RADIO FREQUENCY-HOT WATER DIPS FOR POSTHARVEST CODLING MOTH CONTROL IN APPLES*

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ABSTRACT

A combination radio frequency-hot water dip method was examined as a potential quarantine treatment against fifth instars of the codling moth, Cydia pomonella *L. (Lepidoptera: Tortricidae), in apples,* Malus sylvestris *(L.) var.* domestica *(Borkh.) Mansf., which were intended for export to Japan. The apples were initially exposed to 27.12-MHz radio frequency energy at 12 kW for 2.75 min and were then submerged in a range of hot water dips (48–50C) for different durations. Efficacious tests were at 48C for >2 h, at 49C for >50 min and at 50C for >40 min. Fruit quality tests indicated that the best hot water parameters were at 50C for 40 min. Fruit quality after 2 weeks was cultivar dependent where "Fuji" apples tolerated heat treatment better than "Delicious" and "Gala" apples. None of the treated fruits were acceptable after 60 days. Regardless of cultivar, heat treatment resulted in loss of both peel and fresh colors, coupled with reduced firmness and increased external and internal damage.*

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* Mention of a proprietary product does not constitute an endorsement or recommendation by the U.S. Department of Agriculture (USDA) for its use.

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INTRODUCTION

Fresh apples (*Malus sylvestris* [L.] var. *domestica* [Borkh.] Mansf.) exported to Japan are treated to control codling moth (*Cydia pomonella* L. [Lepidoptera: Tortricidae]) (Ministry of Agriculture, Forestry and Fisheries – Japan 1950). The current postharvest quarantine treatment consists of two components, cold storage at 2.2C for 55 days followed by a 2-h methyl bromide fumigation and at least 2-h chamber venting (Hansen *et al.* 2000). However, future long-term use of methyl bromide fumigation is questionable because of environmental and health concerns (Anon 1990, 1995).

Some potential alternatives to methyl bromide fumigation rely on heat for disinfestation. A treatment has been proposed using forced hot air with low oxygen (Neven *et al.* 2003). Like other conventional methods involving heat, such as hot water dips, this treatment has some significant disadvantages. First, it takes a longer time, between 3 and 6 h, compared with the current 2-h methyl bromide fumigation. Second, the heating rate inside the fruit, where the codling moth larvae are located, decreases with heating time because of a diminishing temperature gradient between heated surface and the interior (Neven and Mitcham 1996; Neven *et al.* 1996; Wang *et al.* 2001b). Thus, heat exposures are much longer on the fruit surface than in the core, which affects the fruit appearance and quality. To be effective, postharvest marketability should be taken into account for any quarantine treatment.

Recently, Feng *et al.* (2004) proposed using hot water dips to control codling moth in sweet cherries, *Prunus avium* L., but this procedure suffers from the same limitations as the forced hot air treatment when applied to apples (Wang *et al.* 2001b). However, if a method that would hasten internal heating can be developed, then hot water may be suitable as a postharvest treatment for apples.

An innovative method of heating is to use radio frequency (RF) energy, where heat is generated from internal resistance when subjected to very rapid alterations of polarity (Headlee and Jobbins 1936). Three radio frequencies have been allocated by the U.S. Federal Communications Commission for industrial purposes: 13.56 ± 0.067, 27.12 ± 0.160 and 40.68 ± 0.020 MHz (Wang *et al.* 2001a). This technology is appealing for postharvest application in that heating is fast and linear with time; energy can penetrate deep into the commodity; there are no chemical residues, and the process has minimal impact on the environment (Tang *et al.* 2000). Radio frequency treatments are also being developed to control stored product pests of walnuts (Wang *et al.* 2001a, 2002b). Adding a hot water component should equalize temperatures from nonuniformed heating caused by radio frequency (Birla *et al.* 2004; Hansen *et al.* 2004a). Thus, combining radio frequency heating with hot water dips should produce fast uniform heating.

Mortality of codling moth larvae is directly related to increase in temperature and duration of exposure (Yokoyama *et al.* 1991; Jones and Waddell 1997). The thermal death kinetics of codling moth larvae have been evaluated by simulating heating effects with the use of a specially designed computer-controlled heating block system (Tang *et al.* 2000; Wang *et al.* 2002a,b; Hansen *et al.* 2004b). Under controlled conditions, a cumulated lethal time model was developed for the fifth instar codling moth wherein the accumulative lethal effect for any combination of temperature–time can be expressed in terms of an equivalent total lethal time at a reference temperature (Tang *et al.* 2000). For example, 1 min at 48C has the same lethal effect as 3.2 min exposure at 46C. This model accounts for the complete thermal history experience by larvae during treatment, including the run-up period, to predict mortality of a population. Thus, the advantage of this model is that it is not limited by the source of heat, such as hot water or vapor heat, as long as temperatures are measured sequentially over time.

