Scoparone and Scopoletin Accumulation and Ultraviolet-C Induced Resistance to Postharvest Decay in Oranges as Influenced by Harvest Date

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ABSTRACT. 'Washington Navel', 'Biondo Comune', 'Tarocco', and 'Valencia Late' orange [*Citrus sinensis* (L.) Obsek] fruit, harvested at various periods of time, were subjected to ultraviolet-C (UV-C) irradiation at 0.5, 1.5, or 3.0 kJ·m⁻² doses and then stored at 7 °C and 90% to 95% relative humidity (RH) for 4 weeks plus one additional week at 20 °C and ≈80% RH. Following UV-C treatment, there was varying amounts of rind browning and necrotic peel damage, depending on cultivar, treatment dose, and harvest date. 'Tarocco' fruit were damaged more easily by UV-C treatment than the other cultivars. 'Valencia L.' were the most resistant to UV-C irradiation, showing no adverse effects at the lowest dosage and having the lowest percentages of damaged fruit at higher dosages. 'Washington Navel' and 'Biondo Comune' oranges showed an intermediate susceptibility to UV-C treatment, with negligible differences between these cultivars. The percentage of damaged fruit after irradiation at the higher UV-C dosages decreased in most fruit samples as the season progressed. UV-C irradiation at 0.5 kJ·m⁻² effectively reduced decay development compared with nontreated fruit. Irradiation with 1.5 kJ·m⁻² was more effective compared with 0.5 kJ·m⁻² only in early harvested fruit. In 'Washington Navel' and 'Biondo Comune' oranges in the later harvests, treatment with 3.0 kJ·m⁻² improved decay control further, compared with 0.5 kJ·m⁻². Following UV-C treatments the phytoalexins, scoparone and scopoletin, accumulated in flavedo tissue depending on the cultivar, fruit age, and UV-C treatment. Both phytoalexins displayed a similar accumulation pattern, however, the levels of scopoletin were very low compared with scoparone. Concentrations of phytoalexins rose as the irradiation dose increased. No scoparone and scopoletin could be detected in nontreated fruit. The highest concentration of phytoalexins among cultivars was recorded in 'Valencia Late' oranges, the lowest in 'Tarocco', with similar intermediate accumulations in 'Washington Navel' and 'Biondo Comune'. In 'Washington Navel', 'Biondo Comune', and 'Tarocco' oranges, the rate of scoparone accumulation was significantly higher in fruit harvested earlier in the season while 'Valencia late' oranges exhibited an opposite trend.

Susceptibility of citrus fruit (*Citrus* L.) to postharvest decay is known to depend upon various pre- and postharvest factors such as climate, cultural practices, harvest date, pre- and postharvest treatments, species, and cultivars (Grierson and Ben-Yehoshua 1986). Blood (pigmented) oranges (*Citrus sinensis*) for example, are known to be much more susceptible to decay than nonpigmented oranges (Schirra et al., 1997) while 'Valencia Late' is one of the most resistant orange cultivars with a long storage life (Chalutz et al., 1981). Induced or preformed natural resistance to postharvest decay plays a major role in the preservation of fruit during development, ripening, and senescence (Ben-Yehoshua et al., 1988; Kim et al., 1991; Wilson et al., 1994). However, when fruit have accomplished their biological role, when the seed becomes mature, the fruit

become weaker and disease resistance usually declines especially during the postharvest period when the fruit is removed from the mother plant (Ben-Yehoshua et al., 1988, 1995; Brady, 1987). This declining fruit resistance was found to parallel fruit senescence. The processes involved are still unknown, but are likely to be very important in formulating approaches for protecting fruit from pathogen and/or insect invasion.

