Sensory and Objective Quality Attributes of Beta-carotene and Lycopene-rich Tomato Fruit

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ABSTRACT. Consumer acceptance of fresh and processed tomato (*Lycopersicon esculentum* Mill.) products is influenced by product appearance, flavor, aroma, and textural properties. Color is a key component that influences a consumer's initial perception of quality. Beta-carotene and lycopene are the principal carotenoids in tomato fruit that impart color. Analytical and sensory analyses of fruit quality constituents were conducted to assess real and perceived differences in fruit quality between orange-pigmented, high-beta-carotene cherry tomato genotypes and conventional lycopene-rich, red-pigmented cherry tomato cultivars. Thirteen sensory attributes were evaluated by untrained consumers under red-masking light conditions where differences in fruit color could not be discerned and then under white light. Panelists preferred the appearance of the red-pigmented cultivars when viewed under white light, but scored many of the other fruit-quality attributes of red- and orange-pigmented genotypes similarly whether they could discern the color or not. Irrespective of light conditions, significant genotype effects were noted for fruit appearance, sweetness, acidity/sourness, bitterness, tomato-like flavor, unpleasant aftertaste, firmness in fingers, juiciness, skin toughness, chewiness, bursting energy, and overall eating quality. Attributes whose scores differed between white and red-masking lights were intensities of tomato aroma, tomato-like flavor, sweetness, bursting energy, juiciness, and overall eating quality. The results demonstrated a color bias favoring red-pigmented fruit and highlight the influence that color has on perception of tomato fruit quality, particularly on tomato-like flavor, juiciness, and overall eating quality. Interactions between fruit chemical constituents likely influenced perceptions of quality. High-beta-carotene genotypes contained higher levels of sugars and soluble solids and equal or higher titratable acidity than the red-pigmented cultivars. Total volatile levels did not differ among genotypes; however, several individual volatiles were significantly higher in high-beta-carotene genotypes.

Trends in consumption of fresh produce are influenced by consumer perceptions of quality and value. For tomato products, objective measurement of fruit chemical constituents, together with sensory evaluation of numerous organoleptic properties, have been developed to help identify and optimize levels of the attributes that best define appearance, taste, aroma, and texture, and contribute to overall fruit quality. Stevens (1979) determined that the fruit sugar and acid content, together with the sugar : acid ratio, were strong determinants of fruit flavor and consumer preference. Volatile compounds that contribute to tomato fruit aroma are also important to fruit flavor. The levels of these aroma compounds were later demonstrated to affect the perception of fruit sweetness and sourness (Baldwin et al., 1998). Efforts have been made to characterize and exploit genetic variation for tomato fruit quality attributes to improve fruit quality (Causse et al., 2001; Jones and Scott, 1984; Saliba-Colombani et al., 2001; Stevens et al., 1977).

Color is a key component that influences a consumer's initial perception of quality in fresh and processed tomato products. The color of ripe tomato fruit is due to the colored carotenoids. In red fruit, the ratio of lycopene to beta-carotene, and the concentration of these carotenoids, determine the hue and intensity of fruit color. Expression of a number of tomato flesh and skin color mutants results in fruit colors that range from green to pale yellow to orange to dark red (Stommel, 1992a).

It is generally assumed that color influences consumer perceptions of the quality, and often, the identity of foodstuffs. DuBose et al. (1980) reported correct identification of fruit-flavored solutions when "correctly" colored, but misidentification of samples with atypical coloration. In that study, as color intensity increased, overall acceptability also increased, although at a diminishing rate. In cherry-flavored sucrose solutions, increasing redness increased perceived sweetness (Johnson and Clydesdale, 1982) or did not affect sweetness but increased flavor intensity (Philipsen 1995). Several foods prepared with and without added color were judged to have stronger and better aroma and a stronger flavor when colored (Christensen, 1983). However, in a subsequent study, Christensen (1985) reported that added color levels in cheese and grape-flavored jelly did not alter perception of aroma or flavor strength. Orange drinks with added red coloring were

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perceived to be sweeter and have greater aroma, but also to have less natural orange flavor than less colored samples (King and Duineveld, 1998).

We have developed cherry tomato breeding lines that produce fruit with high levels of beta-carotene. Fruit are orange-pigmented, making this material a specialty product for use where additional variety, flavor, or retinoid activity is desired. High fruit beta-carotene content is due to expression of the *Beta* gene, which causes beta-carotene to accumulate at the expense of lycopene, and results in orange fruit pigmentation. Orange tomato fruit coloration may also result from expression of the recessive *tangerine* mutant. These orange-pigmented fruit contain little more beta-carotene than conventional red-fruited cultivars, but contain lycopene primarily in the orange-colored *cis*-form, as opposed to the red-colored *trans*-lycopene, which is predominant in red fruit. While beta-carotene is valued for its retinoid activity and lycopene for its antioxidant properties, *cis*-lycopene is of considerable interest to the health community since it is presumably more bioavailable than *trans*-lycopene (Boileau et al., 1999).

