Chapter 2
Carrots of Various Colors

Samantha Schmaelzle and Sherry A. Tanumihardjo

Key Points

- Orange carrots are one of the most widely consumed vegetables and are a significant source of provitamin A carotenoids in the US diet. Breeding efforts to increase the nutritional value of carrots through biofortification have been on the rise.
- Through biofortification, carrots of multiple hues have been bred. The different pigments in the carrots are phytochemical components shown to have potential health benefits beyond providing vitamin A. For example, purple carrots are purple because of anthocyanins, which act as antioxidants, and red carrots are red because of lycopene, which may aid in heart disease prevention. Purple–white, purple–yellow, purple–orange, purple–red, purple–orange–red (POR), red–orange, and orange–yellow have successfully been bred.
- From previous research on solid colored carrots, carrots such as the POR variety will have anthocyanins, β-carotene, and lycopene, respectively, because of their different color components.
- Plant breeders should be encouraged to develop these carrots to provide sources of vitamin A precursors and other phytochemicals.
- Consuming these whole vegetables could have a greater reduction in disease risk than individual compounds, but further research is needed. The consumption of these carrots could provide not only vitamin A but also other functional compounds that have disease-fighting properties and enhance the well-being of humans.

Keywords α-Carotene • α-Retinol • Anthocyanins • Biofortification • Rainbow carrots

Introduction

Carrots are one of the most popular vegetables in the USA and fresh-market carrot consumption has been increasing over the past few decades [1]. Since the introduction of "cut and peel" carrots into the market place, which are also commonly called baby carrots, carrot consumption has increased by 50% in the USA. Carrots are a significant source of vitamin A in the form of α- and β-carotene

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S.A. Tanumihardjo (ed.), *Carotenoids and Human Health*, Nutrition and Health,
DOI 10.1007/978-1-62703-203-2_2, © Springer Science+Business Media New York 2013

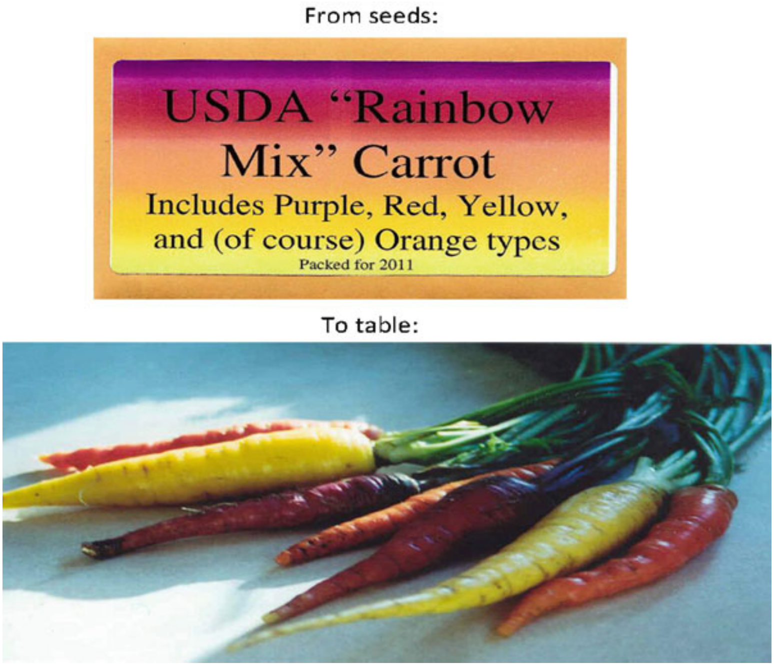

Fig. 2.1 For over a decade, “rainbow” carrot seeds have been distributed to community and youth gardeners in Wisconsin and at various outreach efforts around the world. The harvested carrots are then used as demonstration tools to emphasize color variety among vegetables and their health benefits

accounting for an estimated 30% of the dietary vitamin A in the US diet [2]. Breeding efforts to improve food crops through biofortification (discussed extensively in Chap. 17) have increased the nutritional value of this vegetable [3, 4]. For carrots, biofortification has included increasing the provitamin A content (i.e., α- and β-carotene) as well as other bioactive compounds such as lutein, lycopene, and anthocyanins. These horticultural approaches for improving the nutritional quality and visual appeal of our food supply provide a sustainable, inexpensive complement to medical and social programs for preventing human disease [3].

