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 \( \alpha \)- and \( \beta \)-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).

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. \( \alpha \)- and \( \beta \)-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.
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...
Carrots of many colors... phenolic compounds. The greatest nutritional interest in carrots stems from their phychochemical 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 \( \beta \)-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 \( \alpha \)- and \( \beta \)-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 \( \beta \)-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 Udadyakkerarao 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 processors 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 from whole carrot depending on the processing method. Carrot fiber has become of interest to food processors 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 from whole carrot depending on the processing method. Carrot fiber has become of interest to food processors 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 from whole carrot depending on the processing method.
fiber fraction, high pectic substances in the peels, or the blanching might account for this property. Nawirska and Ukl´anska (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 Kwasiwniwska 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.

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

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


### 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- and β-, γ-, and ε-carotene, 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

<table>
<thead>
<tr>
<th>Yearb</th>
<th>World</th>
<th>Africa</th>
<th>North and Central America</th>
<th>South America</th>
<th>Asia</th>
<th>Europe</th>
<th>Oceania</th>
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<tbody>
<tr>
<td>1970</td>
<td>7908</td>
<td>214</td>
<td>1099</td>
<td>281</td>
<td>1776</td>
<td>3049</td>
<td>117</td>
</tr>
<tr>
<td>1980</td>
<td>10499</td>
<td>383</td>
<td>1328</td>
<td>465</td>
<td>2677</td>
<td>3591</td>
<td>141</td>
</tr>
<tr>
<td>1990</td>
<td>13696</td>
<td>558</td>
<td>1773</td>
<td>630</td>
<td>4003</td>
<td>4304</td>
<td>193</td>
</tr>
<tr>
<td>2000</td>
<td>20489</td>
<td>913</td>
<td>2619</td>
<td>950</td>
<td>8163</td>
<td>7494</td>
<td>350</td>
</tr>
<tr>
<td>2003</td>
<td>23321</td>
<td>1054</td>
<td>2674</td>
<td>982</td>
<td>10801</td>
<td>7484</td>
<td>327</td>
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</table>

bProduction values are average of the preceding 3 y.
cFormer USSR republics included in appropriate European or Asian grouping.
dChange in carrot production from 1970 to 2003, percent.
eChange 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.

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Water %</th>
<th>CHO (g)</th>
<th>Protein (g)</th>
<th>Fat (g)</th>
<th>Fiber (g)</th>
<th>Ash (g)</th>
<th>Vit A (μg)</th>
<th>Vit C (mg)</th>
<th>Fe (mg)</th>
<th>Na (mg)</th>
<th>K (mg)</th>
<th>Mg (mg)</th>
<th>Ca (mg)</th>
<th>P (mg)</th>
<th>RAE[a] (μg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>96</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>88</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Tomato</td>
<td>96</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Spinach</td>
<td>94</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Lettuce, iceberg</td>
<td>91</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Broccoli</td>
<td>95</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Lettuce, romaine</td>
<td>90</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Collards</td>
<td>93</td>
<td>2.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

[a] RAE (retinol activity equivalent) = μg all-trans-retinol + 12 μg dietary all-trans-β-carotene + 12 μg other dietary provitamin A carotenoid.

Carrots of many colors...
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 cultivation 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 (-)-epicatechin. 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 (Oltlho and others 2003).