Little information is available in the literature describing the influence of tomato color on consumer preferences and their relationship to objective quality measurements. Yellow and orange tomatoes have long been reputed to be low acid, leading some people to prefer them and others to shun them. However, Wolf et al. (1979) tested a large number of home-garden tomato cultivars and reported that the yellow and orange tomatoes they tested were actually more acid than the red cultivars evaluated. In simple flavor preference tests, Tones and Quackenbush (1958) found statistically equal preference for fruit of an orange-pigmented high-beta-carotene cultivar in comparison to fruit of two conventional red-pigmented cultivars when fruit color was masked.

The objective of this study was to evaluate whether fruit color affects consumer perceptions of tomato fruit quality. We report the results of analytical evaluations of chemical constituents that contribute to tomato fruit quality in orange-pigmented, high-beta-carotene cherry tomato fruit and conventional red lycopene-rich cherry tomatoes and their relationship to sensory attributes measured by consumer panels.

Materials and Methods

PLANT MATERIAL. Four genotypes were chosen for sensory panel evaluations. These included two USDA high-beta-carotene breeding lines, 02L1058 and 02L1059, and two red-fruited commercial hybrids, 'Mountain Belle' and 'Castlette'. Breeding lines 02L1058 and 02L1059 are F_7 selections developed from an initial cross between the *L. esculentum* fresh-market cultivar Flora-Dade and *L. cheesmanii* f. *minor* (Hook. f.) C.H. Mull., accession LA317, with subsequent backcrosses to 'Flora-Dade', the processing cultivar Spectrum 579, and the North Carolina State Univ. cherry tomato breeding line NC1C. High beta-carotene content in fruit of 02L1058 and 02L1059 is derived from introgression of the dominant *Beta* gene from *L. cheesmanii* into tomato. The cultivar Mountain Belle is a red-fruited cherry tomato hybrid developed at North Carolina State Univ. from the cross of breeding lines NC1C and NC2C. 'Castlette' is a red-fruited hybrid and was a parental line in the development of NC1C and NC2C.

Plants were grown in the greenhouse using standard production practices. Six-week-old plants of each genotype were transplanted to field plots at the Beltsville Agricultural Research Center, Beltsville, Md., into Keyport fine loam soil, a clayey, mixed, mesic Acquis Hapludult. Field-grown plants were spaced

at 0.6-m intervals in single rows on polyethylene-covered raised beds, with beds positioned on 1.5-m centers with trickle irrigation. Pest control and fertilizer regimes followed standard horticultural practices for tomato production in Maryland (University of Maryland, 2000). Ripe fruit of each genotype were harvested daily for 5 d, rinsed with tap water, and evaluated by sensory panelists on the day of harvest.

SENSORY EVALUATION PANELS. Individuals selected for sensory evaluation panels were solicited by e-mail from the $\approx$ 1300 clerical, administrative, technical, and scientific staff of the Beltsville Agricultural Research Center (BARC). A total of 120 untrained volunteers who responded affirmatively to liking and frequently consuming tomatoes participated in the sensory evaluation panels; however, seven failed to correctly complete the ballots and were dropped. There were approximately equal numbers of men and women among the volunteers. Panelists' ages were fairly normally distributed from the early 20s to mid-60s (years).

Fruit evaluations were conducted in a specially designed taste panel facility at BARC with 10 evaluation stations. Each panelist station was outfitted with an overhead light source, a computer monitor with keyboard and mouse for recording sensory attributes, and a light-masked port for delivery of individual fruit samples to the panelist. Lighting conditions that masked color of red- and orange-pigmented tomato fruit were created by inserting two layers of dark red theatrical gels (medium red filter #27; Roscolux, Stamford, Conn.) in mini spotlights over each station. Prior to conducting formal sensory panels, several staff members who would not be participating in the panels independently verified that masked lighting conditions effectively masked the color difference between red and orange tomato fruit to the extent that fruit color could not be discerned.

Experimental design and ballots were prepared using Compusense five (Compusense, Guelph, Ontario, Canada). Sensory terms (Table 1) were developed by the authors and an experienced sensory panel at BARC. Utilizing the computer monitor, panelists scored acceptability or intensity of the sensory attributes listed in Table 1 by marking unstructured line scales digitized from zero to 100. Numerical scores were not visible to the panelists.

Prior to evaluating the four tomato genotypes of interest, panelists were supplied with an unrelated cherry tomato sample under red-masking lights in order to familiarize the panelists with

Table 1. Organoleptic attributes scored for respective tomato genotypes by sensory evaluation panel volunteers.

