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Effect of radio frequency heating as a potential quarantine treatment on the quality of 'Bing' sweet cherry fruit and mortality of codling moth larvae

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Abstract

'Bing' sweet cherry (*Prunnus avium* L.) fruit quality and fifth-instar codling moth (*Cydia pomonella* [L.]) mortality were evaluated after radio frequency (RF) heating. The fruit were heated with radio frequency energy to four target temperatures (50, 52, 53 and 54 °C), held in the RF-heated water for various holding times from 0.5 to 6 min, and stored under simulated air or sea shipment conditions (5 °C for 24 h or 0 °C for 2 weeks, respectively) before quality evaluation. There was no significant effect on cherry color, decay or shrivel, and RF had only a slight effect on berry browning. Regardless of shipment, stem browning and berry pitting were affected by RF-heating. Cherry quality was most affected when fruit were treated with RF and stored to simulate sea shipment. Heating the fruit to 53 or 54 °C assured 100% codling moth larval mortality. Treatments that may provide quarantine security include heating fruit to 52 °C and holding for 4 min, 53 °C for 1.5 min or 54 °C for 1 min, but quality of the cherries following these treatments was only acceptable when fruit were stored to simulate air shipment.

Keywords: Heat treatment; Hot water; Lepidoptera; Phytosanitary; Quality

1. Introduction

'Bing' sweet cherry (*Prunnus avium* L.) fruit must be fumigated with methyl bromide as security against codling moth (*Cydia pomonella* [L.]) infestations for shipment from the U.S. to certain international markets. Methyl bromide fumigation can result in negative effects on cherry quality, especially stem color (Anthon et al., 1975; Hansen et al., 2000). In addition, regulatory and economical concerns regarding the future use of methyl bromide as a postharvest fumigant have increased interest in alternative quarantine treatments.

Gamma irradiation has been considered as an alternative quarantine treatment to control Queensland fruit fly in cherry fruit (Jessup, 1990). More recent studies have considered electron beam irradiation (Drake and Neven, 1997) and microwave treatments for codling moth disinfestation in cherries (Ikediala et al., 1999). Feng et al. (2004) suggested that hot water may provide potential quarantine treatments against codling moth infestations, but only if fruit were air shipped. In addition, their treatments did not reach Probit 9 security. Probit 9 security provides a 99.9968% mortality rate in an insect population or only one survivor out of 30,000 individuals in a population (Paull and Armstrong, 1994).

Radio frequency (RF) energy provides a potential method to rapidly heat cherry fruit and insect larvae, resulting in short heat treatments that may provide insect mortality with less effect on fruit quality. RF heating involves the direct interaction between RF wavelengths of energy and the dielectric properties of any water based body. As a consequence, there is molecular agitation and this movement generates heat within the fruit and the insects simultaneously. Among the methods used to study temperature effects on insect thermal mortality, the heating block system developed at Washington State University, Pullman (Wang et al., 2002a) heats the insects in

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a narrow space between two metal plates that can be heated at different rates, closely mimicking the heating rate generated by hot water, hot air treatments, radio frequency or microwave energy. RF energy has provided 100% insect mortality in walnuts without affecting nut quality (Wang et al., 2002c; Mitcham et al., 2004). Our objective was to determine if heating fruit with RF energy is a potential quarantine treatment for codling moth infestations in 'Bing' sweet cherries.

2. Materials and methods

2.1. Fruit quality analysis experiment

2.1.1. Fruit source

Cherry fruit were obtained from an orchard in Central California on May 28, June 3 and June 4, immediately after being harvested by a commercial crew. Fruit were harvested, packed under commercial conditions, and brought immediately to the Postharvest Laboratory at the University of California, Davis. Fruit were sorted visually for defects and for a uniform mahogany color and were treated on the day of harvest. A total of 600 cherries (25 mm in diameter) for each harvest or repetition were separated into 12 groups of 50 fruit each. Each group of fruit was placed on trays covered with plastic to maintain an 85–95% relative humidity around the fruit and held at 20 °C before being treated to assure uniform initial fruit temperature.