The objective of this study was to examine the efficacy of a combined radio frequency-hot water treatment for controlling codling moth in several commercial cultivars of apples. Different water temperatures were evaluated, using the durations developed from the cumulative lethal model (Hansen *et al.* 2004b). Quality parameters were measured from treated apples after simulated storage conditions.

MATERIALS AND METHODS

Tests were conducted in a 12-kW, 27-MHz pilot-scale radio frequency heater/dryer with an E-200 control panel (Strayfield Fastran, Strayfield International Ltd, Wokingham, U.K.). The interior of the treatment cavity consisted of two 104.8 × 79.4-cm electrodes in which the bottom one was stationary, whereas the top one could be elevated from 200–400 mm. The power coupled in the sample could be tuned slightly by adjusting the lengths of three paired 7.6 cm-wide interconnected parallel plates (top two plates 76 cm long, bottom 66 cm long) above the top electrode so that the functional length could be manipulated. Energy was induced between the electrodes by a high-energy RF generator. Because the unit was rated at 12 kW, maximum efficiency was at 2 amps, which was controlled by lowering or raising the top electrode, changing the dimensions of the target and increasing or decreasing the amount of mass. Most agricultural and biological products are dielectric materials that can generate heat in RF systems, whereas plastic containers are generally transparent to the electromagnetic field in the RF range. Thus, stationary fruits were treated in two low-density polyethylene 38-L bins (Rubbermaid Home Products, Wooster, OH), 61 cm long × 41 cm wide × 22 cm deep, filled with tap water. Internal fruit temperatures (2 mm deep) were measured using a UMI 8 channel conditioner with 0.12C resolution (model FOT-L/CRM/3 m) fiber optic transducers (FISO Technologies Inc., Sainte-Foy, Québec, Canada). Data acquisition was performed using the FISO Commander software (FISO Technologies Inc.) and temperatures measured every 0.05 s.

Hot water dips were conducted in an oblong (94 cm long × 74 cm wide × 58 cm high) holding tank, composed of preformed fiberglass, and were wrapped with an aluminum-coated fiberglass sheet to provide additional insulation. Water was heated by using a 151-L Vangard model 6E727 (Rheem Manufacturing Co., Montgomery, AL) water heater with one-phase electrical connection at 240 V and a maximum of 4,500 W. A microprocessor controlled the water temperature with 0.5C of the target temperature. A Bell & Gossett (Morton Grove, IL) model NRF-22 circulator (115 V, 60 Hz) moved the water at 1 L/s between the holding tank and the water heater through a 2.5-cm-diameter black vinyl tubing. Hydrocooling tanks holding $\simeq$10C water were low-density polyethylene 38-L bins (Rubbermaid Home Products), 61 cm long × 41 cm wide × 22 cm deep.

Bath and internal fruit temperatures were measured using Betatherm model 10K3MBD16 thermistors (Betatherm Corp., Shrewsbury, MA) with accuracy at ±0.1C from 30 to 70C and a response time within 1 s. Temperature data were collected using a data acquisition system (Measurement Computing, Middleboro, MA) composed of a PCI-DAS1000 12-bit board and an SCB-50 screw terminal board with an Instacal (Measurement Computing) version 5.12a board driver. A locally written Visual Basic 6 (Microsoft Corp., Redmond, WA) application program directed the data to specific text files, which were later exported to Quattro Pro (Corel Corp., Orem, UT) version 7 spreadsheets for storage, graphics and analysis.

Size 100, Washington Extra Fancy apples (cultivars "Gala," "Fuji" and "Delicious") freshly harvested and obtained locally, were used for fruit quality tests. Fruits for the efficacy studies were size 100 Delicious apples previously held in 41C regular air storage. To obtain maximum efficiency of 2 amps, 75 apples were treated for each radio frequency exposure. Exposure time (2.75 min) was based on preliminary observations of the duration needed for the internal temperatures to reach near 43C, which is just above the threshold temperature (42C) used in the temperature-time morality model for codling moth larvae (Hansen *et al.* 2004b). For each treatment, the fruits were placed in plastic screened bags to prevent lost larvae from clogging the plumbing, covered with a plastic grid 0.84 cm thick with 1.3-cm squared spaces, and then submerged with two 33-cm square ceramic tiles, 0.6 cm thick. An apple outside the bags in each of the tubs was used to monitor fruit temperatures during radio frequency exposure.