Different colors of fruits and vegetables are due to pigmented disease-fighting phytochemicals, which is one reason the 2010 Dietary Guidelines recommend choosing a variety of fruits and vegetables [5]. Different colors of carrots (i.e., purple, red, white, yellow, and orange; Fig. 2.1) have been around for hundreds of years; however, orange carrots have been the predominant carrot available on the US grocery shelves. Colored carrots have a wide variation of pigments that have different biological benefits when consumed, such as providing vitamin A and decreased chronic disease risks [6]. Because carrots are so widely accepted and consumed among people especially in the USA, increasing the nutrient content could have exponential health benefits. Carrot breeders have developed new lines of novelty carrots that have multiple colors (and therefore, multiple phytochemicals) available in one carrot. For example, the POR carrot has a purple cortex with an orange and red core due to the presence of anthocyanins, α- and β-carotene, and lycopene, respectively [7].

Carotenoids are present in fruits and vegetables that have yellow, orange, and red pigmentation. Carotenoids protect chlorophyll from photooxidation and are accessory, light-harvesting pigments and photoreceptors [3]. Some carotenoids have provitamin A activity, meaning that they can be converted to vitamin A in the body. Other carotenoids support vision (see Chap. 13) and have antioxidant activity (see Chap. 4) in the body. Vitamin A obtained from the diet in fruits and vegetables is often recommended rather than from preformed sources (i.e., retinyl acetate or retinyl palmitate) because of the potential for hypervitaminosis A with supplements and fortified foods [8–10]. When consumed as plant provitamin A carotenoids, the body has more control over how much provitamin A is converted to retinol [11].

Flavonoids are a large group (~4,000 identified) of polyphenolic compounds that are expressed in plants, largely in fruits and vegetables [12]. Isoflavones, flavones, and anthocyanins are a few categories of flavonoids based on their chemical structure and function [13]. Anthocyanins in purple carrot include cyanidin-3-(2″-xylose-6-glucose-galactoside), cyanidin-3-(2″-xylose-galactoside), cyanidin-3-(2″-xylose-6′-sinapoyl-glucose-galactoside), cyanidin-3-(2″-xylose-6′-(4 coumuroyl) glucose-galactoside), and the major one, cyanidin-3-(2″-xylose-6′-feruloyl-glucose-galactoside) [14]. Flavonoids have dietary benefits such as antiallergy, anti-inflammatory, antitumor, and antioxidant characteristics [12]. Evidence exists that certain flavonoids can prevent platelet aggregation [13]. Indeed, dietary intake of flavonoids is quite high compared to other dietary antioxidants, such as vitamins C and E [12].

This chapter outlines why these “rainbow” carrots are important for human consumption, explains the carotenoids and/or phytochemicals in each of the colored carrots, and suggests the health benefit of incorporating multiple pigments into new types.

Types of Carrots, Their Phytochemicals, and Health Benefits

Solid colored carrots have been studied for nutritive benefits and color components to the point that they have been considered a “functional food” [15]. The pigments found in plants play important roles in plant metabolism and visual attraction in nature [3]. The pigments in carrots serve an important role in promoting health because they have been associated with reduced risk of atherosclerosis, cancer, and inflammation [16]. In general, phytochemicals have mechanisms of action in the body including antioxidant effects, modulation of detoxifying enzymes, stimulation of the immune system, modulation of hormone metabolism, and antibacterial and antiviral effects. Fruits and vegetables that are brightly colored—yellow, orange, red, green, blue, and purple—generally contain high amounts of phytochemicals and nutrients. Phytochemicals present in different types of carrots include not only the carotenoids but also flavonoids, such as red or blue anthocyanins.