Various physical stresses, such as rind injury (Ismail et al., 1978), heat treatment (Afek and Sztejnberg, 1994; Ben-Yehoshua et al., 1989), gamma irradiation (Dubery, 1992), and ultraviolet-C (UV-C) irradiation (Kim et al., 1991; Rodov et al., 1992) have been shown to promote production in the flavedo tissue of newly formed compounds, such as scoparone (6,7-dimethoxycoumarin) and scopoletin (7-hydroxy 6-methoxycoumarin), which have been related to induced resistance to postharvest decay. Chalutz et al. (1992) demonstrated that the UV-C dose required for development of maximum resistance in grapefruit (*Citrus ×paradisi* Macfad.) increases as the season progressed. In this study, we investigated the response of orange fruit to UV-C irradiation, as it relates to accumulation of scoparone and scopoletin and induced resistance to decay in relation to cultivar, harvest date, and UV-C doses.

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Materials and Methods

FRUIT. The investigation was conducted on 'Washington Navel', 'Biondo Comune', 'Tarocco', and 'Valencia Late' oranges grown in an experimental grove (southwestern Sardinia, Italy, 39° 55' N) that received standard horticultural practices. 'Washington Navel', 'Biondo Comune', and 'Tarocco' oranges were harvested at bimonthly intervals, from November 1995, when the rind had not yet acquired the full color which is characteristic for each cultivar, to March when fruit were commercially mature. Harvesting of late maturing 'Valencia Late' oranges started 2 months later, in January, March, and May. All harvesting operations were carried out within the first week of each respective month. Each harvest involved a random sampling from 30 trees. Fifteen fruit from each tree were picked from the exterior of the canopy and delivered to the laboratory immediately. Fruit were washed with water and allowed to dry overnight. Fruit were then placed into boxes and removed for UV-C treatment before being returned to boxes for storage.

UV-C TREATMENTS AND STORAGE. UV-C treatment was performed in a small (60 × 120 × 70 cm) ventilated irradiation chamber with four lamps (G15T8 type; Tana Ind., Tel Aviv, Israel), each with a nominal power output of 3.6 W. The peak wavelength emitted by the each lamp was 254 nm. Oranges were placed individually 25 cm from the irradiation source and turned continuously during treatment to provide uniform treatment over the whole fruit surface (Stevens et al., 1998). Temperature inside the treatment chamber remained within 20 ± 2 °C. UV-C dosages were 0.5, 1.5, or 3.0 kJ·m⁻². The UV-C fluency was measured with a UVx radiometer (UV Products Inc., San Gabriel, Calif.) as described previously (D'hallewin et al., 1992). Nontreated fruit served as controls. All experiments were repeated four times (replications) by using 25 fruit per replication. After treatment, fruit were kept in the dark at 21 °C for ≈1 h before storage in a ventilated dark room maintained at 7 °C and 90% to 95% relative humidity (RH) for 4 weeks plus 1 additional week at 20 °C and ≈80% RH simulating a marketing period. Following UV-C treatment and during storage fruit were kept in the dark to minimize any possible photoreactivation processes (Stevens et al., 1998).

PEEL COLOR. Color measurements were taken 1 h following UV-C irradiation and after the simulated marketing period (SMP) on five fruit, individually numbered. Peel color was measured using a colorimeter (series 1500; Macbeth, Newburgh, N.Y.). The measurements were taken at four equally spaced sites around the fruit equator and an average score was calculated. CIELAB L* = lightness, a* = bluish-green/red purple hue component, b* = yellow/blue hue component, were measured. Chroma, C*, and the hue angle h° (0° = red-purple, 90° = yellow, 180° = blue green, 270° = blue) values were calculated according to the requirements described by McGuire (1992). That is, when a* > 0 and b* > 0, h° = arctangent (b*/a*), while when a* < 0 and b* < 0, h° = 180 + arctangent (b*/a*). The instrument's illuminant, calibration plate, and illuminant/viewing geometry were C, orange color (CR-A470 plate), and d/0, respectively (McGuire, 1992).

VISUAL ASSESSMENT. After SMP, fruit were examined and treatment damage was expressed as a percentage of the total number of fruit in the sample. Decay was monitored at the end of SMP and the total decay percentage was calculated.

