Navel Orange Tolerance to Heat Treatments for Disinfesting Mexican Fruit Fly¹

Krista C. Shellie¹ and Robert L. Mangan²

U.S. Department of Agriculture, Agricultural Research Service, Subtropical Agricultural Research Laboratory, 2301 South International Boulevard, Weslaco, TX 78596

ADDITIONAL INDEX WORDS. quarantine, phytosanitary, postharvest, quality, *Anastrepha ludens*, *Citrus sinensis*

ABSTRACT. Navel orange [*Citrus sinensis* (L.) Osbeck] was exposed to moist, forced air at 46 °C for up to 4.5 hours or 50 °C for 2 hours, or immersed for 3 hours in water at 46 °C. Quality attributes of heated and nonheated fruit were compared after 4 weeks of storage at 7 °C and 1 week at 23 °C. The flavor of oranges immersed in water was rated significantly inferior to fruit heated in air and fruit that were not heated. Oranges immersed in hot water also developed a higher incidence of decay during storage than oranges heated in air or nonheated control fruit. The flavor of oranges exposed to moist, forced air at 46 °C for up to 4.5 hours was rated by preference panelists as similar to nonheated controls, even though heated fruit had a significantly lower amount of titratable acidity and a higher ratio of sugar to acid. Fruit exposed to high-temperature forced air developed less decay during subsequent storage than nonheated control fruit. Texas 'N33' navel oranges tolerated exposure to forced air at 46 °C for up to 4.5 hours without deleterious effects on fruit market quality.

Oranges are grown in areas with a climate conducive to the establishment of fruit fly populations. The commercial importance of oranges relative to other citrus species is illustrated by the fact that orange production represents 80% of world citrus fruit production (Baldwin, 1993). Oranges were identified by Norrbom and Kim (1988) as a host for the Mexican fruit fly (*Anastrepha ludens* Loew).

Mexican fruit fly populations are undesirable in navel orange production regions because fruit infested with larvae are rendered unmarketable. Adult females oviposit just under the surface of the fruit, and larvae complete their life cycle inside the fruit while feeding on fruit tissue (Christenson and Foote, 1960). Harvested fruit may contain eggs or larvae of various ages depending on the elapsed time between fly oviposition and fruit harvest. Infested fruit cannot be easily identified by external appearance. Regulatory agencies in many countries enforce established quarantine protocols for marketed fresh produce to ensure that infested fruit do not introduce fruit flies into fly-free production regions. Quarantine protocols include preharvest measures, such as sterile fly release and fly-free growing periods, and postharvest measures, such as commodity heat treatments.

A 13-h vapor heat treatment was first used commercially in Florida in 1929 to disinfest citrus of fruit flies. This vapor heat treatment at 43 °C severely injured some species of citrus, especially navel orange (Sinclair and Lindgren, 1955). Vapor heat fell out of favor in the 1950s because chemical fumigants were cheaper and easier to apply. Phytotoxicity problems with fumigants and environmental and food safety concerns stimulated research to improve vapor heat technology by increasing air flow (Gaffney et al., 1990) and controlling vapor pressure (Gaffney, 1990). These innovative technologies enhanced fruit heating rates and resulted in shorter treatments that provided quarantine security without damaging citrus market quality (Sharp and McGuire, 1996; Shellie et al., 1993; Shellie and Mangan, 1994, 1995, 1996).

Fruit and insect tolerance to heat can be affected by many factors. Tolerance of an insect or a commodity to a postharvest heat treatment can be altered by prior exposure to an abiotic stress (Jang, 1992; Joyce and Shorter, 1994; Lay-Yee and Rose, 1994; Moss and Jang, 1991) or by the life stage of the insect or stage of maturity of the commodity. For example, Sinclair and Lindgren (1955) reported that early-season navel oranges tolerated exposure to vapor heat better than late-season fruit. Nonfeeding, third-instar larvae and mature eggs have been identified as the most heat-tolerant life stage of fruit flies (Heard et al., 1991, 1992; Jang, 1991). Tolerance to heat can also be affected by the method used to heat the commodity. Fruit tolerance to postharvest heat treatments is often lower when water or vapor-saturated air is used as the heating medium. For example, grapefruit (*Citrus paradisi* Macf.) develops phytotoxic symptoms after immersion in water at 43.5 °C for 4.5 h (Miller et al., 1988), after 20 min in water at 48.8 °C (Sharp, 1985), or after 3.75 h in vapor, forced air at 46 °C (Hallman et al., 1990). However, when a vapor-pressure deficit is maintained during heating, grapefruit can be exposed to forced air at 46 °C for up to 5 h without developing phytotoxic symptoms (Shellie and Mangan, 1996). Also, if air temperature does not exceed 43 °C, grapefruit tolerate exposure to vapor forced air (Hallman et al., 1990).

