Short-term Heat Conditioning of Grapefruit to Alleviate Irradiation Injury

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Abstract. 'Marsh' white grapefruit (*Citrus paradisi* Macf.) harvested from exterior canopy positions were less tolerant of 0.5 or 1.0 kGy irradiation than were interior fruit. Irradiation at 0.0, 0.5, or 1.0 kGy resulted in 0.0%, 24.3%, and 37.5% surface pitting of fruit, respectively. Pitting was reduced 30% by temperature conditioning with vapor heat at 38 or 42 °C for 2 hours. Exterior canopy fruit had ≈2-fold more pitting, had greater weight loss, and were firmer than interior canopy fruit. Fruit weight loss increased and firmness decreased as conditioning temperature and irradiation dose increased. Total soluble solids, titratable acidity, and flavor decreased with increasing irradiation dose. The peel of exterior canopy grapefruit was damaged more by irradiation than was that of interior fruit, but irradiation damage was reduced by temperature conditioning.

Irradiation of ≤1.0 kGy is approved by the U.S. Food and Drug Administration for use on fresh fruits and vegetables for quarantine control purposes (Dept. of Health and Human Resources, 1986). Irradiation, an alternative to methyl bromide fumigation for fruit flies, is expected to be approved by the Animal and Plant Health Inspection Service (APHIS) of the U.S. Dept. of Agriculture (USDA) in the near future. A minimum absorbed dose of 0.15 kGy is required to sterilize the Caribbean fruit fly (CFF) (USDA, 1996). Grapefruit exported from Florida to certain foreign and domestic markets must be certified free of the CFF prior to shipment. Currently, most grapefruit designated for markets requiring security against the CFF are grown in certified fly-free zones under the Standard Season Caribbean Fruit Fly Protocol. However, future outbreaks of pest infestation could render current fly-free zones noncertifiable and make the use of alternative quarantine treatments necessary. Cold treatment is an approved quarantine method for grapefruit against the CFF. However, conditioning of fruit for 7 d at 15 °C is required to reduce or eliminate chilling injury to the peel during subsequent low-temperature storage (Hatton and Cubbedge, 1982). Both condi-

tioning temperatures and cold treatment reduce product quality (Ismail et al., 1986).

Grapefruit have a relatively low tolerance to irradiation. Slight peel injury may develop at absorbed dosages of 0.3 kGy (Hatton et al., 1984; Miller and McDonald, 1996), but the tolerance of grapefruit to irradiation varies with harvest season and maturity of peel tissue at harvest (Hatton and Cubbedge, 1982). Irradiation of grapefruit in boxes stacked in pallet units necessarily exposes some fruit in the outermost boxes to higher doses than the minimum required target dose (0.15 kGy) for fruit located in the innermost boxes. The minimum : maximum dose ratio will probably be about 1:2 for pallet units of grapefruit, based on previous dosimetry observations by the authors (unpublished data). Hence, some fruit will probably be exposed to at least 0.3 kGy, a dose that will cause injury to some fruit (Hatton et al., 1984) in commercial applications. Decreasing the sensitivity of grapefruit to low dosage irradiation would provide a margin of safety against peel damage.

Low- and high-temperature conditioning treatments have reduced damage to chilling-sensitive fruits and vegetables during exposure to low temperatures. For example, lowering temperatures to slightly above the chilling temperature for various periods of time reduced chilling injury in several horticultural crops, including grapefruit (Hatton, 1990). Raising temperatures for various periods of time has also reduced chilling injury (Klein and Lurie, 1991; Paull, 1990). Treating grapefruit with thiabendazole [2-(4-thiazolyl) benzimidazole; TBZ] prior to cold treatment reduced peel injury during low-temperature storage (Schifmann-Nadel et al., 1975). In addition, the location of a grapefruit within the tree canopy (exterior or interior) can affect its sensitivity to low-temperature injury (McDonald et al., 1993; Purvis, 1980).

