

# Evaluation of Radio Frequency–Hot Water Treatments for Postharvest Control of Codling Moth in ‘Bing’ Sweet Cherries

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**SUMMARY.** Quarantine regulations require domestic sweet cherries (*Prunus avium*) exported to Japan to be treated to control codling moth [*Cydia pomonella* (Lepidoptera: Tortricidae)]. The current procedure, methyl bromide fumigation, may be discontinued because of health, safety, and environmental concerns. To examine a potential alternative method, ‘Bing’ sweet cherries were each infested with a codling moth larva, submerged in a 38 °C water bath for 6 minutes pretreatment, then exposed to various temperatures generated by radio frequency and held at that temperature for different times: 50 °C for 6 minutes, 51.6 °C for 4 minutes, 53.3 °C for 0.5 minutes, and 54.4 °C for 0.5 minutes. Insect mortality was evaluated 24 hours after treatment and fruit quality was evaluated after treatment and after 7 and 14 days of storage at 1 °C. No larvae survived at the 50 and 51.6 °C treatments. Fruit color of non-infested cherries was darkened as temperature increased. Stem color was severely impacted after 7 days of storage, even in a warm water bath of 38 °C for 6 minutes, as was fruit firmness at the same treatment. Fruit quality loss increased after 14 days of storage, compared to after 7 days of storage. The amount of pitting and bruising of cherries increased with temperature and again this increase was more evident after 14 days of storage.

Japan is a primary market for exports of fresh sweet cherries from the Pacific states. Even though larvae of the codling moth may not occur naturally in cherries (Hansen and Lewis, 2003; Hansen et al., 2003; Wearing and McLaren, 2001; Wearing et al., 2001), quarantine regulations require that domestic sweet cherries must be fumigated with methyl bromide before export to Japan (Hansen et al., 2000; Moffit et al., 1992). However, the future of methyl bromide is uncertain because of environmental health concerns, and international agreements restrict the production and use of this product (United Nations Environmental Programme, 1992). The U.S. Environmental Protection Agency (2004) has exempted the production and import of methyl

bromide for selected quarantine and phytosanitation uses for 2005, but these exemptions are not routine and must be negotiated yearly. To continue to export sweet cherries, alternatives to methyl bromide fumigation must be developed.

Thermal treatments, particularly those initiated by radio frequency (RF), have been proposed (Ikediala et al., 1999, 2002; Tang et al., 2000; Wang et al., 2003). The advantages of RF are that it is very fast, can penetrate fruit to the core, does not involve dangerous chemicals, and leaves no residues. The disadvantages of RF are the circuit-line requirements for installation and non-uniformity of heating. Hansen et al. (2004b) calculated the amount of heat needed to control codling moth larvae in cherries, but reported fruit

damage. Feng et al. (2004) used hot water to control codling moth that had artificially infested, freshly harvested California ‘Bing’ cherries, which maintained acceptable fruit quality for only a short period. If fruit injury could be reduced by faster heating, then further evaluation was needed to identify the time–temperature parameters used in RF–hot water bath combinations to effectively control codling moth larvae and to conduct quality tests on these treated fruit. The objectives of our study were to identify the time–temperature parameters needed for efficacy and to evaluate fruit quality at these settings.

## Material and methods

**FRUIT INFESTATION.** Codling moth larvae came from the colony reared at the USDA-ARS Yakima Agricultural Research Laboratory in Wapato, Wash., where they were maintained >300 generations on a soy–wheat germ–starch artificial diet at ~27 °C, 40% to 58% relative humidity (RH), with a 16-h light/8-h dark photoperiod (Toba and Howell, 1991). Third instars were used to infest fruit, which is the required life stage for evaluation in previous quarantine tests of codling moth on cherries exported to Japan (Hansen et al., 2000). Mature ‘Bing’ cherries were harvested from three orchards located in Washington state (Yakima, Wenatchee, and Stelmilt Hill). Cherries were transported on the day of harvest to the USDA-ARS Yakima Agricultural Research Laboratory (Wapato, Wash.) and treated separately according to location the following day. Each of 50 fruit per treatment replicate was infested with a larva at the stem end, and then every infested fruit was held overnight in a controlled-environment room at 25 °C within a separate, sealed 1-fl oz cup to allow larval penetration in the fruit. Potential treatments based on set temperature durations, and those at the same temperatures but at reduced time periods, were rejected if any survivor was found that resulted in