INTERNAL QUALITY CHARACTERISTICS. Before storage and after SMP, three replications of five healthy fruit were randomly selected for internal quality attributes. The juice was extracted

from individual fruit with a small laboratory hand reamer (Type MPZ2 AG; Braun, Frankfurt, Germany) and juice content was expressed as percentage of fruit weight. Percentage of soluble solids concentration (SSC) was determined with a digital Abbe refractometer (model A1171; Reichert, Wien, Austria). Titratable acidity (TA) was determined by titrating an aliquot of juice to pH 8.2 with 0.1 mol·L⁻¹ NaOH and expressing the result as mol·L⁻¹ of anhydrous citric acid. Maturity index was evaluated as SSC to TA ratio (ratio increasing with maturity).

The experiment was repeated in 1996–97 and 1997–98 with the same experimental design. In addition, scoparone and scopoletin development in flavedo tissue was assessed in 1997–98.

PHYTOALEXIN DETERMINATIONS. Extraction of phytoalexins was performed 6 d after UV-C treatment, as described by Kim et al. (1991). Quantitative analysis was achieved by high-performance liquid chromatography (HPLC) using a pump (model 9012; Varian, Walnut Creek, Calif.) equipped with a manual injection system (10-μL loop) and a reversed-phase column Erbasil-S C₁₈, (Carlo Erba, Milan, Italy), 120 × 10 mm i.d., 0.5 μm particle size. The column was placed in an oven (L 7350; Merck, Darmstadt, Germany) at 50 °C. In all analyses, the mobile phase consisted of combinations of methanol and 0.05 mol·L⁻¹ ammonium acetate buffer (pH 4.25). Step-gradient elution was used: starting with a (v/v) 80 methanol : 20 buffer ratio, changing to 60:40 at 5 min, 40:60 at 10 min, and reaching 20:80 at the stopping time of 18 min. An additional 4-min postrun time was used to return to the 80:20 starting ratio. The flow rate at time 0 was 0.6 mL·min⁻¹ with a step increase of 0.1 mL·min⁻¹ after each 5 min. Quantitative measurement was performed with a fluorescence detector (model 9070; Varian) at elicitation wavelength (Exλ) 350 nm and emission wavelength (Emλ) 430 nm. Retention time for scopoletin and scoparone were 8.9 and 10.9 min, respectively, based on standards: scopoletin (model S-2500; Sigma Chemical Co., St. Louis, Mo.) and scoparone (model D-4912; Sigma). The amounts of the eluted compounds were determined by Varian Work Station software.

DATA ANALYSIS. Analysis of variance (ANOVA) was performed by MSTAT-C software (Michigan State Univ., East Lansing, 1988). Damage and decay percentages were transformed to arcsine values before statistical analysis. Mean separations were calculated by Tukey's Studentized range test at *P* ≤ 0.05 or 0.01 where appropriate.

Results

PEEL COLOR. UV-C irradiation at 0.5 and 1.5 kJ·m⁻² did not affect peel color, as evaluated by the lightness coefficient (L*), hue angle (h°), and chroma (C*), in all orange cultivars tested. The peel color of 'Valencia' oranges was not affected by the UV-C treatment even when the treatment dosage was 3.0 kJ·m⁻² (data not presented). However, the color of the other cultivars was affected by UV-C treatment at 3.0 kJ·m⁻² (Table 1), but only when fruit were picked in November. The UV-C irradiation accelerated development of yellow rather than orange color, compared with nontreated fruit.