The success of large-scale commercial ap-

plications of irradiation to grapefruit as a quarantine treatment will require the development of methods to reduce the potential of irradiation damage. The purpose of this study was to determine if grapefruit canopy position affects the sensitivity of fruit to irradiation and if exposure to short-term, high-temperature conditioning reduces irradiation damage

Materials and Methods

'Marsh' white grapefruit, having a mean diameter of 8.9 cm (commercial size of 40 count/28-L box), were harvested from a commercial grove in St. Lucie County, Fla., on 3, 10, and 17 Mar. 1997. Fruit were picked from ≈50 trees within a production block. On each picking date, 500 fruit were harvested from the exterior (sun exposed) area and 500 from the interior (shaded) area of the tree canopy. The fruit were taken to the U.S. Horticultural Research Laboratory, Orlando, Fla., and 33 fruit from each area of the tree canopy were randomized into six plastic bins containing 66 fruit each. Six fruit in each bin were used for monitoring temperature during treatment and then were discarded. Two plastic bins containing 66 fruit each from the external or interior tree canopy were placed at ambient temperature (20 °C) or conditioned at 38 or 42 °C by vapor heat (free moisture on fruit surface during heat treatment) for 2 h with an airflow of 0.4 m³·s⁻¹. After cooling to ambient conditions for 8 h, fruit were washed on a commercial-type brush bed with soap (Sooty Mold Cleaner; EcoScience, Orlando, Fla.) and water, and waxed (590 HG citrus wax; FMC Corp., Lakeland, Fla.). Following washing and waxing, 10 fruit from each treatment combination (two canopy locations by three temperature treatments) were placed in each of six, 14.1-L (2/5 bu.) commercial citrus boxes. Two boxes of fruit of each treatment combination were then treated at 0, 0.5, or 1.0 kGy using ⁶⁰Co as a radiation source (FTS, Mulberry, Fla.) at a dose rate of 120 Gy·min⁻¹. There were two boxes (subsamples) for each combination of canopy position (interior/exterior), temperature (20, 38, or 42 °C), and irradiation dose (0, 0.5 or 1.0 kGy), for a total of 36 boxes per harvest (replication). Dosages higher than 0.3 kGy were used to test the efficacy of treatments to ameliorate injury.

Following irradiation, all fruit were stored at 10 °C and 90% ± 5% relative humidity for 4 weeks plus 1 additional week at 20 °C. All fruit were rated for postharvest stem-end-rind-breakdown (SERB) (USDA, 1971), peel pitting, and decay, or were rated as sound. Ratings for SERB were based on severity of tissue damage at the calyx end: 1 = no SERB, 2 = slight, 3 = moderate, and 4 = severe, corresponding to necrotic tissue extending 0, <5, 5 to <10, or ≥10 mm from the stem, respectively. Pitting and scald were rated on the extent of aggregate surface area affected: 1 = 0%, 2 = <10% (slight), 3 = 10% to 25% (moderate), and 4 = >25% (severe). Decayed fruit were removed from the box when observed at each inspection and incidence of decay calculated. In addition, a subjective rating was applied on

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Table 1. Condition and quality attributes of grapefruit harvested from interior or exterior canopy, heat-treated at 20, 38, or 42 °C and irradiated at 0, 0.5, or 1.0 kGy, and subsequently stored for 28 d at 10 °C plus 7 d at 20 °C.