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Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
0.7457	horsepower	kW	1.3410
2.5400	inch(es)	cm	0.3937
25.4000	inch(es)	mm	0.0394
1000	mmho/cm	µS·cm <sup>-1</sup>	0.0010
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

**Table 1. Survivorship of third instar codling moth infesting Washington state cherries (one larva per fruit) heated in a radio frequency unit after submersion in 38 °C water bath for 6 min and held at set temperatures<sup>z</sup> for specific times.**

Temp (°C)	Time (min)	Replicates <sup>y</sup> (no.)	Total treated (no.)	Live (no.)	Live (%)
24 <sup>s</sup>	6	10	500	462	92.4
38 <sup>w</sup>	6	10	500	467	93.4
50	4	4	200	0	0
50	5	4	200	0	0
50	6	10	500	0	0
51.6	2	3	150	0	0
51.6	3	4	200	0	0
51.6	4	6	300	0	0
51.6	6	2	100	0	0
53.3	½	7	350	1	0.3
53.3	1	2	100	0	0
54.4	½	6	300	8	2.7
54.4	1	3	150	1	0.7

<sup>s</sup>(1.8 × °C) + 32° = °F.

<sup>w</sup>50 larvae per replicate.

<sup>x</sup>Untreated control.

<sup>y</sup>Pretreatment control.

unequal replication among the treatments (Table 1).

**EXPERIMENTAL UNIT.** Tests were performed in a 12-kW Fastran Radio Frequency heater/dryer with an E-200 control panel (Strayfield International Ltd., Wokingham, U.K.), with the frequency set at 27.12 MHz (Hansen et al., 2004a). Energy was induced between the electrodes by a high-energy RF oscillator (Tang et al., 2000; Wang et al., 2001). The maximum electrical current was 2 amperes based on the 12-kW power capacity of the unit. Power applied to the target material was adjusted by lowering or raising the top electrode, changing the dimensions of the target, and by varying the amount of mass (load). Because metal would interact with the electromagnetic field, material exposed to radio frequency was restricted to vegetable matter, water, and polypropylene plastic.

**TREATMENTS.** In preparation for treatment, cherries were placed in a cotton organandy mesh bag and the opening sealed with rubber bands. Infested fruit were treated directly out of the holding room, exposed to a pretreatment based on fruit heating studies to reduce fruit injury (S.R. Drake et al., unpublished), heat treated, and efficacy evaluated the treatment the following day. For each treatment, 50 cherries in bags were placed into a specially built polypropylene tank (17.5 cm high and 27 cm in diameter) holding 10 L of 38 °C tap water. Water circulated within the tank by the use of a two-speed, 1.5-horsepower Century Lasar Pool/Spa

Motor Pump (Aqua-flo Inc., Chino, Calif.) located outside the unit. Water conductivity was adjusted to 450 to 475  $\mu\text{S}\cdot\text{cm}^{-1}$  by adding 2 mL of sodium hypochlorite and about 5 mL of calcium chloride. Fruit were held in the warm water for 6 min before RF exposure to increase fruit pulp temperature before treatment (the pretreatment).

Internal fruit temperatures (2 cm deep) were measured by inserting a fiber optic transducer probe with 0.12 °C resolution (model FOT-L/CRM/3m; FISO Technologies Inc., Sainte-Foy, Que., Canada), in each of two cherries, near the stem into the middle of the cherry pulp halfway between the pit and the outer skin of the fruit. A third probe was used in the tank to measure water temperature. Data acquisition was performed using the FISO Commandersoftware (FISO Technologies Inc.) with temperatures measured every 0.05 s.