Orange carrots. Orange carrots predominantly contain α- and β-carotene, both of which are orange pigments. These readily available carrots in the USA are high in vitamin A, which is essential for healthy eyes, cell growth, and reproduction. β-Carotene usually receives most attention and α-carotene, another provitamin A carotenoid in carrots, is often overlooked. The human body converts β-carotene directly to vitamin A, which is also important in strengthening the immune system by keeping the skin, lungs, and intestinal track in order (see Chap. 16). α- and β-Carotene are also antioxidants, which are important to fight against heart disease and trap free radicals. α-Carotene may be more powerful than β-carotene in inhibiting processes that may lead to tumor growth (see Chap. 11). α-Carotene is centrally cleaved in the intestinal brush border and reduced to α-retinol and retinol [17]. Biofortification of orange carrots has resulted in carrots with very high levels of α- and β-carotene [4, 14].

Yellow carrots. Yellow carrots contain predominantly the xanthophyll lutein, which is important for healthy eyes and in the fight against macular degeneration (see Chap. 13). Lutein may also prevent lung and other cancers and reduce the risk of atherosclerosis. A human study determined that yellow carrot lutein was 65% as bioavailable as that from a lutein in oil supplement [18].

Red carrots. The rich red pigment in red carrots is lycopene, which is a pigment also found in red tomatoes and pink watermelon. Lycopene is associated with a reduced risk of serum lipid oxidation, heart disease prevention, and a wide variety of cancers (see Chap. 12). Lycopene from red-pigmented carrots is about 40% as bioavailable as that from tomato paste [19]. For consumers who do not like tomatoes, having another food source of lycopene that is widely accepted would be a great option.

Purple and black carrots. Purple carrots get their pigmentation from phytochemicals called anthocyanins that act as powerful antioxidants to sequester harmful free radicals in the body [15, 20]. Sometimes the pigments are so dark that the carrots are called "black." Anthocyanins may prevent heart disease by acting as anti-inflammatory agents and reducing lipid oxidation [15]. Purple carrots were one of the first types to be consumed by humans in the Middle East [21]. Grassman et al. [22] evaluated different colored carrots and their antioxidant capacity. Solid colored purple carrots contained the most phenolic compounds and therefore may lead to higher antioxidant capacity in the human body.

White carrots. Although white carrots lack pigment, they are still a great source of dietary fiber. In comparative studies, white carrots are generally used as a control because they lack the pigmented phytochemicals that colored carrots hold [20].

Rainbow carrots. Efforts to breed carrots of several colors have been on the rise. Purple–white, purple–yellow, purple–orange, purple–red, POR, red–orange, and orange–yellow have successfully been bred. Because multicolored carrots are fairly new types, limited research and information are available on their phytochemical content and effects in animal or human models. From previous research on solid colored carrots, carrots such as the POR variety will have anthocyanins, β-carotene, and lycopene, respectively, because of their different color components. Rainbow carrot seeds have been distributed to community and youth gardeners to build awareness and to use the harvested carrots to demonstrate the diversity of pigments in vegetables (Fig. 2.1).

In Vitro Research

Sun et al. [20] determined the phytochemical profile and antioxidant capacity of seven colored carrots: purple–yellow, purple–orange, red, dark orange, orange, yellow, and white. Anthocyanins were the major phytochemical in purple–yellow and purple–orange carrots, and chlorogenic acid was a major compound in all carrots. Carotenoids did not contribute substantially to total antioxidant capacity, but correlated with it. Purple–yellow carrots had the highest antioxidant capacity, followed by purple–orange carrots, and the other carrots did not differ from each other. These results demonstrate that purple carrots have high antioxidant capacity and content, and therefore human consumption of these carrots may be beneficial.