Attribute	Left label (score = 0)	Right label (score = 100)
Appearance (viewed under white light)	Unacceptable	Excellent
Firmness in fingers	Soft	Hard
Tomato-like aroma	Not at all	Very much
Skin toughness	Tender	Tough
Texture during chewing	Soft	Crunchy
Juiciness	None	Very much
Bursting energy	Limp	Explodes
Sweetness	Not sweet	Very sweet
Acidic or sour	Not acidic	Very acidic
(like vinegar or lemon juice)		
Tomato-like flavor	Not tomatoey	Very tomatoey
Bitter	Not bitter	Very bitter
(like caffeine or quinine)		
Unpleasant aftertaste	None	Very much
Overall eating quality	Bad	Excellent

working under red light, the format and use of the on-screen ballot, and the sensory terms. Subsequent to this preliminary sample, fruit of 02L1058, 02L1059, 'Mountain Belle', and 'Castlette' were presented to panelists under masked lighting conditions. A sample consisted of three tomatoes of one genotype in a 250-mL paper food tray (#50; Fonda Group, Owings Mills, Md.) coded with a three-digit code. The order of presentation of the four genotypes was completely randomized over the 120 panelists. Panelists were instructed to feel, smell, and taste each fruit of the three-fruit sample before marking their scores. Upon completion of evaluations of all four genotypes under masked lighting conditions, panelists took a short break (≈ 10 min), and then the same sample sequence for each panelist was repeated under white lighting. At the end of the ballot, panelists recorded their gender and age by decades. Panelists were asked to maintain confidentiality regarding the types of tomatoes evaluated and the use of special lighting so as not to bias panelists in subsequent sessions. Sensory evaluations were conducted at peak harvest time over 5 d in 12 sessions, with 10 panelists per session.

ANALYTICAL EVALUATIONS. Ten to 15 fruit of each genotype were randomly selected from fruit harvested for each of 12 sensory panel evaluations and bulked for measurement of fruit soluble solids content (SSC), sugars, titratable acidity (TA), and volatile levels. A total of 14 bulked samples were collected; 12 bulked samples from each sensory panel, plus two additional bulks collected from preliminary sensory panels. Ten separate sets of bulked fruit were similarly collected from 10 of the sensory panels for evaluation of fruit carotenoid content.

Each bulked fruit sample for analysis of SSC, sugars, TA, and volatiles was homogenized in a blender for 30 s and the homogenate filtered through two layers of cheesecloth. For volatile analyses, a 25-g aliquot of the filtered extract was transferred to a sealed conical centrifuge tube and 10 mL of a saturated calcium chloride solution was added and mixed. For the other analyses, a 37-g aliquot of the filtered extract was transferred to another centrifuge tube. Both samples were centrifuged at 4 °C to pellet insoluble matter. Flocculent matter was removed from each extract and samples aliquoted to vials for SSC, sugar, TA, and volatile analysis. All samples were stored at -20 °C prior to analysis, except samples for volatile analysis, which were stored at -80 °C.

Soluble solids. Soluble solids content of each bulked fruit sample was measured in non-calcium-containing fruit extracts using a digital, temperature-compensated refractometer (model PR-101; Atago Co., Tokyo).

Sugar content. Sugar content of fruit samples was analyzed as previously described (Stommel, 1992b), with minor modifications. Non-calcium-containing extracts were eluted through a C18 Sep-Pak cartridge (Waters Corp., Milford, Mass.) prior to filtering through a 0.45- μ m membrane filter. Samples were held at 4 °C and sugars assayed via HPLC using a carbohydrate analysis column (Waters Corp.) with an isocratic mobile phase of 75 acetonitrile : 25 distilled water at a flow rate of 1 mL $\cdot$ min⁻¹. Sugars were detected using a refractometer (model 410; Waters Corp.). Relative sweetness for each genotype was estimated using sweetness scores for individual sugars (fructose = 1.8, glucose = 0.7, sucrose = 1.0; Sikorski, 1997) in the equation: relative sweetness = 1.8(mg $\cdot$ g⁻¹ fresh weight fructose) + 0.7(mg $\cdot$ g⁻¹ fresh weight glucose) + 1.0(mg $\cdot$ g⁻¹ fresh weight sucrose).

Titratable acidity. Titratable acidity, expressed as citric acid, was determined by titrating 10-mL aliquots of non-calcium-containing fruit extracts with 1.0 M KOH to pH 8.2 (Mitcham and Kader, 1996).

Tomato volatiles. Two volatile analyses were performed; one for highly polar volatiles (i.e., C₁ to C₃ volatiles with boiling points <100 °C) and one for less polar volatiles. For the more polar volatiles, 5-mL aliquots of calcium supplemented fruit extracts were placed in gas tight 18-mL vials, equilibrated at 20 °C for 10 min at which time 10- μ L headspace samples were collected with a gas-tight syringe and injected at 250 °C into a glass-lined, splitless injection port of a gas chromatograph (GC) (model 6890; Agilent Technologies, Rockville, Md.) equipped with a flame ionization detector (FID), which was used to measure relative volatile vapor levels. For the less polar volatiles, a 1-mL aliquot of each calcium-supplemented fruit extract was placed in a gas-tight, 4-mL glass vial and equilibrated for 5 min at 20 °C. A solid-phase microextraction (SPME) (Supelco Co., Bellefonte, Pa.) fiber coated with polydimethylsiloxane (PDMS) (1 cm long, 100 μ m thick) was used to collect and concentrate volatiles as previously described (Saftner et al., 1999). The sorbed volatiles were desorbed from the fiber for 2 min at 250 °C into a glass-lined, splitless injection port of an Agilent Technologies 6890 GC equipped with a FID to measure relative volatile vapor levels.