### Table 6—Carotenoid content of raw carrots of different colors.*

<table>
<thead>
<tr>
<th>Carrot color</th>
<th>α-Carotene</th>
<th>β-Carotene</th>
<th>Lutein</th>
<th>Lycopene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orange</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>22</td>
<td>128</td>
<td>2.6</td>
<td>nd²</td>
</tr>
<tr>
<td>B</td>
<td>27</td>
<td>69</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>C</td>
<td>40</td>
<td>69</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>D</td>
<td>13 to 31</td>
<td>32 to 66</td>
<td>0.6 to 1.8</td>
<td>nm</td>
</tr>
<tr>
<td>E</td>
<td>47.1</td>
<td>47.5</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>H</td>
<td>10 to 22</td>
<td>18 to 38</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>I</td>
<td>57 to 70</td>
<td>45 to 52</td>
<td>4 to 5</td>
<td>nd</td>
</tr>
<tr>
<td>Dark orange</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>31</td>
<td>185</td>
<td>4.4</td>
<td>17</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>113</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>D</td>
<td>75.8</td>
<td>172</td>
<td>1.0</td>
<td>nm</td>
</tr>
<tr>
<td>F</td>
<td>96 to 192</td>
<td>215 to 311</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.5</td>
<td>1.8</td>
<td>5.1</td>
<td>nd²</td>
</tr>
<tr>
<td>B</td>
<td>0.2</td>
<td>3.6</td>
<td>2.4</td>
<td>0.04</td>
</tr>
<tr>
<td>C</td>
<td>tr</td>
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</tr>
<tr>
<td>D</td>
<td>nd</td>
<td>3.3</td>
<td>1.4 to 2.3</td>
<td>nm</td>
</tr>
<tr>
<td>I</td>
<td>Tr</td>
<td>Tr</td>
<td>5 to 10</td>
<td>nd</td>
</tr>
<tr>
<td>Red</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>A</td>
<td>1.1</td>
<td>3.4</td>
<td>3.2</td>
<td>61</td>
</tr>
<tr>
<td>B</td>
<td>0.2</td>
<td>22</td>
<td>0.2</td>
<td>50</td>
</tr>
<tr>
<td>I</td>
<td>nd to 4</td>
<td>35 to 40</td>
<td>Tr-3</td>
<td>85 to 100</td>
</tr>
<tr>
<td>Purple–white</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>2 to 3</td>
<td>2 to 3</td>
<td>9 to 10</td>
<td>nd</td>
</tr>
<tr>
<td>Purple–orange</td>
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<td>A</td>
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<td>123</td>
<td>11</td>
<td>nd²</td>
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<td>Purple–yellow</td>
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<td>B</td>
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<td>D</td>
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<td>3.1 to 3.8</td>
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<td>C</td>
<td>nd</td>
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</table>

*Carotenoid concentrations of raw carrot, ppm.

²References: A = Surles and others (2004); B = Sun and others (2009); C = Alasalvar and others (2001); D = Nicole and others (2004); E = EL-Qudah (2009); F = Simon and others (2003).

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.
Phenolic compounds and antioxidant capacity

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 Gochnaur 2006). Anthocyanins have also been implicated in improved brain and memory functions (Shih and others 2009).

Anthocyanins are polyphenolic compounds that comprise an anthocyanidin backbone, 2-phenylbenzopyrylium, also referred to as the flavylum cation. The 6 common anthocyanidin backbones are cyanidin, malvidin, delphinidin, peonidin, petunidin, and pelargonidin. These backbones can vary in the number and position of hydroxy groups, methoxy 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 pelargonidin 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) (Cy3XSF), cyanidin-3-(2'-xylose-6-feruloyl-glucose-galactoside) (Cy3XFGG), and cyanidin-3-(2'-xylose-6'-4-coumaroylglucose-galactoside) (Cy3XCGGG) (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 2005).
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 their 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; Håggeger 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).

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.
Carrots of many colors . . .

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 (Moshtagh 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 2001). 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 carotenones 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) (Khaschik 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 carotenones and vitamin A. Approximately 150 high-carotene carrots (an amount grown in 1 m²) 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

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for storage. Studies suggest that the carrot matrix has a negative effect on carotenoid absorption. Serum response to both acute (Brown and others 1999; Bulux and others 1998) and chronic carrot feeding (Rich and others 1999; 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 a carotene–micelle (Rich and others 2003a) was lowest for a carrot juice carotene (lutein, α-carotene > lutein, β-carotene > lutein, blanched–frozen spinach, β-carotene > blanched frozen spinach > carotene, carrot juice). This suggests that, in the duodenum, the more apolar carotenoids 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; Toronnen and others 1996) found a 45% bioavailability of β-carotene in healthy women. These studies show that bioavailability of β-carotene is reduced by the food matrix compared to purified β-carotene (Zhou and others 1996). This is in agreement with the observation that heating of carrot juice did not significantly increase carotene bioavailability in ferrets (Zhou and others 1996).