2.1.2. Treatments

Cherries were pre-warmed in a 38 °C saline water solution and then immediately heated with a 27 MHz, 12 kW batch RF machine (Strayfield International Limited, Workingham, UK). A 10 L polypropylene container, 30 cm in diameter and 20 cm in height (designed and manufactured by D. Slaughter, Dept. Biol. Agric. Eng., UC Davis), was used to hold the fruit (50 per treatment and replication) submerged in a circulating saline solution during pre-warming and RF exposure. The saline solution was used as a medium to avoid overheating of fruit at the contact points with other fruit and to assure heating uniformity by matching the dielectric properties of the fruit with the electrical conductivity of the water during the RF-heating process.

Preliminary testing indicated that holding the cherries in 38 °C water did not cause fruit injury, and the fruit interior warmed from 20 to 38 °C in about 6 min. By pre-warming the fruit, we could reduce the time required to RF heat the cherries to the target temperature.

For the pre-warming process, distilled water containing 50 $\mu L\,L^{-1}$ chlorine to avoid fungal contamination was heated in a large tank to a set point of 42 °C. The hot water was pumped into the 10 L container that would hold the cherries for the treatments; the hot water in the container was 37–38 °C because the tank and plumbing dissipated some of the initial heat. While the hot water was being pumped into the container, the cherries were placed in the container and when the water level in the container covered all the cherries and reached 20 cm height, a centrifugal transfer pump (245 W, 0.0031 $m^3\,s^{-1}$, ATM Bronze Centrifigal Pump, Franklin Electric Bluffton, Indiana) was turned on to circulate the water and fruit inside the container, and a timer was set for a 6 min pre-warming. While the cherries were circulating, 2.3 g of NaCl was added to the water to produce the saline solution with an electrical conductivity of 45–47 mS/m (0.025% NaCl). Although the cherry fruit generally sink in the saline solution, a polypropylene lid was used to cover the container and assure fruit submersion in the saline solution during the RF-heating process.

The saline solution and fruit temperatures were monitored during the pre-warming and RF-heating process using a fiber-optic probe (Fiso Technologies Inc., Que., Canada) with ±0.5 °C accuracy and response time of less than 1.5 s. The fiber-optic probes were used instead of thermocouple probes during the RF treatments to avoid electromagnetic noise and interaction between the metal plates of the RF machine and the electromagnetic fields. Fruit temperature was monitored in two additional cherries during treatment, one on each side of the treatment tank. Only two cherries were monitored because preliminary tests had shown that the temperature difference among the cherries was ±1 °C from the target temperature. A fiber-optic probe was inserted near the cherry stem into the middle part of the cherry cheek halfway between the pit and the outer skin of the fruit. The probe was attached with masking tape to the stem of the cherry to assure that it would not fall off during the treatment. In addition, one fiber-optic probe was placed at the same level as the fruit probes to monitor water temperature during treatments.

Based on the thermal death time curve for fifth-instar codling moth developed at Washington State University (Wang et al., 2002b, 2004), we chose a total of 10 RF-treatments and two controls (Table 1). During RF-treatment, fruit were heated from 38 °C to 50, 52, 53 or 54 °C and the RF-heating time to reach the target temperature was approximately 1–1.5 min. After reaching the target temperature, the fruit were held in the hot water for various holding times designed to provide 100% insect mortality (phytosanitary control) and extra holding times to test the upper limit of fruit tolerance to treatments that may approach Probit 9 security (99.9968% mortality rate). Control treatments consisted of cherries circulating in saline water at 24 or 38 °C for 6 min.

Table 1
Target temperature and holding times for cherry tolerance and insect mortality experiments

Target temperature (°C)	Holding times (min)		
24 (control)	6		
38 (control)	6		
50	4	5[a]	6
52	2[a]	3	4
53	1[a]	1.5	
54	0.5[a]	1	

[a] Thermal-death-time necessary to reach 100% mortality of 600 fifth-instar codling moth larvae.

Immediately after RF treatment, fruit were hydrocooled by pumping 0 °C water into the treatment container while simultaneously draining the hot water until the water temperature decreased to 10 °C. Fruit were then transferred to an ice bath that was maintained at 0 °C and held for 8 min at which time the internal fruit temperature ranged from 3 to 6 °C.