Tomato volatiles were separated using capillary columns [HP-INNOWax (15 m $\times$ 0.25 mm id, 0.50 μ m coating thickness) for more polar volatiles and HP-5 (11 m $\times$ 0.1 mm id, 0.34 μ m coating thickness) for less polar volatiles (Hewlett Packard Co., Palo Alto, Calif.)]. The carrier gas was ultra-purified hydrogen (6.0 research) at a flow velocity of 41 and 56 cm $\cdot$ s⁻¹ for the HP-INNOWax and HP-5 columns, respectively. The temperature program was isothermal for 2 min at 40 °C and then increased at the rate of 30 °C/min to 250 °C and held for 3 min. Injector and detector port temperatures were both 250 °C. Constructing calibration curves for each volatile analyte in each tomato sample is not feasible, and thus total volatile abundance in each tomato sample measured by the two volatile assay procedures is reported in FID area response units of picoamps (pA) rather than absolute amounts of individual analytes. No corrections were made for differences in volatile recovery efficiencies between the two volatile assay procedures. Volatiles were identified using a GC-mass spectrometer procedure as previously described (Saftner et al., 1999).

Carotenoid content. Beta-carotene and lycopene content of bulked fruit samples was performed as described previously (Stommel and Haynes, 1994), with modifications. Fruit collected for carotenoid analysis were frozen at -80 °C and lyophilized immediately before extraction. Comparably sized representative fruit sections from each bulked fruit were combined and homogenized in chilled hexane for beta-carotene extraction and in dichloromethane for lycopene extraction. Homogenized samples were filtered through Whatman No. 2 filter paper (Whatman, Middlesex, U.K.), dried by passage through anhydrous granular sodium sulfate, diluted to 100 mL final volume with extraction solvent, and aliquots filtered through 0.45- μ m membrane filters. Carotenoids in filtered extracts were separated via HPLC using a reverse phase column (Vydac 201TP54 C-18; W.R. Grace and Co., Columbia, Md.) with an isocratic mobile phase of 82% (v/v) acetonitrile : 12% dichloromethane : 6% methanol containing 0.1% di-isopropyl ethylamine at a flow rate of 1 mL $\cdot$ min⁻¹. Beta-carotene and lycopene were detected at 450 and 470 nm, respectively, using a Waters 484 absorbance detector.

Fruit texture. Whole fruit firmness was determined using a texture analyzer (model TA.XT2i; Stable Microsystems, Godalming, Surrey, U.K.). Twenty fruit from each genotype were measured by parallel plate compression and by puncture. Fruit

were positioned with the stem axis horizontal. Measurements were taken on the equator at positions opposing underlying locules. Compression was measured with a 38-mm-diameter flat plate to a deformation of 2.0 mm at 1.0 mm·s⁻¹. Puncture was measured with a 2.0-mm-diameter cylindrical probe to a deformation of 10.0 mm at 1.0 mm·s⁻¹. Both measurements were made on different locules of the same fruit about 90° apart to minimize the effect of the 2-mm compression on the puncture test. Peak forces were analyzed using SAS (SAS Institute, Cary, N.C.).

DATA ANALYSIS. The sensory variables firmness, aroma, bursting energy, skin toughness, chewing texture, juiciness, sweetness, acidic or sour, overall flavor, bitterness, after taste, and overall eating quality were analyzed as three-factor general linear repeated measures models using Proc Mixed (SAS Institute, 1999) with gender, light, and genotype as factors. Appearance was analyzed as a two-factor model since it was rated only under white light. The variables were initially modeled with panel date as a block effect, but since it contributed very little to model variability, it was omitted from the analysis. Assumptions of the general linear model were checked for each variable. When effects were statistically significant, mean comparisons were done with Sidak adjusted *P* values so that the experiment-wise error was 0.05.

Fruit chemical composition data and peak forces for fruit firmness and puncture measurements were analyzed using Proc GLM (SAS Institute, 1999). Mean comparisons were evaluated using Tukey's Studentized range test (HSD) with *P* value of 0.05.

Results and Discussion

Sensory panel evaluations and chemical analyses of fruit quality constituents demonstrated clear differences in components that contribute to fruit appearance, flavor, and texture. Panelists exhibited distinct preferences when fruit color could be discerned under white light. However, distinctions between genotypes were less distinct under masked lighting conditions and panelists scored many of the quality attributes similarly whether they could discern the color or not.

APPEARANCE. Fruit of the red-pigmented cultivars, 'Mountain Belle' and 'Castlette', contained lycopene as the major colored carotenoid and relatively little beta-carotene (Table 2). Consistent with expression of the *Beta* gene, genotypes 02L1058 and 02L1059 contained a high percentage of beta-carotene (94.6% of total colored carotenoids) relative to lycopene. Sensory evaluation of orange-pigmented, high-beta-carotene, and red lycopene-rich genotypes clearly demonstrated that panelists preferred the appearance of the red-pigmented tomatoes when viewed under white light conditions (Table 2). Mean appearance scores of 'Mountain Belle' and 'Castlette' were 43.5% greater than mean scores of the two orange, high-beta-carotene genotypes.