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 in 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) and others (2003) 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 (Faith and others 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
Carrots of many colors... greater for the puree than for the boiled-mashed carrots. The apparent β-carotene to vitamin A conversion efficiencies (44% and 39%, for 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 of red red carrots provided 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 (Moldrem 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 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), fur-
ther research with vitamin A-depleted animals or human subjects
is warranted and may show improved conversion of the provita-
min A carotenoids in the high-carotene carrots. The classic def-
inition 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 re-
sponse 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 sta-
tus 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 car-
rots, 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 car-
rot 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

Diet 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 oth-
ers 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 supple-
mentation with large doses of β-carotene have not shown reduc-
tions in CVD and, in fact, in some cases have increased CVD
risk in certain populations (Rapola and others 1997). Explan-
ations 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 stud-
ies 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 di-
eits 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 (Swanberg 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 toco-
pherols, 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 anti-
oxidants 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 of tocols, cholesterol and fecal bile acids and fat persisted for 3
wk after treatment ended. However, no effects on serum chole-
sterol 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 abil-
ity comparable to the insoluble fibers of cereal grains (Wisker
and others 1994). However, different processing of the carrot treat-
ments, that is, raw, blanched, or canned, altered the distribution
of fiber types, but did not have an effect on these physiologi-
cal 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 (Swanberg 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 car-
rot 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
(Nicole and others 2003). Carrot also improved antioxidant sta-
tus markers through reduction of urinary excretion of thiobar-
bituric acid reactive substances (TBARS), reduced TBARS in the
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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 chole-
sterol 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 ca-
pacity, glucose-adsorbing ability, and amylase inhibition activity
than cellulose (Chau and others 2004). Carrot pomace IFF also
reduced serum cholesterol and triglycerides, increased 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 im-
prove its cholesterol-lowering effect (Chau 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 antioxi-
dant action, but in humans, carrots have not yet clearly shown
desired effects on these parameters. The protective effects of an-
tioxidants may function through mechanisms unrelated to oxida-
tion 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 associa-
tion 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 car-
rot 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 Chi-
nese women (Zhang and others 2009). The Expert Report of the
World Cancer Research Fund and the American Institute for Can-
cer 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
cytochrome-containing foods have a probable association for pro-	ection 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 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 modu-
lation 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 (Briñabia and others 2004) or increase cytotoxic or antipro-
liferative 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 car-
cinogenesis. In hamsters, the insoluble fiber fraction isolated from
 carrot pomace reduced fecal ammonia output and detrimental
colon 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 com-
pounds called polymethylenes (Czea and Hofmann 2004), which
have been identified as having antiinflammatory, antifungal, an-
tibacterial, and platelet-reducing activity (Christensen and Brandt
2006). Polymethylenes have shown in vitro biphasic effects, be-
ing stimulatory at low concentrations and inhibitory or toxic at
high concentrations, suggesting concentration-dependent effects
(Hansen and others 2003). The primary polymethylenes identi-
fied in carrots, falcarinol and falcarkinol, have shown in vitro
antiinflammatory activity (Metzger and others 2008) and an in-
hibitory effect on the development of preneoplastic lesions in the
rat colon (Kobæk-Larsen and others 2005). Falcarkinol 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 col-
or other than orange is sparse. In Mongolian gerbils fed
purple-orange, orange, orange-red, or purple-orange-red car-
rots for 4 wk, total liver antioxidant capacity was higher in all
the colored carrot groups than both the white carrot-fed and vita-
min A-supplemented groups (Mills and others 2008). Black car-
rot 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 demon-
strated 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, sug-
gesting 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 em-
ployed in vitro and the low in vivo bioavailability of these com-
pounds.

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.

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
fiber and dietary fiber. Thus, they may contribute significantly
to hunger control and weight management. Relatively few stud-
ies have specifically tested the effects of fruits and vegetables
on satiety, food intake, and body weight (Rolls and others 2004;
Ello-Martín 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.
Gustafsson 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 (Gustafsson 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 intake. The 1st year (8.4 g fiber in carrots) reduced the satiety response, and total energy intake was lower than the control (no carrots). The 2nd year (6.6 g fiber in carrots) had mixed results (Gustafsson and others 1994). 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.

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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References

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