Treatment	Sound ^z fruit (%)	SERB ^y (%)	Pitting (%)	Decay (%)	Appear value ^x	Weight loss (%)	Firmness (N)
Canopy position							
Interior (I)	82.2 ^w	1.9	14.6	1.3	2.2	4.3	21.4
Exterior (E)	66.5	6.0	26.6	0.9	2.5	4.7	26.6
Temp (°C)							
20	66.7	6.1	25.8	1.4	2.3	4.2	24.9
38	75.6	4.2	19.1	1.1	2.2	4.6	23.5
42	80.8	1.7	16.7	0.8	2.5	4.7	23.7
Dose (kGy)							
0.0	96.4	1.4	0.0	2.2	2.1	4.1	24.5
0.5	70.6	4.4	24.3	1.1	2.3	4.5	24.9
1.0	56.1	6.4	37.5	0.0	2.5	4.9	22.7
Interactions							
Canopy × Temp							
I 20	73.3	2.2	21.7	2.8	2.1	4.1	23.6
I 38	83.9	2.8	13.3	0.0	2.1	4.5	20.7
I 42	89.4	0.6	8.8	1.1	2.3	4.4	20.1
E 20	60.0	10.0	30.0	0.0	2.5	4.3	26.3
E 38	67.2	5.3	25.3	2.2	2.3	4.7	26.3
E 42	72.2	2.8	24.4	0.6	2.6	5.0	27.3
Canopy × Dose							
I 0.0	96.7	3.3	0.0	3.3	2.1	4.0	22.7
I 0.5	80.6	1.1	17.8	0.6	2.2	4.3	22.0
I 1.0	69.4	4.4	26.1	0.0	2.2	4.7	19.6
E 0.0	96.1	2.8	0.0	1.1	2.3	4.2	26.3
E 0.5	60.6	6.5	31.2	1.7	2.4	4.8	27.7
E 1.0	42.8	8.3	48.9	0.0	2.7	4.2	25.9
Temp × Dose							
20 0.0	93.3	3.3	0.0	3.3	2.1	3.6	25.4
20 0.5	64.2	7.5	27.5	0.8	2.3	4.5	25.4
20 1.0	42.5	7.5	50.0	0.0	2.5	4.6	24.0
38 0.0	98.3	0.9	0.0	0.8	2.2	4.3	23.6
38 0.5	70.0	4.8	22.7	2.5	2.5	4.8	24.6
38 1.0	58.3	6.7	35.0	0.0	2.3	4.8	22.3
42 0.0	97.5	0.0	0.0	2.5	2.3	4.4	24.5
42 0.5	77.5	0.0	22.5	0.0	2.5	4.4	24.6
42 1.0	67.5	5.0	27.5	0.0	2.6	5.3	22.0
Significance of main factors and interaction							
Canopy position	*	*	*	NS	*	*	*
Temp	*	*	*	NS	*	*	*
Dose	*	*	*	NS	*	*	*
Canopy × temp	NS	*	NS	*	NS	NS	*
Canopy × dose	*	NS	*	NS	*	NS	*
Temp × dose	NS	NS	*	NS	*	NS	*

^zSound fruit = 100 - (% SERB, pitting and decay).

^ySERB = stem-end-rind-breakdown.

^xAppearance value of 1 = fresh, 2 = fairly fresh, 3 = not fresh.

^wMean of 20 fruit/replicate; three replicates.

^{ns} Nonsignificant or significant by ANOVA at $P \leq 0.05$, respectively.

a box basis for overall fruit appearance. The appearance rating for freshness was: 1 (good), 2 (fair), or 3 (poor), as determined by peel color intensity, peel surface glossiness, and the absence of peel discolorations. Weight loss was determined on each fruit based upon initial fresh weight and weight at each inspection.

Fruit firmness (resistance to compression) expressed as Newtons (N) was determined with an Instron Food Testing System (model 4211; Instron Corp., Canton, Mass.) equipped with a 4.1-cm flat anvil, which compressed the fruit surface 5 mm at a cross-head speed of 5 cm·min⁻¹. Fruit peel color was determined on three pre-marked areas equally spaced around the midsection of each fruit using a Chroma Meter (model 200; Minolta Camera Co., Osaka, Japan) with an 8-mm aperture. The Chroma Meter was calibrated with a white plate in the CIE (1976) 'L*', 'a*', 'b*' color system.