TREATMENT DAMAGE. UV-C irradiation caused varying amounts of visible damage to the fruit, characterized as rind browning and tissue necrosis, depending on cultivar, treatment dose (Table 2), and harvest date. The highest percentages of damaged fruit were recorded in 'Tarocco' oranges which exhibited a very low tolerance to UV-C treatment, where damage was seen even at the

lowest irradiation dosage. Conversely, ‘Valencia Late’ oranges were the most resistant to UV-C treatment. In fact, no treatment damage occurred when UV-C dosage was 0.5 kJ·m⁻², while only 1.0% to 4.9% and 1.9% to 16.1% damaged fruit were detected

following UV-C treatments with 1.5 and 3.0 kJ·m⁻², respectively. ‘Washington Navel’ and ‘Biondo Comune’ oranges exhibited an intermediate susceptibility to UV-C treatment, differences between them being negligible. Harvest date also influenced treat-

Table 1. Effect of UV-C_{254nm} postharvest irradiation on peel color measurements of ‘Washington Navel’, ‘Biondo Comune’, ‘Tarocco’, and ‘Valencia Late’ oranges in relationship to harvest date.

Cultivar	Harvest date	UV-C dose (kJ·m ⁻²)	Lightness (L*)		Hue (h°)		Chroma (C*)	
			Harvest ^z	SMP ^y	Harvest	SMP	Harvest	SMP
Washington Navel	Nov.	0.0	49.8 A ^x	51.6 A	113.9 A	107.1 A	37.5 A	38.8 A
		3.0	53.0 B	62.6 A	111.8 A	96.6 B	41.2 B	67.9 A
	Jan.	0.0	63.5 A	64.1 A	68.9 A	69.0 A	73.1 A	74.6 A
		3.0	64.5 A	63.8 A	67.9 A	68.6 A	70.8 A	72.7 A
	Mar.	0.0	70.3 A	70.2 A	70.3 A	70.3 A	78.0 A	78.1 A
		3.0	70.1 A	70.0 A	70.3 A	70.3 A	77.5 A	77.3 A
Biondo Comune	Nov.	0.0	57.7 A	58.0 A	103.0 A	102.1 A	54.2 A	54.7 A
		3.0	56.3 B	64.9 A	103.1 A	94.9 B	53.5 B	63.7 A
	Jan.	0.0	64.6 A	65.0 A	73.7 A	73.2 A	69.2 A	70.1 A
		3.0	63.9 B	59.0 A	73.2 A	73.1 A	68.6 A	68.7 A
	Mar.	0.0	70.4 A	70.3 A	69.5 A	69.4 A	76.1 A	76.4 A
		3.0	71.2 A	71.0 A	69.3 A	69.4 A	76.1 A	76.1 A
Tarocco	Nov.	0.0	54.8 A	55.1 A	104.6 A	102.9 A	51.7 A	51.7 A
		3.0	56.5 B	63.2 A	102.3 A	97.4 B	53.4 B	64.1 A
	Jan.	0.0	62.9 A	63.4 A	67.0 A	66.6 A	59.0 A	60.2 A
		3.0	61.7 A	60.7 A	66.9 A	66.9 A	61.1 A	61.3 A
	Mar.	0.0	71.7 A	71.7 A	70.3 A	70.3 A	81.2 A	81.3 A
		3.0	71.8 A	71.7 A	69.2 A	69.1 A	82.9 A	82.8 A
Valencia Late	Feb.	0.0	58.1 A	58.1 A	93.8 A	93.8 A	50.6 A	50.1 A
		3.0	60.0 A	59.9 A	95.1 A	95.2 A	49.6 B	49.6 A
	Apr.	0.0	70.0 A	70.0 A	69.5 A	69.6 A	77.1 A	77.4 A
		3.0	69.5 A	69.4 A	73.1 A	72.4 A	78.9 A	79.1 A
	June	0.0	72.5 A	71.8 A	75.4 A	75.4 A	71.9 A	71.7 A
		3.0	71.7 A	71.6 A	75.1 A	75.2 A	72.3 A	72.2 A

^zOne hour following treatment.

^yAfter 4 weeks of storage at 7 °C plus one additional week of simulated marketing period (SMP) at 20 °C.