Immediately after radio frequency exposure, the fruits were submerged in the hot water dip. Temperatures and durations were based on the accumulated lethal model for 100% mortality of the treated larval population. Three hot water dip temperatures (±0.2C) were examined, each with three time periods based on the cumulated lethal time model (48C: 1.5, 2.0 and 2.5 h; 49C: 50, 70 and 90 min; 50C: 30, 40 and 50 min), followed by hydrocooling in ≃10C water bath. The time periods were selected so that complete efficacy should result based on the cumulative lethal model for codling moth larvae (Wang *et al*. 2002b; Hansen *et al*. 2004b). Each of the three replicates consisted of one bath temperature for one duration. The same procedure was done for both the efficacy and fruit quality tests. The tests were repeated three times.

The efficacy tests used codling moth larvae from the colony reared at the U.S. Department of Agriculture (USDA) Wapato laboratory, where they were maintained on a soy-wheat germ-starch artificial diet at ≃27C (81 F), 40–58% relative humidity (RH), with a 16:8-h light : dark photoperiod (Toba and Howell 1991). Previous tests have shown that the fifth instar codling moth is the larval stage most tolerant to heat (Wang *et al*. 2002a). Therefore, late fourth to early fifth instars were removed from the artificial diet, and four larvae were placed on the stem end of each apple. Late fifth instars were excluded because they would form cocoons for pupation instead of feeding. The infested apples were held overnight (12–18 h) at ≃24C (75 F), 60–70% RH, with a 16:8-h light : dark photoperiod. The treated fruits were evaluated the next day by dissecting the fruits and recording the number of live and dead larvae observed. The tests were repeated three times.

To determine fruit quality after treatment, the fruits were treated at the shortest time period for each of the bath temperatures used for the efficacy studies: 90 min at 48C, 50 min at 49C and 30 min at 50C. Quality parameters were evaluated within 2 weeks after treatment and again after 60 days of regular atmosphere (RA) storage (1C). In less than 1 week after RF treatment, fruit quality was determined on 20 fruits, from 50 fruits of each treatment and replication, where 10 fruits were evaluated immediately upon receipt, and 10 fruits were allowed to ripen for 7 days prior to quality evaluation. After 60 days of RA storage, the remaining fruits (approximately 30) were evaluated immediately after removal from storage. Fruit quality was not evaluated after ripening because of poor fruit condition. Quality factors evaluated were external and internal color, firmness, soluble solids (SS), titratable acidity (TA) and external and internal disorders. Color was determined with a color meter (The Color Machine, Pacific Scientific, Silver Springs, MD) using the Hunter L^*, a^*, b^* system and calculated hue values (Hunter and Harold 1987). Two evaluations were made on each fruit for external color, and one evaluation was made for internal color. Firmness was determined on 10 fruits at opposite sides using a texture analyzer (TA-XT2, Texture Technologies, Scarsdale, NY) equipped with a 11.1-mm probe, and values were reported in newtons (N). SS and TA were determined from an aliquot of expressed juice of a longitudinal slice from each of the 10 fruits. An Abbe-type refractometer with a sucrose scale calibrated at 20C was used to determine SS. TA was measured with a titrator (TTT 85, Radiometer, Copenhagen, Denmark). Acids were titrated to pH 8.2 with 0.1-N NaOH and expressed as percent malic acid. Disorders (internal browning and bruising) were evaluated by two laboratory personnel and expressed as percent affected.

Means and SDs were calculated using a Quattro Pro (Corel Corp.) version 7 spreadsheet. Fruit quality parameter data were analyzed using SAS (SAS Institute, Cary, NC). PROC MEANS was used for univariate statistics, and nonparametric tests were used to determine significant differences by first arranging data by PROC RANK and then performing PROC GLM. This approach was equivalent to a Wilcoxon rank sum test for two samples and the Kruskal–Wallis *k*-sample test for more than two samples (Zolman 1993).

