tasty vegetable. Carrots, like other whole foods, are a package that offers more than the sum of its component compounds.

Food-Based Approaches to Increase Carotene Intake

Two related methods to increase provitamin A carotenoid intake are to promote dietary diversification through the inclusion of more vegetables and to increase the amount of carotenoid per serving of vegetable. Increasing vegetable or provitamin A carotenoid intake not only improves vitamin A status, but will also contribute to improved health outcomes.

Vitamin A deficiency

In developing countries, where vegetable carotenoids contribute greater than 80% of the available vitamin A (FAO-WHO 2001), vitamin A deficiency (VAD) is a major public health problem. The highest prevalence of VAD is in parts of Africa and Southeast Asia. VAD affects 140 million preschool-aged children and 1.2 to 3 million children die each year as a result (UN-SCN 2004). According to the World Health Organization's Global Database on Vitamin A Deficiency (WHO 2009), 45 and 122 countries have a public health problem with regard to clinical and subclinical vitamin A deficiency, respectively. Clinical VAD involves overt eye signs, while subclinical VAD is much harder to diagnose (Tanumihardjo 2004). Theoretically, sufficient vitamin A exists in the food supply to meet global needs. However, inequitable distribution and poverty are major hindrances to adequate vitamin A access contributing to VAD. Indeed, poverty contributes to inadequate dietary quality which leads to micronutrient deficiency (Tanumihardjo and others 2007). In these populations, food-based strategies that promote dietary diversification are critical in a sustainable effort to eliminate VAD (Underwood 2004).

Although part of the U.S. population might be getting too much preformed vitamin A through multivitamins and fortified foods (Allen and Haskell 2002; Penniston and Tanumihardjo 2003), the Dietary Guidelines Advisory Committee (2005) identified vitamin A as a shortfall nutrient, along with vitamins C and E, calcium, magnesium, potassium, and fiber. Shortfall nutrients are those likely to be consumed in inadequate amounts. According to the *Continuing Survey of Food Intake by Individuals* (CSFII), 1994 to 1996, the probability of adequate intake for vitamin A in men and women was 47% and 48%, respectively. Based on NHANES 2001 to 2002, 44% of Americans have an inadequate intake of vitamin A from food (Moshfegh and others 2005). Although estimates of inadequacy based on serum vitamin A concentrations from NHANES 1988 to 1994 are low (Ballew and others 2001; Gillespie and others 2004), serum concentrations are not a sensitive measure of status and may underestimate inadequacy, especially in low-income groups (Spannaus-Martin and others 1997). The Dietary Guidelines recommend increased fruit and vegetable consumption for the shortfall nutrients vitamins A and C and magnesium.

Biofortification

Biofortification of foods can increase the nutritive value of the food supply (Tanumihardjo and others 2008). Leaders of nutrition-oriented plant breeding programs have taken this approach through increasing selection of nutrient-rich cultivars. Plant breeding to increase the provitamin A content of selected fruits, vegetable, and staple crops is a strategy that could impact increased vitamin A consumption (Simon and others 2009). Genetic and breeding efforts have increased total carotenoid content, β-carotene, and lycopene for carrot, tomato, pepper, potato, muskmelons, squash (including pumpkin), sweet potato, maize, cassava, and lettuce (Simon and others 2009). Efforts to increase the carotene content in orange carrots were initiated in the late 1970s and have created a high carotene carrot with upwards of 500 ppm total α- and β-carotene (Simon and others 1989).

Biofortification with provitamin A is a sound strategy from the perspective of both under- and over-nutrition of vitamin A. Preformed vitamin A, which is found in animal products and supplements, is efficiently absorbed and epidemiological studies suggest that chronic high intakes of preformed A are associated with hip fractures (Melhus and others 1998; Promislow and others 2002). Carotenoids provide a safer form of vitamin A due to regulated bioconversion in the body (Tanumihardjo 2008). Additionally, this strategy is applicable to the developing world because of the reliance on plant-based foods for up to 80% of their vitamin A needs.

Carrots are a natural target for carotenoid biofortification due to their high levels of consumption in the United States, affordability to consumers (USDA ERS 2007), widespread cultivation worldwide, and potential for increased carotene biosynthesis. Because carotenes in carrots (and other nongreen tissues) are not necessary for growth, they have greater genetic variation for provitamin A content than for storage carbohydrate or protein contents (Simon 1990). Early 20th century orange carrots ranged from 79 to 90 ppm (Simon and others 2009). Successful breeding for increased carotene content through visual selection for darker orange roots has brought current typical orange carrots to greater than 130 ppm carotene. This has been accomplished without adversely affecting culinary quality (Simon 1988; Simon and others 1989). A dark orange "high-carotene-mass" carrot has been developed that contains up to 500 ppm carotene and is the highest natural whole food source of β-carotene (Simon and others 2009). These "high-carotene-mass" carrots have been shown to increase serum β-carotene over typical orange carrots in humans (Tanumihardjo and others 2009a), and modestly, but significantly, increase liver vitamin A stores in Mongolian gerbils (Porter-Dosti and others 2006).