Table 2. Fruit carotenoid content measurements and appearance scores recorded by sensory evaluation panels under white light conditions for beta-carotene and lycopene-rich cherry tomato genotypes.

Genotype	Beta-carotene	Lycopene ($\mu\text{g}\cdot\text{g}^{-1}$ fresh wt)	Appearance ^z
02L1058	46.5 a ^y	2.7 b ^y	55.3 b ^x
02L1059	41.8 a	2.3 b	58.0 b
'Mountain Belle'	3.2 b	31.1 a	82.6 a
'Castlette'	3.7 b	54.2 a	80.0 a

^a0 = unacceptable; 100 = excellent.

^yMean comparisons in columns by Tukey's HSD test at *P* ≤ 0.05.

^zMean comparisons in columns by Sidak's test at *P* ≤ 0.05.

FLAVOR/AROMA ATTRIBUTES. Panelists scored 'Mountain Belle' as the sweetest of the four genotypes under both light conditions, followed by 02L1058 and 02L1059 (Table 3). 'Castlette' was scored significantly less sweet than other genotypes evaluated. Since calculated relative sweetness scores of 02L1058 and 02L1059 were comparable to 'Mountain Belle' one might expect comparable sensory scores for sweetness among these genotypes. Overall, panelists scored sweetness 9.3% higher under white light than under red-masking light, conditions where differences in fruit color could not be discerned (Table 3). A significant genotype × light interaction was not evident (*P* = 0.246).

Genotypes 02L1058 and 02L1059 contained significantly greater levels of fructose than 'Mountain Belle' and 'Castlette' (Table 3). Because fructose has a higher sweetness score than glucose (1.8 vs. 0.7; Sikorski, 1997), this resulted in favorably lower glucose : fructose ratios for the high-beta-carotene genotypes. Levels of glucose and sucrose differed among genotypes evaluated, but not consistently by fruit color. SSC of high-beta-carotene genotypes was greater than either red-pigmented cultivar, 'Castlette' and 'Mountain Belle', likely due to the transfer of favorable genes for SSC from the wild donor parent *L. cheesmanii* (Garvey and Hewitt, 1984; Stommel, 2001).

Sugars as well as acids are important components of tomato fruit flavor and Malundo et al. (1995) found that the balance of sugars to acids in tomato fruit was more important for optimal flavor than were sugar or acid content alone. In one study (Baldwin et al., 1998), SSC was more closely related to tomato fruit sourness, astringency, and bitterness than to sweetness. TA and sensory panel scores for acidity/sourness, bitterness, and unpleasant aftertaste differed among genotypes, but not consistently by color, with 'Castlette' having the highest scores for all three sensory characteristics (Table 4). 'Mountain Belle' had the lowest TA and the lowest score for unpleasant aftertaste in addition to the highest sweetness score, likely influencing panelist perceptions of overall flavor and sweetness as noted above. 'Mountain Belle's high sugar : acid ratio relative to sensory ratings underscores the importance of interactions between multiple quality constituents on fruit flavor. White or red-masking lights did not significantly influence panelists' scores for acidity/sourness or bitterness (*P* = 0.407, *P* = 0.391, respectively).

Significant differences in tomato-like aroma scores among red- and orange-pigmented genotypes were not evident (*P* = 0.512). However, on average, tomato-like aroma was scored higher under white light than under red light (Table 5). The difference in scores is small, 39 vs. 34, but significant. We had expected that aroma scores would be lower when tomatoes were evaluated under white light, the second sub-session for each taster, due to sensory fatigue. The results suggest that panelists may have been more comfortable under white light and tomatoes seemed more "natural" or "more tomatoey" when fruit color could be discerned. Ample ventilation in sensory booths prevented build-up of tomato volatiles and there was no trend to increasing scores with sequential panel sessions on a given day.

Analytical evaluations demonstrated that total volatile content was not significantly different among high-beta-carotene and lycopene-rich genotypes even though hexanal, the predominant volatile in tomatoes, was higher in the lycopene-rich than in the high-beta-carotene genotypes (Table 5). Hexanal, which has a green, grassy aroma (Sigma-Aldrich, 2003), is considered to be important for tomato flavor (Petro-Turza, 1987) and is a major contributor to tomato odor (Buttery et al., 1987). Significantly higher levels of *trans*-2-heptenal [green aroma (Sigma-Aldrich,

Table 3. Fruit sugar composition, relative sweetness, soluble solids content, and overall sensory panel sweetness scores for the high-beta-carotene tomato genotypes 02L1058 and 02L1059 and the lycopene-rich tomato cultivars Mountain Belle and Castlette. The overall influence of light conditions on sensory panel sweetness scores is shown.