Fruit quality can be maintained with a margin of safety by establishing quarantine treatment temperatures and exposures at a severity level that maximizes the heat tolerance margin between insect and fruit (Williamson and Winkelman, 1994). The amount of time required to completely kill fruit fly larvae begins to decrease during exposure to temperatures ≥ 43 °C (Jang, 1991). The objective of this research was to identify a nondamaging hot water or high-temperature forced-air treatment for navel orange that could provide quarantine security against Mexican fruit fly.

Materials and Methods

Experiments were conducted during the 1994 California navel orange season and the 1995 and 1996 Texas navel orange seasons. Texas navel oranges reach commercial maturity by November of each year, and harvest is usually completed by January of the following year. Since the navel orange season in California is different from that in Texas, research was initiated in April 1994 using California navel oranges. The heat tolerance of California

Received for publication 10 Feb. 1997. Accepted for publication 8 Oct. 1997. We appreciate the assistance of Sam Ingle, Eleazar Moreno, and Soraida Mata (USDA-ARS) for conducting heat treatments and evaluating fruit quality. Use of trade names does not imply endorsement of products named or criticism of similar products not mentioned. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹Plant physiologist; email kshellie@pop.tamu.edu.

²Entomologist.

navel oranges was assumed to be representative of heat tolerance in Texas navel oranges.

Tolerance of California navel oranges to two exposure temperatures (moist, forced air at 46 °C for 4 h or moist, forced air at 50 °C for 2 h) and heating medium (water at 46 °C for 3 h) was evaluated in 1994. The influence of exposure duration (3.5, 4.0, or 4.5 h) on the tolerance of Texas navel oranges to moist, forced air at 46 °C was evaluated during the 1995 Texas navel orange season. The impact of fruit maturity (early, middle, or late season) on Texas navel orange tolerance to moist, forced air at 46 °C for 4.5 h was evaluated with fruit harvested during the 1996 Texas navel orange season. The severity of the heat treatments evaluated in 1994 and 1996 was anticipated to provide quarantine security against Mexican fruit fly (R.L. Mangan, unpublished data).

Fruit were harvested twice during the 1994 navel orange season in California and nine times each during the 1995 and 1996 navel orange seasons in Texas. Size 88 (each $\approx$ 300 g) navel oranges of an unknown cultivar were harvested from a commercial grove near Riverside, Calif., on two separate dates during the last 2 weeks of April 1994. The fruit were shipped by commercial carrier service to the USDA-ARS Crop Quality and Fruit Insects Research Unit in Weslaco, Texas, on the same day they were harvested. Texas navel oranges were harvested during the 1995 and 1996 navel orange seasons from experimental research plots at the USDA-ARS Crop Quality and Fruit Insects Research Unit. Size 88 'N33' navel oranges (on sour orange rootstock) were harvested seven times in December 1994, twice in January 1995 (1995 citrus season), and three times each in November 1995, December 1995, and January 1996 (1996 citrus season). Each of the three harvests during November, December, and January in the 1996 citrus season were considered replications for early-, middle-, and late-season fruit, respectively.

Fruit harvested during the 1994, 1995, or 1996 citrus seasons were stored at 23 °C for at least 12 h before treatment to ensure a uniform initial fruit center temperature. Elapsed time from harvest until treatment was no more than 3 d for fruit from the 1994 citrus season and no more than 18 h for Texas fruit harvested in the 1995 and 1996 citrus seasons. The oranges were not degreened, washed, waxed, or treated with any fungicide before treatment. The Texas 'N-33' navel oranges were not treated with any preharvest sprays or plant growth regulators.