Carotenoid Bioavailability

Of the hundreds of carotenoids in nature, only about 40 are present in the typical human diet, and those commonly quantified in human blood are α-carotene, β-carotene, lycopene, lutein, and β-cryptoxanthin (Figure 1) (Khachik and others 1997; Rao and Rao 2007). Serum concentrations of carotenoids vary according to the season of the year (Olmedilla and others 1994), which likely reflects seasonal fluctuations in the food supply (Ziegler and others 1987). Carrots are a unique source for α-carotene and this carotenoid in serum uniquely indicates high carrot consumption (Campbell and others 1994; Yang and others 2008; Tanumihardjo and others 2009a). Because carrots are available year-round, are a widely eaten vegetable in many parts of the world, and most varieties are a concentrated source of α- and β-carotene, efforts have been made to measure their ability to supply dietary carotenes and vitamin A. Approximately 150 high-carotene carrots (an amount grown in 1 m^2) may provide the annual total vitamin A requirements for an adult (Simon 1990).

Effects of carrot matrix and processing

Carotenoids must first be released from the food matrix before they can be solubilized and incorporated into lipid micellar structures for uptake into intestinal mucosal cells. Bioavailability of β-carotene is the fraction of carotenoid that is absorbed and available for utilization in physiologic functions or

for storage. Studies suggest that the carrot matrix has a negative effect on carotenoid absorption. Serum response to both acute (Brown and others 1989; Bulux and others 1998) and chronic carrot feeding (Micozzi and others 1992; Torronen and others 1996) showed reduced bioavailability compared to purified β-carotene.

Carrots contain several food matrix components that may affect carotenoid bioavailability. Evidence from a ferret model suggests that the crystalline form of carotenoids in carrot root chromoplasts and dietary fiber both negatively affect bioavailability (Zhou and others 1996). Detailed *in vitro* research modeling the gastric environment suggests that membrane-bound carotenoids in spinach chloroplasts are more resistant to solubilization into oil than membrane-bound and free crystalline carotenoids in the carotene bodies of carrots (Rich and others 2003a). However, blanching, which disrupts most of the organelles, increases solubilization of both β-carotene and lutein from homogenized spinach by more than 60%, but was shown to have little effect on the solubilization of β-carotene in carrot juice (Rich and others 2003a).

In raw carrot juice, cell walls are removed and the cellular structures containing chromoplasts are disrupted. Blanching of carrot juice further disrupts the membrane-bound carotene bodies, but leaves carotene crystals intact (Rich and others 2003a). It was hypothesized that the carotene–carotene interactions in the crystals are more stable against solubilization than the lipoprotein–carotenoid interactions of the blanched spinach. This is in agreement with the observation that heating of carrot juice did not significantly increase carotene bioavailability in ferrets (Zhou and others 1996).

In a model of the duodenal environment, solubilization of carotenoids into mixed micelles was lowest for carrot juice carotenes ($\text{lutein}_{\text{carrot juice}} > \text{lutein}_{\text{blanched–frozen spinach}}$, $\text{carotene}_{\text{blanched frozen spinach}} > \text{carotene}_{\text{carrot juice}}$), suggesting that, in the duodenum, the more apolar carotenes remaining in the food matrix are less likely to be available for absorption than lutein (Rich and others 2003b). This *in vitro* research is supported by observations in humans that xanthophylls have a higher bioavailability than carotenes from mixed vegetable diets (Van het Hof and others 1999).

As suggested above, food processing, including heating and mechanical and enzymatic treatments, results in softening and disruption of the plant cell wall and organelles (Rich and others 2003a). Pureeing vegetables reduces particle size and increases surface area, which may increase availability of carotenoids to the intestinal lumen (Erdman and others 1993; Parker 1996). This release from the food matrix before absorption is called bioaccessibility (Tanumihardjo 2002). Plasma response of β-carotene from a single meal of cooked carrots (65.1% ± 7.4%) was higher than from raw, ground carrots (41.4% ± 7.4%) in ileostomy volunteers as calculated from a carotenoid mass-balance study (Livny and others 2003). Mild heat treatment of carrots resulted in a small, nonsignificant increase in β-carotene absorption in preruminant calves (Poor and others 1993). In humans, a chronic 4-wk feeding of thermally processed and pureed carrot and spinach increased plasma β-carotene 3 times over that of the raw vegetables (Rock and others 1998). In healthy adults, α- and β-carotene had greater bioavailability from a single test meal in the following order: commercial carrot puree (thermally treated) > boiled–mashed carrots > raw–grated carrots (Edwards and others 2002).