All RF treatments were performed starting with a gap of 24 cm with initial amperage at 1.9 to 2.0. The RF machine then automatically adjusted the gap to around 25.5 cm to maintain the maximum power. Once the cherry on the fiber optic probe with the lower temperature reached the target temperature (mean  $\pm$  SE of difference between two cherry temperatures =  $1.0 \pm 0.1$  °C,  $n = 69$ ), RF heating was stopped. The upper electrode plate was then raised to a gap of 40 cm, and cherries were left in circulating water for the predetermined holding period. The treatments consisted of

four temperatures at different holding periods: 50 °C for 4, 5, or 6 min; 51.6 °C for 2, 3, 4, or 6 min; 53.3 °C for 0.5 or 1.0 min; 54.4 °C for 0.5 or 1 min. Temperatures were based on earlier experimental studies and the durations were the estimated minimum times from Wang et al. (2002) and Hansen et al. (2004b). Treatments were compared to two controls: cherries circulating in tap water at 25 °C for 6 min and at 38 °C for 6 min. After treatment, fruit were cooled for 8 min in a 0 °C water bath.

**FRUIT QUALITY EVALUATIONS.** To simulate commercial conditions (Ikedia et al., 1999; Hansen et al., 2000; Shellie et al., 2001), fruit quality evaluations were determined after 1 and 2 weeks of cold storage at 1 °C and 90% RH following treatment as previously described for the efficacy tests. Three replicates per treatment were used with 30 fruit/treatment/replicate. The quality evaluations consisted of objective and subjective color, firmness, soluble solids content (SSC), titratable acidity (TA) and evaluation for defects (visible burn, rots, internal breakdown). Objective color of the fruit and stems was determined with a colorimeter (ColorFlex, model 45/0; Hunter Assoc., Reston, Va.) using the L\*, a\*, b\* system and calculated hue values (Hunter and Harold, 1987). Firmness was determined using the Universal TA-XT2 texture analyzer (Texture Technologies, Scarsdale, N.Y.) equipped with an 11-mm probe with a penetration distance after contact of 7 mm and values were expressed in Newtons. SSC of the fruit were determined with an Abbe-type refractometer with a sucrose scale calibrated at 20 °C. Acids were titrated to pH 8.2 with 0.1 N sodium hydroxide and expressed as percentage of malic acid. Visual defects of the fruit (burn, pitting, bruising, rot, internal breakdown) and stem (burn) were evaluated by laboratory personnel and reported as percent of the total fruit or stem with any defect. Subjective quality (color) of both fruit and stem was evaluated by the same laboratory personnel and graded on a scale of 1 to 4 (1 = excellent; 2 = good; 3 = fair; 4 = poor). Fruit or stems receiving subjective scores >2.5 were considered unacceptable.

**DATA ANALYSIS.** Temperature and survival data were entered into Quattro Pro 10 spreadsheets (Corel Corp. Ltd., Ottawa, Ont., Canada).

**Table 2. Fruit quality values of mature ‘Bing’ cherries after radio frequency exposures to reach treatment temperatures<sup>z</sup> and held for set times.**