RESULTS AND DISCUSSION

Efficacy data were expressed as the total of the three replicates because any live recovery disqualified that treatment for future evaluations (Table 1). Larval mortality in the controls, which can be used as an indicator of harshness

TABLE 1.
TOTAL NUMBER OF LIVE AND DEAD LARVAE RECOVERED INSIDE FRUIT ("FUJI" APPLES) PER TREATMENT*

Temperature (C)	Time (min)	Number of live larvae	Number of dead larvae
48	Control	75	6
	90	1	202
	120	0	195
	150	0	175
49	Control	78	7
	50	0	203
	70	0	214
	90	0	193
50	Control	84	3
	30	18	161
	40	0	187
	50	0	165

Time is for hot water dip duration. Initial infestation rate for the treatment control and each of three treatment replicates was 96 larvae per 24 apples.

* Combination treatment of radio frequency (27.12 MHz) exposure at 12 kW for 205 s, followed by a hot water dip.

in handling, was low (mean ± SD = 6.9 ± 2.9%). Live larvae were recovered from the 48C treatment for 1.5 h and from the 50C treatment for 30 min. The remaining treatments had no survivors, but the numbers of treated larvae were too low to demonstrate treatment efficacy at the probit-9 level or 99.9968% mortality needed for quarantine security (Hansen *et al*. 2000). However, these treatments should be further evaluated, particularly if they result in little or no fruit damage.

Within 14 days, most of the treatments resulted in unacceptable damage, particularly 48C for 90 min and to a lesser degree, 49C for 50 min (Table 2). Peel *L* color values were not influenced by heat treatment regardless of the cultivar in question. However, peel hue values were strongly influenced by heat treatment and varied with cultivar (Table 3). Peel hue values for Gala apples increased, regardless of temperature or time when compared with control hue values. Peel hue values for Delicious apples decreased when exposed to the heat treatments, except 50C for 30 min, which were similar to the control hue values. Peel hue values for Fuji apples were similar for control apples and apples treated at 48C for 90 min, and increased for apples treated at 49C for 50 min and 50C for 30 min. Peel hue of Gala and Fuji apples is more sensitive to the heat treatment than that of Delicious apples. This increase in hue values for both Gala and Fuji indicates a less red color for heat-treated fruit. However, even the peel color of Delicious apples responded to 48C for 90 min, producing a darker red color. Peel color differences would be of consumer significance, in that hue differences were in excess of 1.0 unit, which is visible to the human eye (Hunter and Harold 1987). Internal color values, both *L* and hue, were influenced by heat treatment, regardless of the cultivar. Apples exposed to 48C for 90 min resulted in decreased *L* and hue values, or a darker less yellow flesh color. In one instance, this difference in flesh color was also evident for apples exposed to 49C for 50 min, but only for Delicious apples.

Heat treatment reduced firmness values, for most treatments of all three apple cultivars (Table 2). Firmness loss was much more pronounced for Gala treated at 48C for 90 min and Delicious apples treated at 48C for 90 min and 49C for 50 min when compared with the firmness values for control apples. Firmness loss was also evident, for apples treated at 49C for 50 min and 50C for 30 min, but to a lesser degree, particularly for Gala and Fuji apples. External peel damage was very significant for Gala and Fuji apples treated at 48C for 90 min. Some external damage was also present for Gala and Fuji apples treated at 49C for 50 min. Peel damage for treated Delicious apples was not evident, regardless of time or temperature of treatment. Some internal breakdown (darkening of the fruit flesh) was present for both Gala and Fuji apples but only when treated at 48C for 90 min. Internal breakdown was very evident for Delicious apples regardless of time or temperature of heat

TABLE 2.
AVERAGE FRUIT QUALITY PARAMETERS AT DAY 14 AFTER RADIO FREQUENCY-HOT WATER SUBMERSION TREATMENT
(BATH TEMPERATURE AND DURATION TIME)

Treatment		Hunter color				Firm (N)	SS (%)	TA (% malic)	Subjective evaluation (%)	
Temperature (C)	Time (min)	Peel		Flesh					Peel damage	Internal breakdown
		L	Hue	*L*	Hue					
"Gala"										
25*	0	54.0a	41.6b	77.3b	92.8a	50.4a	13.2a	0.27a	0b	0b
48	90	55.0a	46.3a	76.5c	90.6b	45.9c	13.2a	0.26a	57a	7a
49	50	55.2a	45.4a	78.7a	93.0a	47.8b	12.7a	0.26a	3b	3ab
50	30	55.4a	46.6a	78.3a	92.1b	48.4b	13.1a	0.27a	0b	0a
"Delicious"										
25*	0	27.4a	18.5a	75.8a	90.0a	48.8a	12.9a	0.22a	0.0a	7c
48	90	28.1a	16.7b	73.1b	88.6b	44.6c	13.0a	0.18a	0.0a	80a
49	50	27.2a	17.4ab	72.7b	87.9ab	44.2c	13.1a	0.20a	0.0a	27b
50	30	27.8a	17.9a	76.0a	89.5a	51.5b	12.7a	0.20a	0.0a	17b
"Fuji"										
25*	0	46.5a	46.5c	76.1a	88.7a	74.8a	14.8a	0.43a	0b	0b
48	90	44.8a	45.3c	73.2b	86.9b	71.0b	14.7a	0.37a	23a	7a
49	50	46.0a	48.1b	75.9a	90.4a	70.6b	14.0a	0.37a	3b	1b
50	30	47.1a	52.8a	75.9a	89.0a	71.9b	14.9a	0.41a	0.0a	0.b