Oranges were exposed to heated, moist, forced air inside a chamber similar to that described by Gaffney et al. (1990). The fruit were placed in a bin with a perforated bottom, and the bin was placed over the outlet vent inside the chamber so that heated air was forced over the surface of the fruit. Dewpoint temperature inside the chamber was maintained 2 °C below the coolest fruit surface by varying the water vapor pressure in the chamber to prevent condensation on the surface of the fruit. Air speed inside the treatment chamber was maintained at 2 m·s⁻¹. The temperature, humidity, and air speed inside the chamber and the fruit surface and center temperatures were recorded every 60 s as described by Shellie and Mangan (1996).

The hot water treatment was accomplished by immersing a single layer of grapefruit in a stainless-steel recirculating water bath. Fruit were held under water by a weighted mesh screen during treatment. Water bath temperature and fruit surface and center temperature were recorded every 60 s during heating.

Thirty fruit from each harvest were randomly allocated into a heat treatment group or a nonheated, control group. Each fruit within a treatment group was numbered on its stem end, and three 2-cm-diameter circles were drawn along its equatorial surface. Flavedo color was measured inside the equatorial circles with a

chromameter (model CR-200; Minolta Corp., Ramsey, N.J.) and reported as an average of three readings (Shellie and Mangan, 1994). Fruit mass and flavedo color were measured before each heat treatment. Control fruit were stored at 23 °C while treated fruit were heated and cooled. Heated fruit were cooled at 23 °C in relatively still air. When heated fruit had cooled to ambient temperature, the fruit were reweighed and flavedo color was remeasured. All 30 of the heated and control fruit were then placed into 1/2 standard cardboard shipping cartons and stored for 4 weeks at 7 °C followed by 1 week at 23 °C (90% relative humidity). Cartons were inspected for decay at weekly intervals during storage. When a decayed fruit was encountered, its number was recorded and the fruit was discarded. After completion of storage, each remaining heat-treated and control fruit was reweighed and flavedo color was remeasured. Fruit were rated subjectively for external appearance, decay, and internal disorders. Twenty decay-free fruit were selected from each treatment group for laboratory analyses [percent juice yield, soluble solids concentration (SSC), titratable acidity (TA), and SSC:TA ratio]. Five decay-free fruit were subjectively rated by an untrained preference panel for flavor and external appearance.

Fruit mass was analyzed as percent loss after treatment and percent loss after storage. Percent loss in mass after treatment and after storage was calculated by dividing the difference between posttreatment or poststorage fresh mass and pretreatment fresh mass by pretreatment fresh mass and multiplying by 100.

Flavedo color was analyzed as a percent change after treatment and as a percent change after storage. Color was measured with a chromameter in the L*, C*, h° color mode (L* = darkness, C* = chroma or color intensity, h° = hue) as suggested by Little (1975). Percent change in flavedo color after treatment and after storage were calculated as a ratio of posttreatment or poststorage L*, C*, or h° to pretreatment L*, C*, or h°, and multiplying by 100.

A 5-point marketability scale, with 0 = excellent, 1 = good, 2 = questionable, 3 = poor, or 4 = unacceptable, was used to rate the external appearance and internal disorders of stored fruit. The untrained preference panel rated flavor and external appearance of stored fruit using a 9.5-cm line scale anchored with the terms "dislike extremely" at the left end and "like extremely" on the right end (Shellie and Mangan, 1994).

Juice was extracted from stored fruit using an electric rotary juicer, and its fresh mass was recorded. Percent juice yield was calculated by dividing the mass of the extracted juice by the fresh mass of the fruit before treatment and multiplying by 100. SSC, TA, and SSC:TA were measured from the extracted juice as described by Shellie et al. (1993).