Genotype	Fructose	Glucose (mg·g ⁻¹ fresh wt)	Sucrose	Total sugars	Glucose: fructose ratio	Relative sweetness ^z	Soluble solids (%)	Sweetness score ^y
						(mg·g ⁻¹ sucrose equivalents)		
02L1058	19.07 a ^x	15.75 b ^x	0.13 b ^x	34.95 a ^x	0.83 c ^x	45.5 a ^x	7.7 a ^x	42.2 b ^w
02L1059	18.74 a	17.76 ab	0.07 b	36.56 a	0.96 bc	46.2 a	7.5 a	41.7 b
'Mountain Belle'	14.65 b	19.41 a	0.58 a	34.64 a	1.38 a	40.5 a	6.8 b	51.4 a
'Castlette'	10.57 c	10.96 c	0.10 b	21.63 b	1.04 b	26.8 b	5.7 c	30.5 c
Light								
Sensory attribute				White		Red		
Sweetness				43.3 A ^v		39.6 B		

^zRelative sweetness = 1.8(mg·g⁻¹ fresh wt fructose) + 0.7(mg·g⁻¹ fresh wt glucose) + 1.0(mg·g⁻¹ fresh wt sucrose).

^y0 = not sweet; 100 = very sweet.

^xMean comparisons in columns by Tukey's HSD test at $P \leq 0.05$.

^wMean comparisons in columns by Sidak's test at $P \leq 0.05$.

^vMean comparisons in rows by Sidak's test at $P \leq 0.05$.

Table 4. Titratable acidity measurements, sugar : acid ratios, and overall sensory panel scores of acidity/sourness, bitterness, and unpleasant aftertaste for fruit of high-beta-carotene tomato genotypes 02L1058 and 02L1059 and lycopene-rich tomato cultivars Mountain Belle and Castlette.

Genotype	Titratable acidity (% citric acid)	Sugar : acid ratio		Acidity/ sourness ^z	Bitterness ^y	Unpleasant aftertaste ^x
		(% total sugar/ % citric acid)				
02L1058	0.46 a ^w	7.6 c ^w		42.4 b ^v	29.0 b ^v	27.2 ab ^v
02L1059	0.41 b	8.9 b		35.2 c	26.3 bc	25.8 b
'Mountain Belle'	0.35 c	9.9 a		36.2 c	22.9 c	20.1 c
'Castlette'	0.44 ab	4.9 d		49.7 a	34.6 a	31.7 a

^z0 = not acidic; 100 = very acidic.

^y0 = not bitter; 100 = very bitter.

^x0 = none; 100 = very much.

^wMean comparisons in columns by Tukey's HSD test at $P \leq 0.05$.

^vMean comparisons in columns by Sidak's test at $P \leq 0.05$.

Table 5. Total volatiles and volatile constituents of high-beta-carotene tomato genotypes 02L1058 and 02L1059 and lycopene-rich tomato cultivars Mountain Belle and Castlette. The overall influence of light conditions on sensory panel scores for tomato-like aroma is shown.

Genotype	Total volatiles	Hexanal	Trans-2-heptenal		Geranylacetone
			(pA) ^z		
02L1058	306 a ^y	196 b	3.2 a		0.6 a
02L1059	291 a	184 b	2.2 a		0.6 a
'Mountain Belle'	403 a	306 a	1.1 b		0.4 b
'Castlette'	361 a	266 ab	1.2 b		0.4 b
Light					
Sensory attribute			White		Red
Tomato-like aroma ^x			39.1 A ^w		34.4 B

^zVolatile abundance reported in flame ionization detector area response units of picoamps (pA).

^yMean comparisons in columns by Tukey's HSD test at $P \leq 0.05$.

^x0 = not at all; 100 = very much.

^wMean comparisons in rows by Sidak's test at $P \leq 0.05$.

2003)] and geranylacetone [floral (Sigma-Aldrich, 2003) or fruity (Heath, 1978) aroma] (2.3 and 1.5-fold higher, respectively) were found in the high-beta-carotene genotypes 02L1058 and 02L1059 in comparison to the lycopene-rich cultivars Mountain Belle and Castlette. *Trans*-2-heptenal and geranylacetone are breakdown products of beta-carotene. There was no significant difference in content of the flavor volatiles *trans*-2-hexenal, *cis*-3-hexenal, acetaldehyde, beta-ionone, acetone, 6-methyl-5-hepten-2-one, 1-penten-3-one, ethyl acetate, ethyl hexanoate, methanol, ethanol, octanol, eugenol, or 2-isobutylthiazole among the four genotypes (data not shown). However, beta-ionone, a floral-odored breakdown product of lycopene, tended to be higher in the lycopene-rich than in the high-beta-carotene genotypes, though levels were consistently low in all samples. Baldwin et al. (1998) found that levels of aroma compounds affected panelist perceptions of sweetness and sourness. It is possible that the magnitude of the differences in volatile constituents noted between lycopene- and beta-carotene-rich fruit in our evaluations was insufficient for an average consumer to detect.