Another relevant carrot matrix component is carotenoid–protein complexes. Denaturing of carotenoid-protein complexes by heating might improve carotenoid availability (Dietz and others 1988). Two α- and β-carotene binding proteins have been identified in carrot root chromoplasts (Milicua and others 1991; Bryant and others 1992; Zhou and others 1994); however, their association with only a small fraction of the total carrot carotenoids makes it unlikely that they have a major influence on carotenoid bioavailability (Zhou and others 1994).

Carrots supply vitamin A

Vitamin A is derived from the diet as preformed retinol or provitamin A carotenoids. The 3 major dietary carotenoids that have provitamin A activity are α-carotene, β-carotene, and β-cryptoxanthin. Two of these carotenoids, namely α- and β-carotene, are highly concentrated in orange carrot and some varieties of purple and red. Carrot supplies 37% of the U.S. available supply of β-carotene (Table 1). In addition to the matrix and processing factors indicated previously, bioavailability of carotenoids is influenced by a number of other factors such as the carotenoid species, the amount of carotenoid in the diet, the presence of absorption enhancers or inhibitors, and the vitamin A status of the host, among others (Castenmiller and West 1998).

Carotenoids are absorbed into intestinal epithelial cells via simple diffusion from mixed micelles and possibly by receptor-mediated transport (Yonekura and Nagao 2007). In humans, provitamin A carotenoids are partly converted to vitamin A in the intestinal mucosa by β-carotene 15, 15′-monooxygenase, through production of retinal, reduction to retinol, and esterification to fatty acids. The resulting retinyl esters and other carotenoids are then packaged into chylomicra for secretion into the lymph and delivery to the bloodstream. In addition to newly absorbed carotenoids from a meal, endogenous carotenoids are present in plasma, making the measurement of absolute bioavailability of carotenoids and vitamin A-value of ingested vegetables difficult (Parker and others 1999). Nevertheless, plasma response to β-carotene is routinely used to measure relative bioavailability from different foods or supplements.

Many studies have conclusively shown that β-carotene is bioavailable from carrots (Rao and Rao 1970; Brown and others 1989; Micozzi and others 1992; Bulux and others 1998; Muller and others 1999; Tanumihardjo and others 2009a) and that processing via cooking or pureeing improves bioavailability (Rock and others 1998; Edwards and others 2002; Livny and others 2003). The relative bioavailability of β-carotene from carrots has been measured by comparing whole plasma β-carotene response from carrots to that from purified β-carotene supplementation. Brown and others (1989) reported 21% bioavailability of β-carotene from intake of 29 mg from cooked carrots in healthy men. Torronen and others (1996) found a 45% bioavailability of β-carotene in healthy women from daily intakes of 12 mg as either raw carrots or carrot juice for 6 wk. Huang and others (2000) provided 12 mg of β-carotene as stir-fried shredded carrots and reported a 33% bioavailability in men. Micozzi and others (1992) provided 12 mg β-carotene as cooked carrots to healthy men for 6 wk and reported 18% bioavailability. The variation between studies is likely related to study design, subject population, and β-carotene supplement formulation (Faulks and Southon 2005). These studies demonstrate that bioavailability of β-carotene from carrots is less than from β-carotene supplements, but do not provide absolute amounts nor indications of how well carrots can supply vitamin A.

Using an extrinsic stable isotope reference method and response in the triacylglycerol-rich lipoprotein fraction of plasma, Edwards and others (2002) were able to measure not only the relative availability of 18.6 mg β-carotene from different carrot preparations, but also to estimate the vitamin A yield. The mass of absorbed α- and β-carotene was almost 2-fold greater from a commercial carrot puree than from mashed–boiled carrots. However, the mass of assimilated vitamin A was only marginally

greater for the puree than for the boiled–mashed carrots. The apparent β-carotene to vitamin A conversion efficiencies (44% and 59%, in the puree and boiled-mashed treatments, respectively) were different and suggested a level of regulation of vitamin A production by the intestine. The β-carotene to vitamin A conversion efficiencies for both carrot preparations were 23% to 28% lower than the efficiencies proposed by the Institute of Medicine Micronutrient Panel of 12 μg β-carotene to 1 μg retinol and 24 μg α-carotene to 1 μg retinol (Institute of Medicine, Food and Nutrition Board 2001). The hypotheses for the lower conversion efficiency include: under-estimation in the model used, the relatively high β-carotene amount, and the relatively replete vitamin A status of the subjects. Evidence suggests that β-carotene absorption efficiency decreases with increasing amount fed (Olson 1987) and conversion efficiency increases in more vitamin A-deficient individuals (Tanumihardjo 2008).