Each year's data were subjected to an analysis of variance (ANOVA) using SAS GLM procedure (SAS Institute, Cary, N.C.). Analyses were based on fruit means or mean ratings of untrained panelists. Treatment and harvests were the main effects in the ANOVA model for 1994 data with six residual degrees of freedom. Three orthogonal contrasts compared nonheated to heated fruit, water immersion to heating in air, and 50 to 46 °C air. The ANOVA used to evaluate the main effect of exposure duration in 1995 considered the nine sequential harvests as three replicated blocks. Three orthogonal contrasts were used to assess differences between nonheated and heat-treated fruit and to test for a linear or quadratic relationship among exposure durations. The effect of fruit maturity in the 1996 data was evaluated using a split-plot ANOVA, with fruit maturity (early, middle, or late season) as the main plot, and heat treatment (0 or 4.5 h) and its interaction with maturity as the subplot. Unless otherwise noted, only results significant at $P \leq 0.05$ are discussed.

Results

All of the oranges harvested for this study had reached minimum commercial maturity (8.5% SSC). California oranges had a higher percent TA (0.57 $\pm$ 0.13) and SSC (12.6 $\pm$ 0.9) than Texas 'N33' navel oranges (0.41 $\pm$ 0.07 and 11.0 $\pm$ 1.1, respectively); therefore, Texas 'N33' navel oranges had a higher SSC:TA (28.7 $\pm$ 6.2) than California navel oranges (22.7 $\pm$ 4.0). Texas navel oranges were $\approx$ 100 g larger (321.2 $\pm$ 22) than oranges obtained from California (230.8 $\pm$ 47.8). The flavado hue value of Texas oranges was closer to yellow or less red (94.5 $\pm$ 9.8) than California oranges (69.1 $\pm$ 2.7).

NAVEL ORANGE SEASON, 1994. The temperature inside the forced-air chamber reached 50 and 46 °C, respectively, within 10 min after treatment initiation (Fig. 1). Dewpoint temperature inside the forced-air chamber increased gradually during the first 60 min of treatment and then remained at least 2 °C below the chamber temperature during treatment. The temperature of the water bath remained at 46 °C during treatment.

The heating profiles at the fruit center illustrate that immersion in hot water resulted in a more severe heat dose than heating in similar temperature air (Fig. 2a). Oranges immersed in water and oranges exposed to 50 °C moist, forced air required $\approx$ 80 min for their centers to reach 45 °C. Oranges exposed to moist forced air

at 46 °C took about twice as long ($\approx$ 160 min) for their center temperature to reach 45 °C. After reaching 45 °C, the center temperature of fruit immersed in water or exposed to 46 °C air remained relatively unchanged (increased $\approx$ 0.8 and $\approx$ 0.2 °C, respectively) for the duration of the heat treatment. The center temperature of oranges exposed to forced air at 50 °C exceeded that of the other heat treatments for $\approx$ 40 min and reached a maximum of 48 °C. The degree-minutes that accumulated at the fruit center during heating (sum of temperature each minute divided by the number of minutes) was highest during water immersion (42.9), intermediate during exposure to forced air at 46 °C (41.2), and lowest during exposure to forced air at 50 °C (40.2).

The greatest difference among fruit center temperatures during any of the heat treatments was within the first 30 min of hot water immersion, when the fruit center temperature was below 40 °C (Fig. 2b). After the first 30 min, oranges immersed in hot water heated more uniformly than oranges heated in forced air. For example, after 90 min of exposure, there was a difference of 0.7, 1.5, and 2.2 °C among center temperatures of oranges heated by water, 46 or 50 °C forced air, respectively.

The flavado h° and C^* of California navel oranges that were heated in 1994 were different from their nontreated control fruit (Table 1). Heating the fruit by either immersion in water or exposure to air resulted in a shift toward yellow within the yellow

Fig. 1. Average ($n = 2$) dry and wet bulb temperature inside the forced-air chamber and water bath temperature during navel orange heat treatments during the 1994 citrus season: ● moist, forced-air at 50 °C for 2 h, ▲ moist, forced-air at 46 °C for 4 h, or ■ water at 46 °C for 3 h. Open symbols denote dewpoint temperature.

to red color quadrant compared to nonheated control fruit. Oranges exposed to hot water or hot air also had greater color intensity or C^* after storage than nonheated control fruit (Table 1). The flavedo C^* of heated fruit was 67.6 (SD 0.9) compared to 64.5 (SD 0.7) for nonheated control fruit. Fruit exposed to 46 °C air also had higher C^* values (67.4, SD 2.4) than fruit exposed to 50 °C air (66.8, SD 0.3). These changes in flavedo h° and C^* were undetectable by preference panelists, since their ratings for fruit color and appearance were similar for heated and nonheated fruit (data not shown).