Significant genotype, light condition, and genotype $\times$ light condition effects were evident for the intensity of tomato-like flavor ($P < 0.0001$, $P = 0.0002$, and $P = 0.046$, respectively). Under white light, 'Mountain Belle' and 'Castlette' were not significantly different from one another for tomato-like flavor intensity (58.4 vs. 51.2) (Table 6). 'Mountain Belle' had tomato-like flavor intensity scores $\approx 20\%$ greater than either 02L1058 or 02L1059, while 02L1058 was comparable in tomato-like flavor intensity to 'Castlette'. Under masking light conditions, differences in tomato-like flavor intensity between red and orange-pigmented genotypes were less apparent, with scores of high-beta-carotene genotypes comparable to red-fruited cultivars, thus highlighting the importance of product color on perceptions of tomato-like flavor intensity. Consistent with this observation, panelists scored tomato-like flavor intensity an average of 16.8% higher under white light than under red-masking light for red-pigmented cultivars (58.4 vs. 50.2 and 51.2 vs. 43.6) and found no significant differences in tomato-like flavor intensity for orange-pigmented genotypes under these conditions.

TEXTURAL ATTRIBUTES. Significant light, genotype, and light $\times$ genotype effects were noted for fruit juiciness ($P < 0.0001$, $P < 0.0001$, and $P = 0.039$, respectively). Both red-pigmented cultivars had an average 25% higher mean juiciness score in comparison to orange-pigmented genotypes when evaluated under white light conditions (72.7 and 68.1 vs. 58.2 and 54.6) (Table 6).

Table 6. Sensory panel tomato-like flavor and fruit juiciness scores under white light and red-masking light conditions for high-beta-carotene tomato genotypes 02L1058 and 02L1059 and lycopene-rich tomato cultivars Mountain Belle and Castlette.

Genotype	Tomato-like flavor ^z		Fruit juiciness ^y	
	Light		Light	
	White	Red	White	Red
02L1058	47.6 bc ^x A ^w	46.0 ab A	58.2 b ^x A ^w	57.1 b A
02L1059	43.7 c A	41.6 b A	54.6 b A	51.7 b A
'Mountain Belle'	58.4 a A	50.2 a B	72.7 a A	66.6 a B
'Castlette'	51.2 ab A	43.6 ab B	68.1 a A	58.7 b B

^z0 = not tomatoey; 100 = very tomatoey.

^y0 = none; 100 = very much.

^xGenotype mean comparisons within light (i.e., in columns) with different a, b, c letters are significantly different by Sidak's test at $P \leq 0.05$.

^wLight mean comparisons within genotype (i.e., in rows) with different A, B letters are significantly different by Sidak's test at $P \leq 0.05$.

'Mountain Belle', but not 'Castlette', had a higher juiciness score in comparison to other genotypes when fruit color was masked, but differences were not as great as those observed under white light conditions. Similar to other sensory attributes scored under masked and nonmasked light conditions, there was a significant difference between fruit juiciness scores recorded under white light vs. red-masking light, particularly for 'Castlette' (68.1 vs. 58.7). Panelists scored fruit juiciness significantly higher under white light conditions (on average 12% higher) for the red-pigmented cultivars Mountain Belle and Castlette.

The orange-pigmented genotype 02L1058 was consistently firmer and tougher by all sensory measurements and the puncture test, followed by 02L1058, 'Castlette', and 'Mountain Belle'. The compression firmness followed the same pattern with the notable exception that 'Castlette' was the firmest, although not significantly different from the orange-pigmented genotypes. Note that 'Mountain Belle' had the lowest puncture force and the highest bursting energy, implying that the skin and outer pericarp ruptured fairly easily, deformed easily [lower maximum force required to compress a fixed distance (compression F_{max})] and farther before rupture (puncture deformation, data not shown), and released the contents of the fruit more "explosively" than the other lines. It is unclear why bursting energy scores were higher under white light than under red-masking light conditions, 56.3 vs. 51.5. Wolters and van Gemert (1990) found that firmness in the mouth was negatively related to consumer quality ratings, but that optimal tomato quality attributes combined the firmness of a beefsteak type fruit and the full flavored aroma of a cherry type. Selection of appropriate parents to make hybrid combinations with these high-beta-carotene breeding lines will be needed to diminish skin toughness in resulting cultivars. Significant genotype $\times$ light effects were not noted for fruit firmness, skin toughness, or chewing texture ($P = 0.225$, $P = 0.406$, and $P = 0.231$, respectively).

Overall eating quality of 02L1058, 02L1059, 'Mountain Belle', and 'Castlette' evaluated by sensory panels under white light and red-masking light conditions was the only sensory attribute with a significant gender effect ($P = 0.022$). Males generally scored overall eating quality approximately six points higher than women (12.5% of mean) (Table 8). Similar to a number of other quality attributes, overall eating quality scores were significantly higher (12.6%) under white light conditions where panelists could discern fruit color differences. Irrespective of light conditions, 'Mountain Belle' had significantly higher (27.7%) overall eating quality scores than either high-beta-carotene genotype or the red-pigmented cultivar Castlette. Eating quality of the high-beta-carotene genotypes 02L1058 and 02L1059 was comparable to 'Castlette', thus demonstrating the influence of multiple fruit attributes on overall eating quality.