After hydrocooling, cherries were removed from the water, gently blotted dry on cheese cloth and stored in vented plastic bags under simulated transport conditions. From each treatment, half of the cherries (25 fruit) were stored at 5 °C for 24 h to simulate air shipment (AIR). The other 25 fruit were stored at 0 °C for 2 weeks to simulate sea shipment (SEA). After storage and prior to quality evaluation, cherries were transferred in the vented plastic bags to 20 °C with 90–95% relative humidity for 15–20 h to simulate distribution and retail conditions.

2.1.3. *Quality evaluations*

Fruit skin color was measured on both cheeks of each fruit using a Minolta Chromameter (model CR-300; Ramsey, N.J.). The Chromameter was calibrated with a Minolta white calibration plate (No. 22633012, with coordinates $Y = 92.90$, $x = 3134$, $y = 3192$). The readings were reported as hue values, where color angles are classified as red (0°), yellow (90°), green (180°), blue (270°) or an intermediate color between any pair of these colors. Fruit firmness was measured non-destructively as deformation force (FirmTech1, BioWorks, Stillwater, Okla).

Cherry quality was assessed based on visual evaluation of stem browning, berry browning, pitting, skin cracking, decay and shrivel, and an overall quality condition score. Stem browning was evaluated on a scale of 0–4: 0 = none, 1 = 1–25%, 2 = 26–50%, 3 = 51–75%, 4 = 76–100% brown. Berry browning, pitting and decay were evaluated on a scale of 0–3: 0 = none, 1 = slight (1–25% of the fruit surface), 2 = moderate (26–50% of the fruit surface), 3 = severe (>50% of the fruit surface). Skin cracking was evaluated on a scale of 0–3: 0 = none, 1 = slight (1–2 mm long, shallow crack), 2 = moderate (2–4 mm long, deep crack), 3 = severe (>5 mm long, deep crack). Shrivel was evaluated as 0 = none or slight shrivel or 1 = obvious shrivel. Overall condition was evaluated by visual marketability scores ranging from 0 = very good, 1 = some damage but still good and marketable, 2 = obvious damage but still marketable, 3 = unmarketable. For all subjective scales, values beyond 1.5 were considered as the limit for marketability based on fruit quality, except for stem browning, where 2 was considered as the limit for marketability.

2.2. *Infested cherry experiment*

In a separate test, fruit obtained from a commercial orchard were stored at 0 °C prior to treatment. The two control treatments and the 10 RF treatments used for the quality analysis were also tested with infested cherry fruit (Table 1). Fifth-instar codling moths were reared at USDA, ARS Fresno, California and obtained 1 day before treatment. There were five replications of each treatment with infested cherries conducted on separate days.

For each replication, at least 600 cherries were sorted for good condition and each fruit placed individually into a plastic cup (29.5 cm^3) with one codling moth per cup. Cups were sealed with lids that had two or three perforations to permit gas exchange, and held overnight at 20 °C to allow the larvae to go inside the cherry flesh.

Each treatment and replicate had a total of 50 cherries, which were divided and placed into five silk mesh bags (20 cm × 10.5 cm), 10 cherries per bag. For each bag, we selected only infested cherries in which the larva was inside the cherry flesh. If the total count of infested fruit inside the bag did not sum up to 10, we inserted non-infested cherries to bring the total to 10. The bags were closed with a rubber band to assure that if an insect came out of the cherry it would remain inside the bag. The treatments were performed under the same conditions as described for the quality analysis experiment and the fruit temperature was monitored with two additional fruit attached to the fiber-optic probes as described for the quality analysis experiment. After treatment and hydrocooling, the 10 cherries from each silk bag/treatment were transferred to a plastic container (250 g). Larvae outside the fruit were separated and the cup was held overnight at 20 °C before mortality determination.

The following day, the cherries from the plastic containers were examined and opened to find the larva. The total count of larvae inside or outside the cherry after treatment was determined. Larval death count consisted of classifying larvae as dead or alive. Larvae were considered dead if there was no movement when prodded with a blunt instrument. Percent mortality was calculated by the total number of dead larvae per treatment divided by the total number of larvae recovered per treatment and multiplied by 100. Percent mortality of larvae inside the cherry or outside the cherry was also calculated.