Immersing oranges in water for 3 h at 46 °C had a deleterious effect on fruit flavor, mass, and decay incidence. The flavor of oranges immersed in water was rated by preference panelists as significantly inferior to oranges heated in air and to nonheated controls (Table 1). Oranges immersed in hot water also lost a significantly larger percent of their mass during storage than oranges heated in air or nonheated controls. Incidence of postharvest decay during storage was 10% ($n = 40$) for oranges immersed in water at 46 °C, whereas 8.3 % ($n = 120$) of unheated control fruit developed decay. Oranges exposed to moist, forced air at 46 or 50 °C had a 5% and 0% ($n = 40$) decay incidence, respectively.

NAVEL ORANGE SEASON, 1995-96. Chamber and dewpoint temperature for moist, forced-air treatments conducted in 1995 and 1996 were similar to those presented in Fig. 1 for forced-air treatments at 46 °C. The rate of heating at the fruit center in tests

conducted in 1995 and 1996 was also similar to that presented in Fig. 2 for forced-air treatments at 46 °C. A 100-g discrepancy in mass between California and Texas navel oranges did not result in detectable differences in the rate of heating at the center of the fruit (data not shown).

Texas navel oranges exposed to moist, forced air at 46 °C for 3.5, 4.0, or 4.5 h were similar in all measured quality attributes except flavedo C^* . Fruit heated for 3.5, 4.0, or 4.5 h showed a 19%, 15%, or 11% increase in flavedo C^* . Control fruit presented a 15% increase in C^* . Different fruit maturity during the nine harvests evaluated in 1995 had a greater effect on fruit quality attributes than the forced-air heat treatments. For example, percent TA decreased from 0.44 during the first three harvests to 0.42 and 0.40 during the subsequent blocks of consecutive harvests. The SSC:TA ratio increased from 24.7 for the first block of harvests to 27.4 and 27.9 during subsequent harvests. A gradual decrease in percent L^* (106, 104, 98) and C^* change (120, 119, and 108), and a change in h° (85, 80, 75) of flavedo tissue was also evident among harvest blocks. Percent juice yield decreased from an average of 50% for the first two harvest blocks to 46% for the last harvest block.

Exposing early-, middle-, or late-season Texas navel oranges to forced air at 46 °C for 4.5 h in 1996 significantly lowered TA and percent juice yield and significantly increased SSC:TA ratio (Table 2). The magnitude of the difference in TA and SSC:TA ratio

Fig. 2. Average ($n = 15$) heating rate at the center of navel oranges during exposure to ● moist, forced-air at 50 °C for 2 h, ▲ moist, forced-air at 46 °C for 4 h, or during immersion in ■ water at 46 °C for 3 h during the 1994 citrus season: (a) orange center temperature, (b) range among orange center temperatures.

Table 1. California navel orange quality attributes in 1994 with or without a heat treatment and after storage for 4 weeks at 7 °C and 1 week at 23 °C.

Source	Hue angle ^z	Chroma ^y (% change)	Flavor ^x	Mass ^y (% change)
Control	69.3	101.578	6.956	8.460
46 °C water	71.2	105.997	4.437	10.452
46 °C moist air	70.4	106.555	6.489	7.444
50 °C moist air	70.4	105.538	6.954	8.009
Control vs. heat	-1.36*	-4.452**	0.996	-0.175
Water vs. air	0.8	-0.045	-2.285**	2.726*
50 vs. 46°C air	0.0	-1.017*	0.465	0.569
SE ^w (control)	0.392	0.134	0.252	0.521
SE (each treatment)	0.680	0.232	0.436	0.903
SED (control vs. heat)	0.555	0.189	0.354	0.734
SED (water vs. air)	0.833	0.284	0.534	1.106
SED (50 vs. 46 °C air)	0.961	0.328	0.617	1.277

^zHue angles of 90° to 0° are in the yellow to red quadrant, respectively.