Means in a column, with in cultivars, not followed by a common letter are significantly different ($P \leq 0.05$).
* Control (not treated).
SS, soluble solids; TA, titratable acidity.

TABLE 3.
SIGNIFICANT DIFFERENCES BASED ON FRUIT QUALITY PARAMETERS WITHIN 14 DAYS AFTER RADIO FREQUENCY-HOT WATER SUBMERSION TREATMENT, WILCOXON RANK SUM TEST FOR TWO SAMPLES AND THE KRUSKAL–WALLIS *k*-SAMPLE TEST FOR MORE THAN TWO SAMPLES

Cultivar	Peel color			Flesh color			Firm (N)	SSC (%)	TA (% malic)	IB (%)
	L	*a*	*b*	*L*	*a*	*b*				
Among all treatments										
Gala	ns	**	**	**	ns	*	*	ns	ns	ns
Red	ns	*	*	*	ns	ns	ns	ns	**	*
Fuji	ns	ns	**	ns	**	ns	ns	ns	**	**
Between control and 48C, 90-min exposure time										
Gala	ns	*	*	ns	*	*	*	ns	ns	ns
Red	ns	*	*	*	ns	ns	ns	ns	*	*
Fuji	ns	ns	*	*	*	ns	ns	ns	*	*
Between control and 49C, 50-min exposure time										
Gala	ns	*	*	*	ns	ns	*	*	ns	ns
Red	ns	*	*	*	ns	ns	ns	ns	*	ns
Fuji	ns	ns	*	ns	ns	ns	ns	*	*	ns
Between control and 50C, 30-min exposure time										
Gala	ns	*	ns	*	ns	*	ns	ns	ns	ns
Red	ns	*	*	ns	ns	ns	ns	ns	*	ns
Fuji	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* 0.05; ** 0.01.
Difference from control indicates damage.
SS, soluble solids; TA, titratable acidity; IB, internal breakdown; ns, not significant.

treatment, with apples treated at 48C for 90 min displaying 80% breakdown, and 27 and 17% for apples treated at 49C for 50 min and 50C for 30 min, respectively. The 50C treatment for 30 min tended to have less overall damage than the other two temperature treatments (Table 3). The least sensitive cultivar was Fuji, where no significant differences were found between those treated for 30 min at 50C and control apples. Gala, perhaps because of its lighter color, showed external and internal damage. Delicious apples displayed no external damage, but extremely high internal damage. The peel of Delicious apples is resistant to wear and may be the cause of little or no external peel damage.

After 60 days of RA storage, all fruits regardless of cultivar were damaged beyond retail consideration, and no measurements were taken. Enhanced fruit respiration as a result of heating may have caused fruit degradation and the rapid decline in fruit quality after RF treatment. Fruit damage has been reported on numerous occasions for various treatments intended to meet quarantine requirements (Chapman 1940; Kenworthy 1944; Lay-Yee 1993; Drake and Moffitt 1998). This combination treatment would not be suitable for fruits in long-term cold storage.

CONCLUSIONS

Pretreating apples with RF energy before hot water submersion reduced efficacy exposure time compared to previous vapor heat treatments (Neven *et al.* 1996). However, apples are heat sensitive, and future thermal treatments are more likely to be successful with Fuji, Delicious and other dark cultivars rather than the pale-skinned cultivars. Future refinements should emphasize development of techniques that increase heat resistance in fruits and high-temperature (51C) short-duration treatments because of their high efficiency (>99.39% mortality) while maintaining good fruit quality. More larvae will need to be treated in order to demonstrate quarantine security. However, the final treatment will take less than an hour, which is more efficient than any current or anticipated postharvest treatment for apples.

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