A study utilizing intrinsically labeled vegetables found β-carotene to vitamin A conversion factors of 15 μg β-carotene to 1 μg retinol and 21 to 1 μg for an intake of 10.3 mg β-carotene from steamed–pureed carrots and steamed–pureed spinach, respectively (Tang and others 2005). These results for carrot are close to the Inst. of Medicine's value, but the spinach conversion factor is higher, suggesting that β-carotene is more bioavailable from carrot chromoplasts than from spinach chloroplasts.

In a study of lactating women fed a standardized amount of 6 mg β-carotene in the form of a supplement, raw grated carrot, or pureed papaya for 60 d, the serum retinol concentrations improved in all of the treatment groups as compared with the placebo (Ncube and others 2001). As with most studies of carotenoid bioavailability, there was much individual variation. However, in all individuals who were severely malnourished, the relative dose response test, a qualitative measure of vitamin A liver reserves, improved in all intervention groups. Greater improvement occurred in the papaya group compared with the carrot group suggesting that crystalline β-carotene from carrot chromoplasts may be less bioavailable than β-carotene dissolved in lipid droplets of yellow–orange fruit chromoplasts. Higher β-carotene bioavailability from orange fruit was also supported by a study in Indonesian schoolchildren, although green leafy vegetables were included in the carrot-fed group (De Pee and others 1998).

Vitamin A is required for visual dark adaptation in dim light. Insufficient vitamin A can result in night-blindness. A study in night-blind, pregnant Nepali women used recovery from impaired dark adaptation as a functional endpoint for daily supplementation with amaranth leaves, carrots, goat liver, vitamin A-fortified rice, or retinyl palmitate (Haskell and others 2005). Cooked and pureed carrots performed as well as all of the other treatment groups in improving dark adaptation and self-reported recovery from night-blindness.

The body of evidence from these carrot studies suggests that carrots are a bioavailable source of β-carotene; that processing the vegetable by grating, heating, and/or pureeing improves the bioavailability; and that the carotene bioavailability may be intermediate to fruits and leafy green vegetables. Additionally, carrots appear to be a valuable source of vitamin A for deficient populations, especially if processed and provided in adequate quantities.

Bioavailability studies with carrots of various colors

The first carrots were purple and yellow, but have mainly been supplanted in the West by the orange cultivars of today. Colorful specialty carrots have been "re-discovered" by modern plant breeders interested in improving and diversifying the nutrition of the food supply. In addition to efforts to improve the flavor, texture, and horticultural quality of colored carrots, research has focused on the bioavailability and putative health benefits of the different pigments that color these carrots.

The relative bioavailability of lycopene in red carrots was determined in 2 similar crossover studies in humans fed carrot or tomato paste muffins at 5 mg lycopene/day for 11 d (Horvitz and others 2004). The first study included muffins made from red carrots, white carrots, and tomato paste. The second study determined if carrot fiber affected lycopene availability by feeding tomato paste muffins with or without white carrots. Lycopene and β-carotene were available from red carrot, but lycopene absorption was negatively affected by carrot fiber. Combined results from both studies suggested that lycopene in red carrot is about 44% as available as that from tomato paste. A study with red carrot lycopene in vitamin A-depleted Mongolian gerbils confirmed that lycopene is bioavailable and suggested a possible interaction between β-carotene and lycopene that decreases lycopene availability (Mills and others 2007). Additionally, because the red carrot also contained β-carotene, and thus could supply vitamin A, the vitamin A value of the red carrot was calculated to be 3.5 μg β-carotene to 1 μg retinol in this model. This is more favorable than the current Institute of Medicine value of 12 to 1 μg in humans (Institute of Medicine, Food and Nutrition Board 2001). *In vitro* research found red carrots prevented oxidation of cholesterol during heating comparably to purple, orange, and dark orange carrots (Sun and others 2009). In consideration of these findings, red carrots could serve as an option for delivering important vitamin A nutrition and the antioxidant lycopene.

Lutein bioavailability from yellow carrot was examined in humans by feeding 1.7 mg lutein/day from yellow carrots or a lutein supplement dissolved in oil, and white carrots as a negative control (Molldrem and others 2004). The subjects were fed carrot smoothies, muffins, and soup for breakfast and lunch for 7 d. The lutein from yellow carrots significantly increased serum concentrations and was found to be 65% as bioavailable as the lutein supplement. The yellow carrot treatment also maintained serum β-carotene concentrations, whereas the lutein treatment did not. Bioavailability of crystalline lutein, which is the form found in most supplements, is highly variable between and within subjects (Tanumihardjo and others 2005). While yellow carrots are not a concentrated source of lutein compared to other vegetables, especially green leaves, they may serve as an alternative bioavailable source of lutein.