^yMeans based on average rating of 13 judges using a 9.5-cm line scale with 1 = dislike extremely and 9 = like extremely.

^xThe difference between poststorage and pretreatment values divided by pretreatment value and multiplied by 100.

^wError df = 6, n = 6 for control; n = 2 for each heat treatment.

*,**Significant at $P \leq 0.05$ or 0.01, respectively.

between heated and nonheated fruit was greatest for late-season fruit. Heated fruit were rated by preference panelists as acceptable yet inferior in appearance to nonheated control fruit. Fruit harvested early, mid, or late season were significantly different in amount of TA, SSC, SSC:TA, juice yield, and flavado h° and C*. Exposure to heat had no significant influence on flavado C* or h°.

Navel oranges exposed in 1996 to forced air at 46 °C for 4.5 h developed less decay during storage than nonheated control fruit. Only 1% of all (n = 270) heated oranges developed decay (green mold) during storage, whereas 10% of all (n = 270) nonheated, control fruit developed decay during storage.

Discussion

The tolerance of navel orange to heat was altered by heating in water versus heating in air. It is unlikely that the small difference in heat dose between oranges immersed in water and oranges

heated in air at 46 °C (1.7 degree-minutes and 0.6 °C center temperature) explains the observed differences in off-flavor and surface decay. A more likely explanation may be that direct contact with water at 46 °C caused irreversible damage to flavado tissue, and off-flavor developed as a result of damaged oil glands. Impaired gas exchange caused by immersion in water may also have induced anaerobic respiration and contributed to off-flavor development.

The elevated incidence of decay after immersion in hot water observed in 1994 supports results reported by McGuire for grapefruit (1991a) and provides additional evidence that incidence of decay after exposure to heat indicates whether a heat treatment was above or below fruit tolerance. McGuire (1991a) reported a higher incidence of decay and off-flavor development after grapefruit were immersed in hot (48 °C) water than after grapefruit were exposed to forced air at 48 °C and concluded that hot water immersion caused irreversible damage to fruit tissue. Conversely,

Table 2. Texas 'N33' navel orange quality attributes in 1996 after 46 °C moist, forced-air treatment for 4.5 h followed by storage for 4 weeks at 7 °C and 1 week at 23 °C.

Source	Acidity		Juice (%)	Preference rating ^z		Hue value ^y	Chroma ^y (% change)
	(%)	SSC:TA		Flavor	Appearance		
Early season	0.4288	24.74	50.1	6.9	7.1	80.8	133.7
Heated	0.3962	26.44	48.7	6.8	7.1	80.8	134.2
Control	0.4613	23.04	51.5	7.1	7.1	80.8	133.2
Mid-season	0.3734	31.33	43.5	6.9	6.5	75.2	109.8
Heated	0.3517	32.85	42.1	7.0	6.3	75.6	109.9
Control	0.3951	29.81	45.0	6.8	6.8	74.7	109.6
Late season	0.3518	34.56	36.1	6.8	7.1	74.2	106.3
Heated	0.2839	41.42	31.2	6.5	6.7	74.5	104.2
Control	0.4197	27.70	41.1	7.0	7.5	73.8	108.3
SE (H,M) ^x	0.02, 0.03	0.4, 1.4	1.9, 2.6	NS	0.3	0.6	2.5
Significance ^w	M × H,M	M × H,M	H,M	NS	H	M	M

^zMeans based on ratings from 20 judges using a 9.5-cm line scale with 1 = dislike extremely and 9 = like extremely.

^yMeasured with a chromameter (model CR-200; Minolta Corp., Ramsey, N.J.) in L*, C*, h° color mode. Hue angles of 90° to 0° are in the yellow to red quadrant, respectively. Percent change calculated by dividing the difference between poststorage and pretreatment value by pretreatment value and multiplying by 100.

^xStandard error heat df = 6, maturity df = 4, n = 3; M = fruit maturity, H = heat treatment.

^wSignificant at $P \leq 0.05$.