Chroma* (C*) and hue angle (h°) values were calculated (McGuire, 1992). After firmness and color were measured on seven fruit per box, total soluble solids (TSS), titratable acidity (TA), and pH were determined by standard methods. For juice flavor, 14 fruit halves (seven of stem-end and seven blossom end) per treatment of interior canopy fruit only were reamed with a Sunkist juicer and the juice was strained and presented to panelists in 30-mL paper cups. Untrained but experienced panelists scored flavor preference using a modified hedonic scale that ranged from 1 (extremely unacceptable) to 100 (extremely acceptable).

The 2 × 3 × 3 factorial with canopy position (interior or exterior), conditioning temperature (20, 38, or 42 °C), and irradiation level (0.0, 0.5, 1.0 kGy) as main effects was analyzed with ANOVA procedures (SAS Institute, Cary, N.C.). Harvest served as blocks (replications) only in the experimental design.

Error sums of squares for harvests were partitioned in the analysis but the effects of harvest are not presented or discussed.

Results

Sound fruit. Averaged over all treatments, 82% of interior and 67% of exterior canopy fruit were sound (fruit without SERB, pitting or decay) (Table 1). The conditioning temperature increased, while increasing the irradiation dose decreased, the percentage of sound fruit. The negative effect of irradiation dose was greater for exterior than for interior fruit.

Stem-end rind breakdown. Fruit from the exterior canopy had three times as much SERB as did fruit from the interior canopy (Table 1). Increasing conditioning temperature prior to irradiation reduced SERB, but increasing the dose increased SERB. As conditioning temperature increased, SERB declined for exte-

rior fruit, whereas SERB for interior fruit was reduced only by exposure to 42 °C.

Pitting. Pitting began to develop on fruit peel 7 to 10 d after irradiation treatment, with increased frequency and severity during storage (data not shown). Pitting developed randomly in flavedo tissue, small lesions gradually advancing to contiguous tissue, affecting both oil cells and intercellular tissue. Pitting was observed on 15% and 27% of interior and exterior fruit, respectively. The percentage of pitted fruit decreased as conditioning temperature increased; however, 17% of the fruit conditioned at 42 °C were pitted (Table 1). No pitting developed on nonirradiated fruit, but the percentage of pitted fruit increased from 24% to 38% as irradiation dose increased from 0.5 to 1.0 kGy. Fruit exposed to 42 °C prior to irradiation at 1.0 kGy had less pitting than those held at 20 or 38 °C, but temperature had little effect on the incidence of pitting for fruit treated with 0.5 kGy. Percentage of pitting was higher on exterior than on interior irradiated fruit, regardless of dose.

Decay. Decay averaged 1.1% over all treatment combinations, and was not affected by fruit location in the canopy, conditioning temperature, or irradiation dose (Table 1). The canopy × temperature interaction was significant, as indicated by maximum decay of interior fruit at 20 °C (2.8%), whereas the maximum (2.2%) in exterior fruit occurred at 38 °C.

Appearance. The mean value for fruit appearance was 2.3 and varied from 2.1 to 2.7 among treatment combinations (Table 1). The appearance of interior fruit was better than that of exterior fruit, as indicated by scores of 2.2 and 2.5, respectively. Fruit exposed to the highest conditioning temperature were not as fresh (low gloss, off color) in appearance as control fruit or those conditioned at 38 °C. Appearance rating of interior fruit changed little as dose increased, whereas that of exterior fruit decreased. The decline in appearance rating was accentuated at the highest conditioning temperature.

Weight loss. Weight loss was greater for exterior than for interior fruit, and increased with conditioning temperature and irradiation dose (Table 1).

Firmness. Exterior fruit were firmer than interior fruit at the final inspection (Table 1). Temperature conditioning and an irradiation dose of 1.0 kGy softened fruit. Interior fruit softened when exposed to both 38 and 42 °C conditioning temperatures, while exterior fruit did not. A dose of 1.0 kGy softened fruit regardless of canopy location, but fruit irradiated at 1.0 kGy softened more when conditioned at 42 °C than at 20 or 38 °C.