High-β-carotene, dark-orange carrots were compared with typical orange carrots to determine if increased carotene content was bioavailable during a sustained-feeding cross-over study (Tanumihardjo and others 2009a). Orange, dark-orange, and white carrot muffins providing 2.6, 7, and 0 mg β-carotene/d, respectively, were fed for 11 d to healthy young adults. Compared with baseline, the dark-orange and orange carrot muffins increased serum β-carotene concentration 127% and 85%, respectively. This increase was different between treatments in the first 20-d period alone, that is, the dark-orange carrot treatment significantly raised α- and β-carotene serum concentrations above the typical orange carrot treatment.

Dark-orange carrots were also studied in Mongolian gerbils (Porter-Dosti and others 2006), which allows the measurement of liver vitamin A stores, the gold-standard for evaluating vitamin A status (Tanumihardjo 2004). When diets were equalized to carrot content, the dark-orange carrot treatment resulted in double the liver β-carotene content compared with typical orange carrots, but only 10% greater liver vitamin A stores. The vitamin A conversion factors were estimated to be 9 to 11 μg β-carotene to 1 μg retinol for the typical orange carrots and about 23 μg to 1 μg for the dark-orange carrots (Simon and others 2008). This study utilized gerbils with adequate vitamin A status. Because improved bioconversion with lower liver vitamin A reserves has

been demonstrated in animal models (Tanumihardjo 2008), further research with vitamin A-depleted animals or human subjects is warranted and may show improved conversion of the provitamin A carotenoids in the high-carotene carrots. The classic definition of bioavailability includes all β-carotene absorbed from the food, yet human studies are not able to assess the β-carotene stored in tissues. Therefore, studies that merely look at serum response in humans need to be cautiously interpreted. If dark-orange carrots were widely adopted, they could readily increase consumption of β-carotene and potentially impact vitamin A status of individuals at risk for deficiency.

Purple carrots are colored by a family of blue–red pigments called anthocyanins. The vitamin A value of purple–orange carrots, and purple–orange-red carrots were compared to orange carrots in Mongolian gerbils (Porter-Dosti and others 2006; Mills and others 2008). Liver stores of β-carotene and vitamin A in the gerbils did not differ suggesting that the higher phenolic and anthocyanin contents of purple carrots (Alasalvar and others 2001; Nicolle and others 2004; Grassmann and others 2007; Sun and others 2009) do not interfere with the bioavailability of β-carotene from purple carrots. More recently, a study of 5 healthy, young female subjects compared the relative bioavailability of 10.3 mg β-carotene from an acute feeding of purple–orange and orange carrot breakfast smoothies, with white carrot smoothies as a negative control (Arscott and others 2009). Analysis of area-under-the-curve for plasma β-carotene for 0 to 144 h showed that the orange and purple-orange carrots increased plasma β-carotene 5.4- and 4.5-old, respectively, compared to the white carrots, indicating a small, but significant 32% greater response from the orange than from the purple–orange carrots. However, when only the first 24 h were compared, there was no difference in plasma β-carotene response between purple and orange carrot treatments. Anthocyanins are rapidly absorbed, appearing in plasma by 30 min and achieving maximum concentration by 4 h (Kurilich and others 2005; Charron and others 2009), so if they were to exert an effect on β-carotene absorption in this study, it would be expected in this time period. This study confirmed that β-carotene was as bioavailable from purple–orange as orange carrots.

Health Effects

Diets rich in fruits and vegetables have been associated with reduced risk of degenerative diseases including some cancers (Riboli and Norat 2003; Lee and others 2009; Zhang and others 2009) and cardiovascular disease (CVD) (Mente and others 2009). Carotenoids are abundant in plant-based foods and have been implicated as the beneficial substances in these diets in the prevention of disease. The proposed mechanisms include provitamin A activity, antioxidant free radical scavenger activity that offers protection against LDL oxidation (Krinsky and Johnson 2005), increased cell-to-cell communication via gap junctions (Bertram and Vine 2005), and immunomodulatory effects (Chew and Park 2004).

Cardiovascular disease

The epidemiologic literature relating carotenoids to CVD is conflicting and has been reviewed by Voutilainen and others (2006). Clinical intervention trials that have focused on supplementation with large doses of β-carotene have not shown reductions in CVD and, in fact, in some cases have increased CVD risk in certain populations (Rapola and others 1997). Explanations proposed for the discrepancy between observational and intervention studies include: the possibility that β-carotene is not the active compound, but only an indicator of intake of some other nutrient, phytochemical, or beneficial dietary or lifestyle factor; the relatively high dosages used in the intervention studies provided a much higher "exposure" than natural food sources; and subjects in the intervention trials were already in higher risk groups that might have been in progressed states of disease.