^xMean separation within rows for a color measurement by Tukey’s studentized range test, $P \leq 0.01$.

Table 2. Influence of UV-C_{254nm} postharvest irradiation on treatment damage and decay percentages in ‘Washington Navel’, ‘Biondo Comune’, ‘Tarocco’, and ‘Valencia Late’ oranges harvested at various maturity stages and stored 4 weeks at 7 °C plus 1 additional week at 20 °C.^z

Cultivar	Harvest date	UV-C _{254 nm} doses (kJ·m ⁻²)							
		0.5	1.5	3.0	0.0	0.5	1.5	3.0	
		Treatment damage (%)			Decay (%)				
Washington Navel	Nov.	3.1 C(B)	17.5 B(A)	44.2 A(A)	15.8 A(B)	7.9 B(B)	9.4 B(A)	9.9 B(A)	
	Jan.	5.0 A(A)	4.0 A(B)	5.8 A(B)	37.1 A(A)	10.0 B(AB)	5.1 C(B)	2.0 C(B)	
	Mar.	5.1 B(A)	5.1 B(B)	9.1 A(B)	28.1 A(A)	10.7 B(A)	7.9 BC(A)	2.9 C(B)	
Biondo Comune	Nov.	5.0 C(B)	24.9 B(A)	62.8 A(A)	18.0 A(C)	11.8 B(A)	11.1 B(A)	12.9 B(A)	
	Jan.	8.1 B(A)	7.9 B(B)	10.3 A(B)	24.8 A(B)	8.8 B(B)	7.1 B(B)	1.1 C(C)	
	Mar.	9.2 B(A)	3.8 C(C)	13.0 A(B)	31.1 A(A)	12.9 B(A)	9.9 B(AB)	5.0 C(B)	
Tarocco	Nov.	30.2 C(C)	51.9 B(B)	77.8 A(A)	50.9 A(B)	20.3 B(A)	7.3 C(C)	18.1 B(A)	
	Jan.	44.8 B(A)	67.8 A(A)	75.0 A(A)	53.6 A(AB)	18.8 B(A)	12.3 C(B)	20.8 B(A)	
	Mar.	37.7 B(B)	42.0 B(C)	56.2 A(B)	62.0 A(A)	20.1 B(A)	19.1 B(A)	18.8 B(A)	
Valencia Late	Feb.	0.0 C(A)	4.9 B(A)	16.1 A(A)	7.9 A(A)	1.8 B(B)	4.9 A(A)	2.0 B(A)	
	Apr.	0.0 C(A)	2.2 B(B)	4.2 A(B)	6.9 A(A)	5.2 A(A)	2.0 B(A)	1.8 B(A)	
	June	0.0 B(A)	1.0 A(B)	1.9 A(B)	10.2 A(A)	1.0 B(B)	2.0 B(A)	1.9 B(A)	

^zIn each row or column grouping, mean separation by Tukey’s studentized range test, $P \leq 0.01$. Upper case letters without parentheses relate to comparisons of the effects of treatments, within each harvest date. Uppercase case letters in parentheses relate to comparisons of the influence of different harvest dates, within each cultivar, and treatment dose.

Table 3. Quality attributes of 'Washington Navel', 'Biondo Comune', 'Tarocco', and 'Valencia Late' oranges harvested at various picking dates and stored 4 weeks at 7 °C plus one additional week of simulated marketing period (SMP) at 20 °C.