Peel color. The color of the peel of exterior fruit was darker than that of interior fruit, as indicated by a lower L* value (Table 2). The peel of exterior fruit was a more vivid yellow than that of interior fruit as indicated by the higher chroma value. Irradiation had no effect on fruit color.

TSS, TA, and pH. Total soluble solids were not affected by treatment, but TA decreased as irradiation dose increased to 1.0 kGy (Table 2). The pH of exterior fruit was higher than that

of interior fruit. The pH increased with temperature and irradiation dose. Although differences in pH were significant, their magnitude was small and probably of little practical importance. The mean TSS : TA ratio was 8.5:1 over all treatments, and increased as conditioning temperature increased from 38 to 42 °C (data not shown).

Flavor. The flavor preference rating of juice of interior canopy (exterior fruit not rated for flavor) fruit was affected by both conditioning temperature and irradiation dose (Table 3). Juice preference decreased as irradiation dose increased, except for fruit conditioned at 42 °C. The lowest preference rating for control (20 °C) and fruit treated at 1.0 kGy occurred when they were conditioned at 38 °C, whereas those treated at 0.5 kGy had the lowest rating when conditioned at 42 °C.

Discussion

Grapefruit harvested from the interior canopy were less sensitive to irradiation than those from the exterior canopy following 4 weeks of storage at 10 °C plus one week at 20 °C. McDonald et al. (1993) reported less peel pitting following low temperature storage of interior than of exterior canopy fruit. They suggested that the greater susceptibility of exterior grapefruit to pitting may be the consequence of accelerated senescence. Exterior canopy fruit may be more mature and there-

fore more susceptible to irradiation injury.

Heat treatments reduced peel pitting of irradiated fruit, but only at the higher dosage. Conditioning by short-term heat treatment decreased sensitivity to induced stress, as previously reported by Paull (1990) and Klein and Lurie (1991). However, the level of irradiation-induced pitting remained higher than the 5% incidence allowed for US #1 grade. In addition, irradiation treatment increased SERB, fruit appearance index, and weight loss, and reduced firmness. Juice flavor rating also decreased as irradiation dose increased for interior fruit. The flavor response of exterior fruit would probably parallel that for interior fruit. The sensitivity of grapefruit peel was too great to tolerate the stress induced by irradiation at 0.5 or 1.0 kGy, even with the combined treatment of short-term heat conditioning, but conditioning may provide protection against peel injury at doses of irradiation lower than 0.5 kGy. Our results indicate that peel injury can be reduced, but not eliminated, by application of heat prior to irradiation; in addition, we confirmed earlier reports that interior canopy fruit are less sensitive than exterior fruit.

Literature Cited

Hatton, T.T. 1990. Reduction of chilling injury with temperature and manipulation, p. 269–280. In: C-Y Wang (ed.). Chilling injury of horticultural crops. CRC Press, Boca Raton, Fla.

Table 2. Color, total soluble solids (TSS), titratable acidity (TA), and pH of grapefruit harvested from interior or exterior canopy positions, heat-treated at 20, 38, or 42 °C, and irradiated at 0.0, 0.5, or 1.0 kGy, and stored for 28 d at 10 °C plus 7 d at 20 °C.

Treatments	Color values ^z			TSS (%)	TA (%) ^y	pH
	L*	Chroma*	h°			
Canopy position						
Interior	79.8	53.0	94.3	10.0	1.20	3.30
Exterior	77.9	54.0	94.2	10.3	1.20	3.34
Temperature (°C)						
20	78.9	53.5	94.2	10.2	1.20	3.30
38	79.0	53.4	94.2	10.1	1.20	3.30
42	78.7	53.6	94.3	10.1	1.10	3.40
Dose (kGy)						
0.0	79.0	54.5	94.5	10.4	1.22	3.30
0.5	78.9	53.2	94.3	10.1	1.20	3.32
1.0	78.6	52.9	93.8	10.0	1.17	3.35
Significance of main factors						
Canopy	*	*	NS	NS	NS	*
Temp	NS	NS	NS	NS	NS	*
Dose	NS	NS	NS	NS	*	*

^zCIE (International Commission on Illumination) (1976) color system.