Population-based studies also show an association between diets high in fiber and decreased risk for CVD (Van Horn and others 2008). High-fiber diets are associated with lower LDL cholesterol levels, body-mass index, blood-pressure, and triglyceride levels. Soluble fibers appear to be the most effective in lowering plasma LDL cholesterol levels. Fibers make up 3% to 4% of carrot weight, of which over 50% is soluble fiber (Svanberg and others 1997). As carrots are a rich source of both carotenoids and fiber, and one of the major vegetables consumed in the western world, a number of studies have looked at how carrots may exert effects in relation to the disease process of CVD.

The results of a large-scale prospective study reported that both α- and β-carotene intake, and carrot consumption, but not tocopherols, vitamin C, or other carotenoids were inversely related to CVD mortality in elderly men (Buijsse and others 2008). They were unable to find a correlation between CVD risk and multiple antioxidant scores ruling out that a diet rich in multiple antioxidants is protective. Because carrots were the major source of both α- and β-carotene, the beneficial association may be related to carrots themselves, a result of some other substances in carrots, or a healthy diet or lifestyle that is high in carrots.

Intervention trials with carrots are few and limited to short-term measurable endpoints. The effects of carrots on lipid metabolism are conflicting. Human subjects that consumed 200 g carrot daily for 3 wk had 11% reduction in serum cholesterol, 50% increase in fecal bile acids and fecal fats, and a modest, but significant 25% increase in stool weight (Robertson and others 1979). The effects on cholesterol and fecal bile acids and fat persisted for 3 wk after treatment ended. However, no effects on serum cholesterol were obtained with higher levels of carrots or carrot fiber in healthy men (Jenkins and others 1979) or women (Wisker and others 1994). A study in young females fed between 405 and 688 g carrot (15 g fiber) for 3 wk found that fibers in carrots were highly fermentable (soluble) and also had good stool bulking ability comparable to the insoluble fibers of cereal grains (Wisker and others 1994). However, different processing of the carrot treatments, that is, raw, blanched, or canned, altered the distribution of fiber types, but did not have an effect on these physiological parameters, or on serum high-density lipoprotein cholesterol levels or fecal bile acid secretion. Differences between studies with regard to physiological response to carrots could be due to differences in proportions of digestible carbohydrates between cultivars (Svanberg and others 1997).

Oxidative modification of LDL cholesterol has been considered to play a role in atherogenesis and coronary artery disease (Diaz and others 1997). Dietary antioxidants are proposed to protect against LDL oxidation. In a 2-wk intervention in healthy men fed 330 mL tomato juice, carrot juice, or 10 g spinach powder, all 3 treatments enhanced lipoprotein carotenoid concentrations, but only tomato juice reduced plasma lipid peroxidation as measured by plasma malonaldehyde and *ex vivo* LDL oxidation (Bub and others 2000). In a similar study, neither tomato nor carrot juice had an effect on lipid peroxidation (Briviba and others 2004).

Research in animals has examined the effects of whole carrot and fibers extracted from carrot pomace on lipid metabolism and antioxidant status. Cholesterol-fed rats on 15% carrot diet had lower liver cholesterol and triglycerides and also reduced serum cholesterol through apparent reduction in absorption and increase in the percentage of cholesterol excreted as bile acids (Nicolle and others 2003). Carrot also improved antioxidant status markers through reduction of urinary excretion of thiobarbituric acid reactive substances (TBARS), reduced TBARS in the

heart, increase in plasma vitamin E, and increase in plasma ferric-reducing ability of plasma (FRAP). In mice, carrot also lowered plasma and liver cholesterol and triglycerides and induced an increase of neutral sterol fecal excretion (Nicolle and others 2004). FRAP values were also increased and the plasma vitamin E to triglyceride ratio was improved by carrot feeding. The soluble fiber fraction of carrots, specifically the pectins and fermentable hemicelluloses, might be responsible for the reduction in cholesterol compared to cellulose.

Carrot pomace is the byproduct of the carrot juicing industry, as well as the "baby" carrot or cut-and-peel industry. Researchers are interested in describing the characteristics and potential health-promoting effects of this byproduct as a functional fiber for adding to foods. The insoluble fiber fraction (IFF) of carrot pomace had higher water- and oil-holding capacities, cation-exchange capacity, glucose-adsorbing ability, and amylase inhibition activity than cellulose (Chau and others 2004). Carrot pomace IFF also reduced serum cholesterol and triglycerides, increased serum HDL:LDL, and increased fecal lipids, cholesterol, and bile acids in hamsters (Hsu and others 2006). Research by this same group suggested that micronization of the carrot pomace IFF may improve its cholesterol-lowering effect (Chou and others 2008) and also measures of intestinal health (Chau and others 2007).