2.3. *Statistical analysis*

For the cherry quality experiment, the experimental design consisted of two shipment procedures (air and sea) and 12 treatments (Table 1). A two-way factorial design was employed for shipment/treatment combination using the 25 fruit from each shipment/treatment combination as subsamples for each replicate. There were a total of three replicates in the experiment; each harvest was considered as a replication. Fruit quality characteristics were measured for each sub-sample and the average was used as the replicate; each quality trait was considered fixed. Analysis of variance was computed by SAS Version 8.0 (SAS Institute Inc., Cary, NC). Least square means were employed because of missing values in some treatments. Multiple mean comparisons were performed using Tukey–Kramer adjustment which was necessary due to the large number of mean comparisons required, and the need to maintain a low experiment wise error rate ($\alpha = 0.05$) for the experiment.

The infested cherry experiment consisted of 12 treatments (Table 1) with five replications. Data were analyzed by a completely randomized design using SAS Version 8.0 (SAS Institute Inc.). Multiple mean comparisons were performed using Tukey–Kramer adjustment.

3. Results and discussion

3.1. Quality evaluation

Pre-warming the fruit for 6 min allowed a short (1–1.5 min) RF-heating time to reach the target temperature (Fig. 1). During the RF-heating, the fruit and saline solution were heated from 38 °C until the lowest temperature of the two stationary fruit reached the assigned target temperature (Table 1). We choose to monitor the temperature only on two additional cherries since preliminary tests had shown that the temperature variation among the fruit was ±1 °C from target temperature and to avoid puncturing the fruit to avoid breakdown during simulated transport conditions. The RF-heating rate was linear and rapid (12 ± 1 °C/min). This short RF-heating time may result in less damage to the fruit from heat. In contrast, hot water treatments required 5–10 min at 50–54 °C, respectively, to assure 100% insect mortality (Feng et al., 2004), and approximately 5 min microwave heating time was needed to reach 55 °C without pre-warming the fruit to obtain 98% larval mortality (Ikediala et al., 1999). While the hot water treatments required longer times to reach target temperatures, RF energy treatment required only a few minutes, reducing fruit exposure to heat. Furthermore, immediate hydrocooling of the fruit permitted rapid heat alleviation and was necessary to promptly store the fruit at low temperatures (0 or 5 °C) in plastic bags without added condensation.

The main effect of treatment was significant for stem browning, berry browning, pitting, skin cracking, overall condition and fruit firmness (Table 2). Regardless of the RF-treatment, shipment type affected the overall condition, color and firmness of the fruit resulting in fruit with lower overall condition score, darker skin color and lower fruit firmness following simulated sea shipment compared to simulated air shipment (Tables 2 and 3). There was a significant interaction between shipment and treatment for stem browning, berry browning and pitting and the results are presented as the mean values following air or sea shipment conditions where Tukey–Kramer analysis showed only main effects of

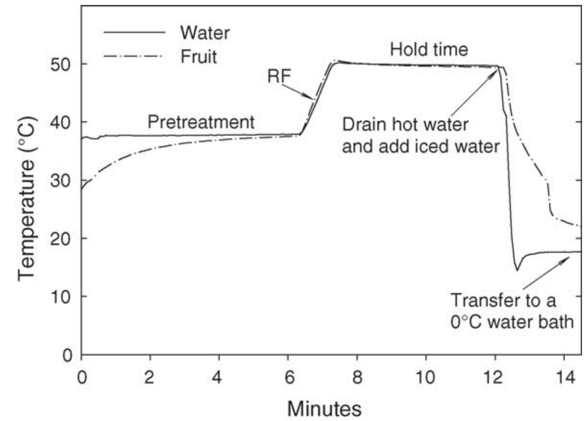

Fig. 1. Heating rate of water and fruit during the pretreatment and RF treatment (50 °C for 5 min). Fruit were then placed in iced water (0 °C) for hydrocooling.

the treatments (Table 2). Interaction effects are shown in Figs. 2–4.