Source <sup>y</sup>	Treatment		Week	Fruit			Stem			SSC (%) <sup>v</sup>	Pit <sup>u</sup>	Bruise <sup>u</sup>
	Temp (°C)	Time (min)		L <sup>x</sup>	Hue <sup>x</sup>	Vis. <sup>w</sup>	L <sup>x</sup>	Hue <sup>x</sup>	Vis. <sup>w</sup>			
1	25 <sup>t</sup>	6	1	22.9	15.7	1.0	26.7	95.1	1.6	20.8	1.0	1.0
	38 <sup>s</sup>	6	1	23.6	14.9	1.3	25.1	86.4*	1.8	20.9	1.0	1.0
	50	6	1	23.9	15.0	1.1	20.6**	72.4*	2.5**	20.4	1.0	1.0
	51.6	4	1	24.6* <sup>r</sup>	13.3*	1.3*	19.5**	63.2**	3.0**	20.2	1.1	1.2
	53.3	0.5	1	24.8*	10.8**	1.3*	17.6**	58.2**	3.5**	20.6	1.2	1.1
	54.4	0.5	1	24.1	14.0*	1.4*	18.3**	58.5**	3.7**	20.5	1.2	1.1
	25	6	2	22.9	12.2	1.1	25.7	90.3	2.0	20.5	1.1	1.0
	38	6	2	22.8	6.6*	1.8*	23.4	78.6	2.6**	20.5	1.5	1.0
	50	6	2	23.3	8.3*	2.1**	18.7**	67.7**	2.8**	19.7	1.8*	1.6**
	51.6	4	2	23.6	8.6**	2.5**	18.6**	62.6**	3.4**	20.0*	1.9**	2.0**
2	53.3	0.5	2	24.1	6.1**	2.8**	17.6**	55.7**	4.0**	20.2	2.6**	2.4**
	54.4	0.5	2	25.6*	8.1	2.4**	17.3**	54.4**	4.0**	19.5**	2.3*	2.1**
	25	6	1	22.7	17.2	1.7	26.6	103.7	1.6	23.1	1.1	1.0
	38	6	1	21.8	19.0*	1.2	25.1	93.3*	2.3*	21.3*	1.0	1.0
	50	6	1	23.7	17.8	1.4	22.5*	90.1*	2.5*	22.1	1.2	1.3
	51.6	4	1	25.6**	22.0	2.0**	19.3**	71.1**	3.3**	23.1	1.2	2.0*
	53.3	0.5	1	26.1**	19.1**	1.2	22.5*	85.5**	2.8**	22.4	1.1	1.2**
	54.4	0.5	1	26.3**	20.1*	2.1**	18.6**	64.6*	3.7**	22.0	1.4	1.8**
	25	6	2	24.7	14.0	1.6	27.4	103.8	1.9	23.1	1.0	1.0
	38	6	2	25.1	15.3	2.1*	23.1*	87.2*	2.9**	21.5*	1.3	1.3*
3	50	6	2	24.0	17.3*	2.3*	20.3**	78.4*	3.8**	22.3	1.8*	2.0*
	51.6	4	2	23.7	16.1	2.9**	17.9**	59.2**	4.0**	24.4*	2.5**	2.3**
	53.3	0.5	2	25.8	15.6	2.2*	20.1**	78.5**	3.7**	22.5	2.3**	1.5**
	54.4	0.5	2	24.9	15.5	2.8**	17.9**	60.3**	4.0**	22.4	2.5**	2.2**
	25	6	1	23.8	13.5	1.3	29.6	102.3	1.3	23.1	1.2	1.0
	38	6	1	24.6	12.5	1.4	23.5*	80.6*	2.5**	23.9	1.0	1.0
	50	6	1	24.4	15.1	1.1	22.6*	79.7*	2.8**	23.6*	1.1	1.0
	51.6	4	1	23.3	15.8	1.3	20.5**	70.0**	3.3**	22.6	1.3	1.1
	53.3	0.5	1	23.6	13.6	1.6	21.0*	69.1*	3.2*	22.5*	1.6	1.5**
	54.4	0.5	1	24.2	11.9	1.6	17.3**	49.7**	4.0**	22.9	1.5	1.1
3	25	6	2	20.9	19.5	1.2	28.4	100.9	1.6	23.2	1.1	1.0
	38	6	2	20.9	24.6	1.7	22.9*	76.2**	3.0**	23.7	1.5	1.2
	50	6	2	21.4	21.8	2.4**	20.1**	70.2**	3.8**	23.3*	2.2**	2.2**
	51.6	4	2	21.5	19.8	2.6**	18.1**	54.0**	3.7**	23.5	2.6**	2.3**
	53.3	0.5	2	21.5	24.6	2.8**	19.5**	63.8**	3.8**	23.0	2.8**	2.7**
	54.4	0.5	2	22.2**	25.1	3.2**	17.3**	51.9**	4.0**	22.3	3.2**	2.6**

<sup>z</sup>(1.8 × °C) + 32° = °F.