Data on the contribution of carrots to protect humans from the pathogenesis of CVD are inconclusive. Feeding animals carrots demonstrates beneficial effects on lipid metabolism and antioxidant action, but in humans, carrots have not yet clearly shown desired effects on these parameters. The protective effects of antioxidants may function through mechanisms unrelated to oxidation of LDL (Keaney and others 1993; Diaz and others 1997); thus, it may be that carrots exert their effects on alternative biomarkers of the pathogenesis of CVD.

Cancer

As suggested earlier for CVD, the carotenoid association with protection from cancers may actually be indicative of some other factors such as a healthy diet or lifestyle, or another beneficial phytochemical or nutrient. A systematic review of the association between high total carotenoid intake or serum concentration and lung cancer risk indicated a small, but significant, reduction in risk, but significant reductions were not found for individual carotenoids (Gallichio and others 2008). The evidence that carrots have an impact on the protection from cancer may be primarily through its association with a high-vegetable dietary pattern. Nonetheless, a pooled analysis of 13 studies found carrot intake to have a significant inverse association with renal cell cancer (Lee and others 2009). Carrot intake was also found to be inversely related to breast cancer incidence among Chinese women (Zhang and others 2009). The Expert Report of the World Cancer Research Fund and the American Institute for Cancer Research (2007) judged that probable evidence for the role of carotenoid-containing foods in cancer prevention is limited to the mouth and pharynx, larynx, and lung. β-Carotene- and lycopene-containing foods have a probable association for protection from esophageal and prostate cancers, respectively. Data on carrots contributed to the evidence-base for the association of nonstarchy vegetables and oral and lung cancers and limited, but consistent, evidence from case-control studies supported a role of carrots in protection from cancer of the cervix.

Few mechanistic studies of carrots and the cancer process have been performed. Lymphocyte DNA strand breakage was reduced in healthy men consuming 330 mL tomato juice (40 mg lycopene) or carrot juice (22.3 mg β-carotene and 15.7 mg α-carotene) for 2 wk (Pool-Zobel and others 1997). Oxidative base damage was reduced only with the carrot juice. Healthy men consuming tomato juice or carrot juice for 2 wk experienced a time-delayed modulation of immune functions (Watzl and others 2003). Research by the same group demonstrated that carrot or tomato juice consumption did not decrease lipid peroxidation in plasma or feces (Briviba and others 2004) or increase cytotoxic or antiproliferative activity of fecal water on colon adenocarcinoma cells (Schnabele and others 2008). Both tomato and carrot juice only led to minor changes in luminal biomarkers relevant to colon carcinogenesis. In hamsters, the insoluble fiber fraction isolated from carrot pomace reduced fecal ammonia output and detrimental colonic bacterial enzymes, β-D-glucuronidase, β-D-glucosidase, mucinase, and urease, potentially reducing the exposure of the intestinal lumen to harmful compounds (Chau and others 2005).

The bitter off-flavor of carrots is attributed to a group of compounds called polyacetylenes (Czepa and Hofmann 2004), which have been identified as having antiinflammatory, antifungal, antibacterial, and platelet-reducing activity (Christensen and Brandt 2006). Polyacetylenes have shown *in vitro* biphasic effects, being stimulatory at low concentrations and inhibitory or toxic at high concentrations, suggesting concentration-dependent effects (Hansen and others 2003). The primary polyacetylenes identified in carrots, falcarinol and falcarindiol, have shown *in vitro* antiinflammatory activity (Metzger and others 2008) and an inhibitory effect on the development of preneoplastic lesions in the rat colon (Kobæk-Larsen and others 2005). Falcarinol appears to be bioavailable in humans (Brandt and others 2004), appearing in serum in concentrations similar to the range shown to have *in vitro* physiologic effect (Hansen and others 2003).

Information on the chemoprotective activity of carrot colors other than orange is sparse. In Mongolian gerbils fed purple–orange, orange, orange–red, or purple–orange–red carrots for 4 wk, total liver antioxidant capacity was higher in all the colored carrot groups than both the white carrot-fed and vitamin A-supplemented groups (Mills and others 2008). Black carrot anthocyanin-rich extract displayed 80% *in vitro* inhibition of colorectal adenocarcinoma (HT-29) and promyelocytic leukemia (HL-60) cells (Netzel and others 2007). *In vitro* research demonstrated all anthocyanin-rich extracts from 7 different fruits and vegetables suppressed HT29 cell growth, but to various degrees, in the order: purple corn > chokeberry and bilberry > purple carrot and grape > radish and elderberry (Jing and others 2008). Anthocyanin chemical structure affected chemoprotection, suggesting foods with different anthocyanin profiles have differing anti-cancer activities. Caution in interpreting *in vitro* studies of anthocyanins is warranted due to the high concentrations employed *in vitro* and the low *in vivo* bioavailability of these compounds.