Cultivar	Harvest date	Juice (%)		SSC (%)		TA (mol·L ⁻¹)		SSC:TA	
		Harvest ^z	SMP ^y	Harvest	SMP	Harvest	SMP	Harvest	SMP
Washington Navel	Nov.	44.0 C ^x	41.6 C	9.9 C	10.1 C	0.07 A	0.07 A	141 B	145 C
	Jan.	51.5 A	50.3 A	12.0 A	11.3 B	0.05 B	0.04 A	240 A	283 B
	Mar.	49.6 B	48.7 B	11.0 B	11.8 A	0.04 B	0.04 A	275 A	295 A
Biondo Comune	Nov.	41.1 B	40.8 B	8.0 C	8.4 C	0.06 A	0.05 A	133 C	168 C
	Jan.	44.9 A	43.8 A	10.5 B	11.2 B	0.05 AB	0.04 B	210 B	280 B
	Mar.	46.3 A	43.4 A	12.1 A	12.2 A	0.04 B	0.04 B	302 A	305 A
Tarocco	Nov.	39.0 C	38.9 C	9.6 C	10.8 C	0.10 A	0.10 A	96 C	108 C
	Jan.	46.5 B	48.7 B	12.3 B	12.0 B	0.08 B	0.06 B	154 B	200 B
	Mar.	51.6 A	52.3 A	12.8 A	12.9 A	0.05 C	0.05 C	256 A	258 A
Valencia Late	Feb.	37.3 C	36.6 C	9.2 C	9.5 C	0.07 A	0.07 A	131 C	136 C
	Apr.	46.2 B	47.2 B	10.1 B	10.1 B	0.06 AB	0.05 B	168 B	202 B
	June	51.0 A	51.9 A	11.7 A	11.6 A	0.05 B	0.05 B	234 A	232 A

^zOne hour following treatment.

^yAfter 4 weeks of storage at 7 °C plus 1 additional week of simulated marketing period (SMP) at 20 °C.

^xMean separation within columns for each cultivar by Tukey's studentized range test. $P \leq 0.01$, $n = 36$.

ment damage. The percentage of damaged fruit after irradiation at 1.5 or 3.0 kJ·m⁻² was maximum in oranges harvested early in the season, when fruit was at the color breaking stage, then decreased significantly, based on most color criteria, as the season progressed.

ROTS. Decay development was affected by cultivar and picking date (Table 2). 'Tarocco' was found to be highly susceptible to decay while 'Valencia Late' was the most resistant. 'Washington Navel', and 'Biondo Comune' had a similar intermediate resistance. Decay percentage in nontreated fruit increased as the season progressed. UV-C irradiation at 0.5 kJ·m⁻² reduced decay development remarkably in comparison with nontreated fruit in all samples. Treatment at 1.5 kJ·m⁻² gave significant benefits with respect to 0.5 kJ·m⁻² only in early harvested fruit. In 'Washington Navel' and 'Biondo Comune' oranges harvested in January and March, irradiation with 3.0 kJ·m⁻² improved decay control further, as compared with the lower dosage.

INTERNAL QUALITY CHARACTERISTICS. There were no differences in internal fruit quality attributes between UV-C treated and

nontreated fruit at any harvest time, therefore, all data are reported as means of treated and nontreated fruit (Table 3). Juice and SSC percentages increased in all cultivars as the season progressed while TA decreased. The opposite trends of SSC and TA resulted in a remarkable increase in SSC to TA ratio.

SCOPARONE AND SCOPOLETIN ACCUMULATION. Fruit response to increasing UV-C treatment (Table 4) in terms of scoparone accumulation in the flavedo tissue was cultivar dependent. The greatest increases of scoparone were recorded in 'Valencia Late' oranges, the smallest in 'Tarocco', with similar intermediate increases in 'Washington Navel' and 'Biondo Comune' oranges. Irradiation with UV-C induced a substantial rise in the levels of both scoparone and scopoletin, up to levels reported to be effective in inhibiting decay development (Ben-Yehoshua et al., 1992; Kim et al., 1991). Scoparone accumulation increased as the irradiation dose increased. Levels of scoparone in 'Washington Navel', 'Biondo Comune', and 'Valencia Late' oranges irradiated with 3.0 kJ·m⁻² UV-C light were ≈2- to 3-fold higher than those of fruit treated with 0.5 kJ·m⁻². Response to UV-C stimuli

Table 4. Quantity of scoparone and scopoletin in flavedo tissue 6 d postirradiation in 'Washington Navel', 'Biondo Comune', 'Tarocco', and 'Valencia Late' oranges in relation to harvest date.