<sup>y</sup>Source (all Washington state): 1 = Yakima; 2 = Wenatchee; 3 = Stemilt Hill.

<sup>x</sup>Objective color determined with a colorimeter (ColorFlex, model 45/0; Hunter Assoc., Reston, Va.) using the L\*, a\*, b\* Hunter system.

<sup>w</sup>Vis. = visual observation of fruit quality; scale: 1 = excellent; 2 = good; 3 = fair; 4 = poor.

<sup>v</sup>SSC = soluble solids content.

<sup>u</sup>Pit/bruise = visual measurement of pitting and bruising; scale: 1 = excellent; 2 = good; 3 = fair; 4 = poor.

<sup>t</sup>Untreated control.

<sup>r</sup>Pretreatment control.

<sup>s</sup>Comparison tests by *t* test between control (25 °C) and treated.

<sup>\*</sup>Significant at *P* ≤ 0.05 or 0.01, respectively.

Univariate statistics were calculated by using means procedure and analysis of variance was conducted on the fruit quality parameter data by using the general linear model procedure (SAS Institute, Cary, N.C.). Because quarantine security has a strict standard (no survivors in 30,000 treated population) (Hansen et al., 2000), efficacy data were summed by treatment.

## Results and discussion

Although Ikediala et al. (2002)

did initial studies on the effect of RF heating on codling moth in cherries, our study was the first attempt to define heating parameters for efficacious codling moth control (99.9986% mortality of treated population) and to record extensive fruit quality values for those treatments. The pretreatment at 38 °C used immediately before the radio frequency did not increase larval mortality (Table 1). No survivors were found from the 50 and 51.6 °C treatments, which had the longest exposure

times. No larvae survived the 53.3 °C treatment for 1 min, but larval survival for 53.3 °C for 0.5 min and both 54.4 °C treatments precluded both 53.3 and 54.4 °C procedures from becoming quarantine treatments.

Post-treatment fruit quality was evaluated after 7 and 14 d of storage at 1 °C. Fruit color of non-infested cherries darkened as temperature increased (Table 2). Fruit color values (*a* and *b*) also changed as temperature increased, but these changes would not be visible



to the consumer because hue values did not change with temperature. Stem color was severely impacted by heat generated by radio frequency. Stems in a warm water bath (38 °C for 6 min), a very mild heat treatment, darkened by 3.5 units (L values). More darkening was evident when stems were exposed to higher temperatures. This darkening of the stems was accompanied with a reduction in green color and significantly lower hue values. A change of one unit in color is visible to the human eye. Cherry firmness was reduced even with a mild heat treatment (38 °C for 6 min) and when cherries were exposed to higher temperature, loss of fruit firmness was very significant. Subjective quality evaluations of both cherry fruit and stem indicated that increased heat reduced both visual fruit and stem quality; after 2 weeks of storage this quality loss was even more evident. The amount of pitting and bruising of cherries increased with temperature and this increase was more evident after 2 weeks of storage. The same patterns of damage were observed for cherries from all sources, although those from Yakima seemed to have the most heat tolerant stems and those from Stemilt Hill had the most heat tolerant fruit (Table 2).

This study demonstrated the efficacy of using heat to control codling moth larvae infesting cherries. Thermal methods, including the use of radio frequency energy, have potential for replacing methyl bromide fumigation. However, all of the heat treatments used in this study, including the pretreatment at 38 °C for 6 min, resulted in unacceptable damage, particularly to the stems. Undamaged stems are an essential quality for the marketing of fresh cherries. Unless stem quality can be maintained, this procedure does not have any opportunity for success in its current form. Some procedure must be found to protect the stems during heat treatments. Fruit firmness also decreased at the higher temperatures, even during treatments that had larval survivors. Furthermore, treated fruit tended to deteriorate quicker than untreated fruit during storage. It is likely that increased respiration during the experiment resulted in accelerated fruit aging.

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