The chemoprotective mechanisms associated with carrots are as inconclusive as those for CVD. Evidence points to beneficial effects of carrots as part of a healthy lifestyle, which includes a diet rich in a variety of fruits, vegetables, and other whole foods. Excessive carrot consumption ($\geq$1 kg/d juiced or raw), which has been reported in rare cases, may be associated with leucopenia (Shoenfeld and others 1982) and amenorrhea (Kemmann and others 1983; Mikkelsen and others 2009).

Satiety and glucose metabolism

Dietary fiber increases satiety and decreases energy intake (Howarth and others 2001). Fruits and vegetables are a food group that is usually low in fat content and energy density, and high in water and dietary fiber. Thus, they may contribute significantly to hunger control and weight management. Relatively few studies have specifically tested the effects of fruits and vegetables on satiety, food intake, and body weight (Rolls and others 2004; Ello-Martin and others 2007; Tanumihardjo and others 2009b). Some efforts have been made to specifically assess the effects of carrots and their components on these parameters.

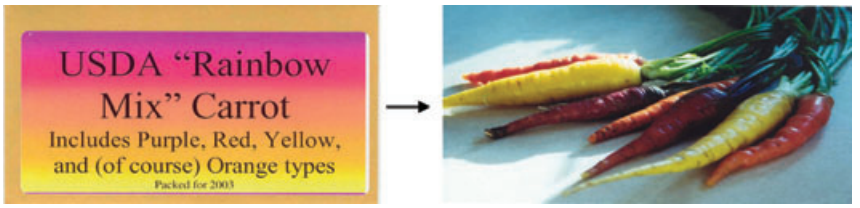

Figure 4—In an effort to gain public awareness, carrot seeds from biofortified varieties are distributed to local community and youth gardens through outreach activities. This results in direct consumption of these "functional" carrots by consumers.

Gustaffson and others (1994) found that in isocaloric meals, the larger the carrot portion (100, 200, and 300 g carrot containing 2.9, 5.8, and 8.7 g fiber, respectively), the lower the glucose and insulin/C-peptide responses and the higher the satiety scores. The minimum serving size causing an effect was 200 g. However, effects of processing and cooking with 2 different carrot harvests had mixed results (Gustaffson and others 1995). The 1st year (4.4 g fiber in carrots), the raw carrot treatment enhanced satiety, and reduced glucose and C-peptide responses more than the cooked. The 2nd year (6.6 g fiber in carrots) only the glucose response was affected by processing. Thus, energy density rather than cooking method may have affected satiety. Alternatively, the exponentially higher viscosity elicited by the higher fiber dose (Svanberg and others 1995) may have unexplained metabolic consequences.

Another study examined whether the physical structure or fiber content of carrots exerts an effect on satiety by feeding 200 g whole cooked carrots (structure and fiber), cooked pureed carrots (no structure, some fiber), and carrot nutrients (no structure, no fiber) to healthy adult women (Moorehead and others 2006). They measured satiety as well as subsequent energy intakes the rest of the day and found that the whole carrots and blended carrots had higher satiety scores than the carrot nutrients. Subsequent energy intakes increased in the following order: whole carrots < blended carrots < carrot nutrients. Thus, both fiber content and structure played a beneficial role. This research is supported by a recent fruit and vegetable weight-loss intervention targeted to obese individuals, which fed carrots at least 3 times per week, showing small, but significant, weight loss at 3 mo and baseline weight maintenance at 18 mo (Tanumihardjo and others 2009b). Additionally, carrots may have played a role in maintaining glycemic control in type 2 diabetic subjects fed carrot cake for 24 d (Brynes and Frost 2007). More study is warranted to compare carrots with other vegetables, effects of processing, and added fiber isolates on satiety and weight management.

Conclusions

Functional foods provide benefit beyond basic nutrition. Biofortified carrots not only provide vitamin A but may contribute to optimal health. More research is needed to better understand the contribution of carrots to health and the mechanisms involved. Carrot feeding studies in specific populations, such as older adults or hypercholesterolemic individuals, could provide information unique to these oxidatively challenged groups. Combined with measurement of alternative markers of oxidative stress, such as the production of F_2-isoprostanes, or surrogate markers of cardiovascular health, such as platelet aggregation or endothelial function, new insights may be elucidated concerning the effects of various phytochemicals in carrots. Macronutrient, fiber, and phytochemical analyses of carrots used in these studies are critical because genetic variability may preclude generalization of effects to all carrots. Additionally, more information is needed regarding the metabolic products and *in vivo* mechanisms of action of carrot compounds, such as anthocyanins, phenolic acids, and polyacetylenes.

In an effort to enhance consumer awareness over the past decade, carrot seeds from biofortified varieties have been distributed every spring to community and youth gardening initiatives leading to direct consumption of specialty carrots of various colors (Figure 4). Most epidemiologic research points to a diet high in fruit and vegetables in combating disease and colorful carrots may certainly contribute to this benefit.

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