Cultivar	Harvest date	UV-C _{254 nm} doses (kJ·m ⁻²)					
		0.5	1.5	3.0	0.5	1.5	3.0
		Scoparone ^z (μg·g ⁻¹ fresh wt)			Scopoletin ^z (μg·g ⁻¹ fresh wt)		
Washington Navel	Nov.	55.1 b(a)	60.5 b(a)	100.7 a(a)	7.8 b(a)	12.0 a(ba)	16.0 a(a)
	Jan.	45.0 b(a)	48.3 b(c)	93.3 a(b)	9.0 b(a)	6.8 b(b)	13.1 a(a)
	Mar.	44.2 c(a)	57.2 b(b)	90.5 a(b)	3.8 b(b)	10.5 a(ba)	13.5 a(a)
Biondo Comune	Nov.	47.5 c(a)	57.1 b(a)	80.8 a(a)	6.1 a(a)	9.7 a(a)	10.1 a(a)
	Jan.	30.1 c(b)	45.2 b(b)	70.6 a(b)	8.2 a(a)	8.8 a(a)	10.1 a(a)
	Mar.	29.5 c(b)	41.6 b(b)	70.5 a(b)	2.8 b(c)	7.4 b(a)	8.4 a(c)
Tarocco	Nov.	20.2 c(a)	32.8 b(a)	60.4 a(a)	5.4 a(a)	6.2 a(a)	12.8 a(a)
	Jan.	1.1 b(b)	1.9 a(b)	2.4 a(b)	0.8 b(b)	1.7 a(c)	2.6 a(b)
	Mar.	2.5 a(b)	3.2 a(b)	1.9 b(b)	0.6 b(b)	3.0 a(b)	2.0 b(b)
Valencia Late	Feb.	50.5 c(b)	61.9 b(c)	102.3 a(c)	13.7 b(a)	18.5 b(b)	25.7 a(b)
	Apr.	70.2 c(a)	190.2 b(a)	236.5 a(a)	18.7 c(a)	65.5 b(a)	74.8 a(a)
	June	70.2 c(a)	135.1 b(b)	195.3 a(b)	13.8 b(a)	19.7 a(b)	25.9 a(b)

^zIn each row or column grouping, mean separation by Tukey's studentized range test, $P \leq 0.05$. Lower case letters without parentheses relate to comparisons of the effects of UV-C doses, within each harvest date. Lower case letters in parentheses relate to comparisons of the influence of different harvest dates, within each cultivar, and treatment dose.

was also affected by fruit age. In 'Washington Navel', 'Biondo Comune', and 'Tarocco' oranges, the rate of scoparone accumulation was significantly higher in fruit harvested earlier in the season, while 'Valencia Late' oranges showed an opposite trend. The concentration of scopoletin was very low in comparison with scoparone. Differences in scopoletin occurrence in relationship to cultivar, UV-C doses, and picking date displayed a pattern similar to scoparone. Levels of scoparone and scopoletin in nontreated fruit were negligible in all measurements.

Discussion

UV-C irradiation of 'Washington Navel', 'Biondo Comune', 'Tarocco', and 'Valencia Late' oranges resulted in the following conspicuous effects: a) increased visible damage to all cultivars, with the exception of 'Valencia Late' oranges which had, in this 3-year study, no damage after treatment with 0.5 kJ·m⁻²; b) reduced decay in all cultivars, most clearly in 'Valencia Late' oranges; and c) elicitation of the phytoalexins, scoparone and scopoletin, in all cultivars, especially 'Valencia Late'. The treatments led to no adverse effects on SSC, maturity index, and juice content. UV-C irradiation at 3.0 kJ·m⁻² affected color development to all cultivars harvested in November compared to nontreated fruit, with the exception of 'Valencia Late' oranges. Previous studies on peaches [*Prunus persica* L. Batsch (Peach Group)] (Lu et al., 1993) described the effects of UV irradiation at a dosage of 7.5×10^4 erg·mm⁻².