^{NS}Nonsignificant at $P \leq 0.05$.

heat treatments that do not cause irreversible damage have been found to decrease the incidence of decay (McGuire, 1991b). The reduced incidence of decay observed in this study after navel oranges were exposed to moist, forced air suggests that the moist, forced-air treatments evaluated in this study did not exceed the limits of navel orange heat tolerance.

The increase in flavedo C* and h° that were apparent after exposure of California navel oranges to heat was not apparent after heating early-, middle-, and late-season Texas navel oranges. The increase in flavedo C* and change in h° was most likely due to synthesis of carotenoids in the peel during storage. This interpretation is further supported by the decline in C* and h° as fruit matured from early to late season. When variance for fruit maturity was partitioned in 1996, it became apparent that exposure to heat did not significantly influence flavedo C* or h°.

The tolerance of navel oranges relative to grapefruit (*Citrus paradisi* Macf.), 'Valencia' orange, or tangerine (*Citrus reticulata* Blanco) to forced-air heating is difficult to discern from this study. No heat-associated damage was detected in red-fleshed grapefruit when fruit center temperature reached 48 °C (Shellie and Mangan, 1996). However, off-flavor developed in 'Valencia' orange (Shellie and Mangan, 1994) and 'Dancy' tangerine (Shellie et al., 1993) when fruit center temperature exceeded 45 or 44 °C, respectively. This suggests that grapefruit is more tolerant to forced-air heating than 'Valencia' orange or 'Dancy' tangerine. The absence of off-flavor or decay in navel orange after reaching a fruit center temperature of 48 °C (2 h at 50 °C) suggests that the heat tolerance of navel oranges may be most similar to grapefruit. However, this interpretation may overestimate navel orange heat tolerance, since the center temperature in the present study was held above 45 °C for only 40 min.

For forced air to be applied successfully on a commercial scale, it is mandatory that the treatment times and temperatures do not compromise the market quality of the treated fruit. Treatment times and temperatures should therefore never exceed the minimum required for quarantine security against a target pest. For example, a commercial scale forced-air chamber with a capacity of heating 5 t of fruit may need to be preheated before loading to facilitate rapid fruit heating and to avoid long exposure times. If fruit are heated inside commercial-size harvest bins, the heat may need to be removed after treatment by hydro or forced-air cooling to prevent fruit located in the center of a bin from overheating. Fruit may also require sizing before heating to ensure sufficient heating of large fruit and to avoid overheating of smaller fruit.

Based on results of this study, we conclude that Texas 'N33' navel oranges tolerate exposure to forced air at 46 °C for up to 4.5 h without deleterious effects on fruit market quality. A heat treatment of this magnitude will most likely provide quarantine security against Mexican fruit fly and the Caribbean fruit fly [*Anastrepha suspensa* (Loew); Sharp and McGuire, 1996]. Further elucidation of factors that enhance the margin between heat tolerance of navel oranges and that of Mexican fruit fly will assist in optimizing commercialization of high-temperature forced-air treatments.