^yPercent citric acid.

NS, *Nonsignificant or significant by ANOVA at $P \leq 0.05$, respectively.

Table 3. Flavor index values of interior canopy grapefruit only, heat treated at 20, 38, or 42 °C and irradiated at 0, 0.5, or 1.0 kGy, and stored for 28 d at 10 °C plus 7 d at 20 °C.

Dose (kGy)	Temp (°C)			Mean
	20	38	42	
0.0	80.0 ^a	77.5	80.0	79.2
0.5	77.5	60.0	52.5	63.3
1.0	57.5	47.5	65.0	56.7
Mean	71.7	61.7	65.8	
Significance of main factors and interaction ^y				
Temperature (T)	*			
Dose (D)	*			
T × D	*			

^a0 = extremely unacceptable, 100 = extremely acceptable.

^yFactors or interactions not shown are nonsignificant.

*Significant at $P \leq 0.05$ by ANOVA.

- Hatton, T.T. and R.H. Cubbedge. 1982. Conditioning Florida grapefruit to reduce chilling injury during low-temperature storage. *J. Amer. Soc. Hort. Sci.* 107:57-60.
- Hatton, T.T., R.H. Cubbedge, L.A. Risse, P.W. Hale, D.H. Spalding, D. von Windeguth, and V. Chew. 1984. Phytotoxic responses of Florida grapefruit to low-dose irradiation. *J. Amer. Soc. Hort. Sci.* 109:607-610.
- Ismail, M.A., T.T. Hatton, D.J. Dezman, and W.R. Miller. 1986. In transit cold treatment of Florida grapefruit shipped to Japan in refrigerated van containers: Problems and recommendations. *Proc. Fla. State Hort. Soc.* 99:114-121.
- Klein, J.D. and S. Lurie. 1991. Postharvest heat treatment and fruit quality. *Postharvest News and Info.* 1:15-19.
- McDonald, R.E., H.E. Nordby, and T.G. McCullum. 1993. Epicuticular wax morphology and composition are related to grapefruit chilling injury. *HortScience* 28:311-312.
- McGuire, R.G. 1992. Reporting of objective color measurements. *HortScience* 27:1254-1255.
- Miller, W.R. and R.E. McDonald. 1996. Postharvest quality of GA-treated Florida grapefruit after gamma irradiation with TBZ and storage. *Postharvest Biol. Technol.* 7:253-260.
- Paull, R.E. 1990. Postharvest heat treatments and fruit ripening. *Postharvest News and Info.* 1:355-363.
- Purvis, A.C. 1980. Influence of canopy depth on susceptibility of 'Marsh' grapefruit to chilling injury. *HortScience* 15:731-733.
- Schiffmann-Nadel, M., E. Chalutz, J. Waks, and M. Dagan. 1975. Reduction of chilling injury in grapefruit by thiabendazole and benomyl during long-term storage. *J. Amer. Soc. Hort. Sci.* 100:270-272.
- U.S. Dept. of Agriculture. 1971. Market diseases of citrus and other subtropical fruits. U.S. Dept. Agr., Agr. Res. Serv., Agr. Hdbk. No. 398.
- U.S. Dept. of Agriculture. 1996. Dept. of Agriculture, Animal and Plant Health Insp. Serv. Docket No. 95-008-1. The application of irradiation to phytosanitary problems. Federal Register, U.S. Govt. Printing Office 61(95):24433-24439.
- U.S. Dept. of Health and Human Resources. 1986. U.S. Dept. of Health and Human Resources, Food and Drug Administration. Final Rule, Docket No. 81N-004. Irradiation in the production, processing, and handling of food. Federal Register, U.S. Govt. Printing Office 56(75):13375-13399.