Animal Research

Animal research is often performed to look at tissue storage and bioefficacy of the provitamin A carotenoids to make vitamin A. Studies of this sort are either not possible with humans due to the invasiveness of looking at tissue distribution or require isotopic tracers, which are expensive. Although not all animals are good models for carotenoid metabolic studies, Mongolian gerbils are useful and have been extensively used for provitamin A carotenoid studies including carrots [7, 14, 23].

Two animal studies used biofortified high β-carotene orange carrots and purple carrots to assess the bioavailability of the β-carotene in Mongolian gerbils [14]. In the first study, gerbils received a diet containing powdered orange, purple, white alone, or white carrot with a β-carotene supplement. In the second study, high-β-carotene orange, orange, purple, or white carrot powder diets were fed. After 21 days of feeding, the effects of carrot type or supplement on serum and liver β-carotene, α-carotene, and vitamin A concentrations were analyzed.

Liver stores of β-carotene and vitamin A did not differ between orange and purple carrot diets, when equal amounts of β-carotene from each of the diets were consumed [14]. Therefore, the anthocyanins from the purple carrot did not interfere with the bioavailability of β-carotene. Second, both the orange and the purple carrot diet resulted in higher liver vitamin A concentrations compared with the supplement, demonstrating that carotenoids from whole foods fed throughout the day are more consistently converted to vitamin A than single supplement doses. Finally, high-β-carotene carrots resulted in more than twofold higher β-carotene and 10% higher vitamin A liver stores compared with typical orange carrots [14]. These results suggest that high-β-carotene carrots may be an alternative source of vitamin A to typical carrots in areas of vitamin A deficiency. This was the first study to show that biofortified high-β-carotene orange carrots increase the vitamin A concentration in liver when compared with typical orange carrots in gerbils.

In another animal study, Mills et al. [7] measured the antioxidant potential and vitamin A bioefficacy of four biofortified carrot varieties—purple/orange, POR, orange/red, and orange. Each type of carrot was fed to Mongolian gerbils ($n = 11$/group, 6 groups) for 4 weeks. After treatment, antioxidant capacity, carotenoid, and retinol concentrations were analyzed in the liver and serum. Liver antioxidant capacity and vitamin A stores from the four colored carrot-fed gerbils were significantly higher than the white carrot-fed negative control group. Antioxidant capacity was also higher than the vitamin A-supplemented positive control group [7], suggesting that the bioactive compounds in the colored carrots enhanced liver antioxidant capacity.

Indeed, the antioxidant capacity of serum did not differ among the treatment groups, but was greater in the liver extracts from gerbils fed colored carrots compared with gerbils fed white carrots [7]. Antioxidant feeding interventions have mixed results, either showing little or no effect on antioxidant capacity in serum. This study may have been too short to see a serum antioxidant effect and serum is likely not a sensitive indicator of what is occurring at the tissue level.

Bioavailability competition between lycopene and β-carotene in the orange/red carrot variety may occur. In previous research, orange/red carrots fed to humans [19] and gerbils [23] showed lower bioavailability of lycopene than when fed tomato paste, which does not contain as much β-carotene as the red carrot. Intake of the orange and orange/red carrots yielded similar vitamin A bioefficacies in the gerbils [23]; and therefore, lycopene bioavailability may be more negatively affected than β-carotene bioefficacy when the two carotenoids interact.

The enhancement of liver antioxidant capacity observed in gerbils consuming biofortified carrots was likely due to the combined bioactivities of multiple compounds rather than the individual activities of carotenoids, anthocyanins, or phenolic acids, illustrating the synergistic benefit associated with intake of whole foods.

Human Studies with Various Colored Carrots

Unlike animal studies where absolute bioefficacy can be measured directly from liver stores of vitamin A, human bioavailability studies with various solid colored carrots have examined relative bioavailability using serum concentration changes over time with chronic feeding. Several human studies have shown varying bioavailabilities of specific phytochemicals from different colored carrots.