Literature Cited

- Baldwin, E.A. 1993. Citrus Fruit. In: G. Seymour, J. Taylor, and G. Tucker (eds.). Biochemistry of fruit ripening. Chapman & Hall, London.
- Christenson, L.D. and R.H. Foote. 1960. Biology of fruit flies, p. 171–192. In: E.A. Steinhaus and R.F. Smith (eds.). Annual review of entomology. Annual Reviews, Palo Alto, Calif.
- Gaffney, J.J. 1990. Warm air/vapor heat research facility for heating fruits for insect quarantine treatments. Amer. Soc. Agr. Eng. Paper 906615.
- Gaffney, J.J., G.J. Hallman, and J.L. Sharp. 1990. Vapor heat research unit for insect quarantine treatments. J. Econ. Entomol. 83:1965–1971.
- Hallman, G.J., J.J. Gaffney, and J.L. Sharp. 1990. Vapor heat treatment for grapefruit infested with Caribbean fruit fly (Diptera: Tephritidae). J. Econ. Entomol. 83:1475–1478.
- Heard, T.A., N.W. Heather, and R.J. Corcoran. 1991. Dose-mortality relationships for eggs and larvae of *Bactrocera tryoni* (Diptera: Tephritidae) immersed in hot water. J. Econ. Entomol. 84:1768–1770.
- Heard, T.A., N.W. Heather, and P.M. Peterson. 1992. Relative tolerance to vapor heat treatment of eggs and larvae of *Bactrocera tryoni* (Diptera: Tephritidae) in mangoes. J. Econ. Entomol. 85:461–463.
- Jang, E.B. 1991. Thermal death kinetics and heat tolerance in early and late third instars of the oriental fruit fly (Diptera: Tephritidae). J. Econ. Entomol. 84:1298–1303.
- Jang, E.B. 1992. Heat shock proteins and thermotolerance in a cultured cell line from the Mediterranean fruit fly, *Ceratitis capitata*. Arch. Insect. Biochem. Physiol. 19:93–103.
- Joyce, D.C. and A.J. Shorter. 1994. High-temperature conditioning reduces hot water treatment injury of 'Kensington Pride' mango fruit. HortScience 29:1047–1051.
- Lay-Yee, M. and K.J. Rose. 1994. Quality of 'Fantasia' nectarines following forced-air heat treatments for insect disinfestation. HortScience 29:663–666.
- Little, A.C. 1975. Off on a tangent. J. Food Sci. 40:410–411.
- McGuire, R.G. 1991a. Market quality of grapefruit after heat quarantine treatments. HortScience 26:1393–1395.
- McGuire, R.G. 1991b. Concomitant decay reductions when mangoes are treated with heat to control infestations of Caribbean fruit flies. Plant Dis. 75:946–949.
- Miller, W.R., R.E. McDonald, and T.T. Hatton. 1988. Phytotoxicity of grapefruit exposed to hot water immersion treatment. Proc. Fla. State Hort. Soc. 101:192–195.
- Moss, J.L. and E.B. Jang. 1991. Effects of age and metabolic stress on heat tolerance of Mediterranean fruit fly (Diptera: Tephritidae) eggs. J. Econ. Entomol. 84:537–541.
- Norrbom, A.J. and K.C. Kim. 1988. A list of the reported host plants of the species of *Anastrepha* (Diptera: Tephritidae). USDA–Animal Plant Health Inspection Serv., Plant Protection Quarantine, Washington, D.C. APHIS 81-52.
- Sharp, J.L. 1985. Submersion of florida grapefruit in heated water to kill stages of Caribbean fruit fly, *Anastrepha suspensa*. Proc. Fla. State Hort. Soc. 98:78–80.
- Sharp, J.L. and R.G. McGuire. 1996. Control of Caribbean fruit fly (Diptera: Tephritidae) in navel orange by forced hot air. J. Econ. Entomol. 89:1181–1185.
- Shellie, K.C., K.J. Farce, and R.L. Mangan. 1993. Phytotoxic response of 'Dancy' tangerine to high-temperature, moist, forced-air treatment for fruit fly disinfestation. J. Amer. Soc. Hort. Sci. 118:481–485.
- Shellie, K.C. and R.L. Mangan. 1994. Postharvest quality of 'Valencia' orange after exposure to hot, moist, forced air for fruit fly disinfestation. HortScience 29:1524–1527.
- Shellie, K.C. and R.L. Mangan. 1995. Heating rate and tolerance of naturally degreened 'Dancy' tangerine to high temperature, forced air for fruit fly disinfestation. HortTechnology 5:40–43.
- Shellie, K.C. and R.L. Mangan. 1996. Tolerance of red-fleshed grapefruit to a constant or stepped temperature, forced-air quarantine heat treatment. Postharvest Biol. Technol. 7:151–159.
- Sinclair, W.B. and D.L. Lindgren. 1955. Vapor heat sterilization of California citrus and avocado fruits against fruit-fly insects. J. Econ. Entomol. 48:133–138.
- Williamson, M. and P. Winkelman. 1994. Heat treatment facilities, p. 249–271. In: R. Paull and J.W. Armstrong (eds.). Insect pests and fresh horticultural products. CAB Intl., Wallingford U.K.