This study provides, for the first time, an indication of the potential of UV-C irradiation as a possible nonchemical postharvest treatment of citrus fruit. The major benefit may be decay control by induction of the endogenous resistance mechanisms of oranges as demonstrated previously (Ben-Yehoshua et al., 1992; Droby et al., 1993; Kim et al., 1991; Rodov et al., 1992).

The seasonally varying susceptibility of citrus fruit to abiotic stresses such as low or high temperatures is well documented, but the physiological basis of this relationship needs to be elucidated. McGuire and Reeder (1992) have shown that early and late-season 'Marsh' grapefruit are more easily damaged by hot air treatment (46, 48, and 50 °C for 3, 5 or 7 min) than midseason fruit. Postharvest dipping of 'Tarocco' oranges in water at 53 °C does not cause adverse effects with fruit harvested when commercially mature (Schirra et al., 1997), while treatment causes burns and darkening of flavedo tissue when treated oranges are harvested earlier or later in the season. Similarly, postharvest conditioning (37 °C for 30 h) or 3 min dipping in water at 50 °C causes visible damages to the peel of 'Olinda' and 'Campbell' oranges harvested at color breakage (Schirra and D'hallewin, unpublished data), whereas when fruit are harvested during the midseason no treatment damage occurs. Thus far, it appears that early and late-season grapefruit are much more sensitive to low temperature than midseason fruit (Schirra et al., 1998), while desert lemons [*Citrus limon* (L.) Burm.] (Houck et al., 1990) and blood oranges (Schirra et al., 1997; Schirra and D'hallewin, unpublished data) are more susceptible when they are harvested early in the season.

Unlike previous reports (Droby et al., 1993; Stevens et al., 1991) that discussed decay control by UV-C treatment without describing its phytotoxic effects, this work reports the potentially detrimental effects to the peel quality caused by UV-C irradiation with all orange cultivars tested. Adverse effects of UV-C treatment on oranges were reported previously by Rodov et al. (1992) and D'hallewin et al. (1993). In this study, 'Valencia Late' oranges appeared to be relatively resistant to UV-C damage as

premature fruit showed minimal damage even at the higher doses of irradiation used in this study.

The close relationship between reduction of decay and induction of the phytoalexins, scoparone and scopoletin, up to the levels reported to be capable of controlling pathogens (Kim et al., 1991) is interesting. Earlier investigations have shown that inoculation of fruit with pathogens or treatment with the antagonist yeast was able to induce phytoalexin production and improve decay control in citrus fruit (Rodov et al., 1994). Thus UV-C irradiation may represent another abiotic elicitor of the production of these two phytoalexins. It is relevant to point out that UV-C irradiation was more effective in inducing higher levels of the phytoalexins in 'Valencia Late' oranges harvested late rather than early in the season. This may be of particular importance because citrus fruit at the end of season have usually lost much of their resistance (Ben-Yehoshua et al., 1995). 'Tarocco' oranges, unlike 'Valencia Late', showed less induction of phytoalexins at the end of the season than at the beginning. However, total induction of phytoalexins in this cultivar was small at all harvests and decay susceptibility was high.

Elicitation of phytoalexins and reduction of decay were also found in UV-C-treated kumquat fruit [*Fortunella margarita* (Lour.) Swingle] (D'hallewin et al., 1992; Rodov et al., 1992). Considering that fresh kumquats are consumed along with the peel and no fungicide treatments are permitted for this fruit, there is a need for further studies on a large scale which may confirm the effectiveness of new postharvest treatments such as UV-C irradiation in decay control of citrus fruit. Positive results on the outcome of UV-C treatment, which is environmentally friendly, may replace more conventional fungicide treatments.

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