Two studies showed that lycopene and β-carotene are bioavailable from red carrots in humans [19]. The first study fed muffins made from red carrots at 5 mg lycopene/day compared with white carrots as a negative control for a period of 11 days. The second study determined the effect of carrot fiber on lycopene bioavailability by feeding tomato paste muffins with or without white carrots. Lycopene and β-carotene were bioavailable from red carrot, but lycopene absorption was negatively affected by carrot fiber. Combined results from both studies suggested that lycopene in red carrot is 44% as bioavailable as that from tomato paste and a serum plateau occurred at ≥20 mg lycopene/day [19].

Anthocyanins from purple carrots are bioavailable and can be absorbed intact as shown by a feeding study [24]. Varying amounts (250–500 g) of raw or cooked purple carrots were fed to human subjects. The four different anthocyanins observed were found intact in plasma by 30 min and peaked at 2 h after consumption. Cooking of the carrots increased the recovery of some anthocyanins. The reduced recovery of anthocyanins from the larger amount of carrots fed suggested saturation of absorption mechanisms.

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 [18]. The subjects were fed carrot smoothies, muffins, and soup for breakfast and lunch for 7 days. 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 [25]. While yellow carrots are not a concentrated source of lutein compared to other vegetables such as green leaves, they may serve as an alternative bioavailable source of lutein especially considering the popularity of carrots in the US diet.

All of this research demonstrated that the compounds in these carrots had high bioavailability. However, a study with two different orange carrots did not show a difference in α- and β-carotene uptake and clearance in the serum between the two types [4]. Subjects received all three treatments of white, orange, or dark orange carrot muffins for 11 days with a 10-day washout period between treatments. The lack of difference between the orange and dark orange carrots may have been due to the prolonged time that the subjects were on a low carotenoid diet causing more bioconversion to vitamin A. Other tissues may have shown differences but were not accessible as in the animal studies with a similar design [14].

Arscott et al. [26] determined that anthocyanins in purple–orange carrots do not influence the bioavailability of β-carotene in young women. Using three treatment groups (i.e., purple/orange, orange, and white carrot smoothies) Arscott conducted a 3 × 3 crossover, acute feeding trial with five female subjects. Subjects were fed a carrot-containing breakfast after a carotenoid and anthocyanin washout period and blood samples were taken periodically for the next week. Both the orange and purple–orange carrot β-carotene peaks were elevated, but not different, suggesting that anthocyanins had no effect on β-carotene concentrations in serum. No effect of treatment was found for plasma antioxidant activity, which is a similar outcome as the animal study [7]. The design of this study is valuable, but a higher number of subjects and acute studies combined with chronic feedings might show a greater effect of the different compounds interacting with one another.

Conclusion

Further research with multicolored carrots and humans must be done to determine the interactions of beneficial compounds because they may compete with each other for release or uptake from the carrot. This research could lead to more varieties of carrots on grocery shelves and into the hands of consumers. The development of new and more potent sources of provitamin A carotenoids in horticultural crops, including carrots, and improvement of production shelf-life and consumer acceptance of these crops can make an important contribution to improving human health [3]. Increasing vegetable consumption, including carrots, was associated with modest weight loss in obese individuals [27]. In taste evaluation, the carrots of various colors were well-received and liked by consumers, especially when they were not blindfolded [28]. With this information, plant breeders should be encouraged to develop these carrots to provide sources of both vitamin A precursors and phytochemicals. Consuming these whole foods has an equal or greater reduction in disease risk than individual compounds [29].

As described in the multicolored carrot research, consuming fruits and vegetables that contain multiple bioactive compounds may have a more synergistic benefit than simply taking supplements or individual compounds. The consumption of these carrots could provide not only vitamin A but also other functional compounds that have disease-fighting properties and could enhance the well-being of humans.

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http://www.springer.com/978-1-62703-203-2

Carotenoids and Human Health
Tanumihardjo, S.A. (Ed.)
2013, XXIII, 331 p. 58 illus., 30 illus. in color.,
ISBN: 978-1-62703-203-2
A product of Humana Press