In summary, significant genotype effects were noted for fruit appearance, firmness in the fingers, skin toughness, chewiness, bursting energy, acidity/sourness, bitterness, unpleasant aftertaste, sweetness, and overall eating quality. Attributes whose scores differed between white light and red-masking light conditions were intensities of tomato-like aroma, tomato-like flavor, sweetness, bursting energy, and juiciness, plus overall eating quality. However, the difference between scores for a number of these attributes was only about five points on a 100-point scale. 'Mountain Belle' had a number of attributes that contributed to its superior overall eating quality scores. 'Mountain Belle' was scored sweetest, low in acidity/sourness, bitterness, and unpleasant aftertaste, least firm and tough, but most "explosive" when bitten. Surprisingly,

Table 7. Fruit puncture and compression analysis and overall sensory panel scores of textural attributes of high-beta-carotene tomato genotypes 02L1058 and 02L1059 and lycopene-rich tomato cultivars Mountain Belle and Castlette. The overall influence of light conditions on sensory panel scores for fruit bursting energy is shown.

Genotype	Firmness in fingers ^z	Chewing texture ^y	Skin toughness ^x	Bursting energy ^w	Puncture (F _{max}) (N) ^v	Compression (F _{max}) (N) ^u
02L1058	71.8 ab [†]	52.1 ab [†]	63.5 a [†]	50.6 b [†]	6.3 ab ^s	5.0 a ^s
02L1059	73.4 a	55.1 a	66.3 a	50.6 b	6.4 a	5.5 a
'Mountain Belle'	59.9 c	43.6 c	50.9 b	59.1 a	5.6 b	4.1 b
'Castlette'	68.5 b	48.0 bc	56.0 b	55.2 ab	6.2 ab	5.5 a

Sensory attribute			Light	
			White	Red
Bursting energy			56.3 A ^r	51.5 B

^z0 = soft; 100 = hard.

^y0 = soft; 100 = crunchy.

^x0 = tender; 100 = tough.

^w0 = limp; 100 = explodes.

^vMaximum force in Newtons (N) required for fruit puncture measured with a 2.0-mm-diameter cylindrical probe.

^uMaximum force in Newtons (N) required for fruit deformation of 2.0 mm measured with a 38-mm-diameter flat plate.

[†]Mean comparisons in columns by Sidak's test at $P \leq 0.05$.

^sMean comparisons in columns by Tukey's HSD test at $P \leq 0.05$.

^rMean comparisons in rows by Sidak's test at $P \leq 0.05$.

Table 8. Influence of gender, light conditions and genotype on sensory panel scores of overall eating quality for high-beta-carotene tomato genotypes 02L1058 and 02L1059 and lycopene-rich tomato cultivars Mountain Belle and Castlette.

Overall eating quality ^z				Genotype	Overall eating quality
Gender		Light			
Female	Male	White	Red	02L1058	48.2 b ^y
46.7 B ^x	52.9 A	52.8 A	46.9 B	02L1059	45.3 b
				'Mountain Belle'	59.5 a
				'Castlette'	46.3 b

^z0 = bad; 100 = excellent.

^yMean comparisons in columns by Sidak's test at $P \leq 0.05$.

^xMean comparisons in rows by Sidak's test at $P \leq 0.05$.

SSC of 'Mountain Belle' was only intermediate; however, it had the lowest TA, making it seem sweeter. High-beta-carotene genotypes were scored firmer and crunchier and had tougher skin than named cultivars. The results clearly demonstrate that no single attribute is predictive of overall eating quality. Sweetness, sourness, appearance, color, aroma, and texture are all important components of eating quality.

Consumer preferences for fresh horticultural products are varied. Demand for a product is a function of the product price, alternatively priced products, consumer income, population, socioeconomic and demographic factors, and consumer tastes and preferences (Tomek and Robinson, 1972). Premium quality tomatoes and specialty tomato products do attract a loyal consumer following that is willing to pay a premium price for these products (Goldman, 1988). Surprisingly, in a 1993 study, Brumfield et al. found that consumer perceptions of product characteristics such as color, freshness, nutrition, and appearance did not significantly influence tomato purchase patterns, but that product price and income were more important determinants of purchase patterns. In contrast, today's supermarkets stock a variety of specialty tomato products with growing sales. These products include premium quality cluster tomatoes sold on the vine, vine-ripened

greenhouse-grown tomatoes, and specialty cherry and elongated cherry (grape) tomato cultivars, all of which command premium prices in the marketplace. In addition to product quality attributes, other product aspects influence consumer preference. Johansson et al. (1999) found that perceptions of product quality, plus information on whether tomatoes were produced using conventional or ecologically based production practices, influenced consumer preference. The availability and variety of tomato products currently found in the marketplace demonstrate the opportunities for added product variety.

The sensory panel studies, together with analytical evaluation of quality constituents, demonstrated the importance of panelist expectations of fruit color on perceptions of cherry tomato fruit appearance, flavor, aroma, textural attributes, and overall eating quality. Although panelists preferred red fruit when they could discern fruit color, sensory scores indicated that orange fruit were acceptable for the marketplace. Breeding for enhanced textural properties and optimal blends of flavor attributes in high-beta-carotene genotypes should further enhance consumer acceptance and niche market opportunities for premium priced, value-added products where color variation or enhanced retinoid activity is prized.

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