Fruit from the sea shipment had a significantly higher level of stem browning compared to fruit from the air shipment (Fig. 2). Among the treatments, RF-heating resulted in significant stem browning compared to control fruit. The highest level of stem browning was produced by heating cherries to 54 °C with a hold period of 1 min, which gave similar stem browning to heating cherries to 53 °C for 1.5 min or 52 °C for 3 or 4 min; suggesting that the longest holding times at higher target temperatures produced more stem browning following sea shipment (Fig. 2). These results agree with results from hot water-treated cherries, where Feng et al. (2004) reported that higher temperature treatments resulted in greater stem browning. Treating cherries with microwave energy (915 MHz) also affected stem greenness more with increasing temperatures (Ikediala et al., 1999). In contrast, there was a low value for stem browning when fruit were air shipped, with no significant differences among RF-heated fruit (Fig. 2). There was also a lower level of stem browning in the control treatments during air shipment compared to control treatments during sea shipment, suggesting that the length of sea transportation limits cherry quality. Among the sea shipment treatments, there were significant differences in stem browning between the controls and the treatments with the highest temperatures and longest exposures, 50 °C for 6 min, 52 °C for 3 and 4 min, 53 and 54 °C for 1 min (Fig. 2), with no significant differences among all RF treatments.

Skin color was significant for shipment type at $P < 0.0007$, but not for treatment (Table 2). Fruit firmness was signif-

Table 2
ANOVA P values ($\alpha = 0.05$) for the effect of shipment, treatment and shipment × treatment interaction for cherry quality traits

	Stem browning	Berry browning	Pitting	Skin cracking	Decay	Shrivel	Overall condition	Hue	Firmness
Shipment (S)	<0.0001[a]	<0.0001	<0.0001	0.9403	0.1095	0.0249	<0.0001	0.0007	<0.0001
Treatment (T)	0.0002	0.0004	<0.0001	<0.0001	0.6315	0.7463	<0.0001	0.0915	0.0414
$S \times T$	0.0276	0.0461	0.0153	0.5111	0.6315	0.7463	0.5321	0.3870	0.2538

[a] $P \leq 0.05$ indicate a significant effect at the 5% level from the shipment, treatment or $S \times T$ interaction on the quality trait.

Table 3
Effect of treatment within shipment for cherry color (hue°), firmness, skin cracking and overall external condition of 'Bing' sweet cherries following radio frequency treatment

Treatment		Hue		Firmness (N)		Skin cracking[a]		Overall condition[b]	
Temperature (°C)	Time (min)	Air	Sea	Air	Sea	Air	Sea	Air	Sea
24	6	18.8a[c]	18.3c	2.9a	2.9a	0.0d	0.0c	0.2c	1.0c
38	6	19.3a	18.9bc	2.7a	2.9a	0.0d	0.0c	0.1c	1.1bc
50	4	18.9a	20.1abc	2.7a	2.3b	0.4abc	0.4ab	0.8ab	1.9ab
	5	19.1a	21.2a	2.6a	2.3b	0.7a	0.5ab	0.9a	2.1a
	6	20.2a	20.3abc	2.6a	2.3b	0.6a	0.6a	0.9a	2.4a
52	2	19.4a	19.7abc	2.8a	2.3b	0.2bcd	0.3abc	0.4bc	1.7abc
	3	19.7a	20.2abc	2.5a	2.4b	0.5abc	0.4ab	0.8ab	2.1a
	4	19.5a	20.5ab	2.6a	2.3b	0.5ab	0.5ab	0.9a	2.1a
53	1	19.0a	20.7ab	2.9a	2.3b	0.1cd	0.3abc	0.6abc	1.8abc
	1.5	18.7a	19.8abc	2.8a	2.3b	0.2bcd	0.2bc	0.7ab	2.1a
54	0.5	18.7a	19.8abc	2.9a	2.4b	0.1cd	0.2abc	0.6abc	1.9a
	1	18.4a	19.8abc	2.9a	2.4b	0.2bcd	0.2bc	0.8ab	2.1a

[a] Skin cracking: 0 = none, 1 = slight, 2 = moderate, 3 = severe.
[b] Overall condition: 0 = very good, 1 = some damage but still good and marketable, 2 = obvious damage but still marketable, 3 = unmarketable.
[c] Mean separation using Tukey–Kramer adjustment. Different letters (a–d) indicate significant differences among treatments ($\alpha = 0.05$) within shipment.

icant for both shipment and treatment (Table 2). Although there were no firmness differences among the treatments for the air shipped fruit there were firmness differences among the treatments following simulated sea shipment. The fruit treated with RF were significantly less firm than the control fruit following simulated sea shipment (Table 3). However, fruit were significantly more firm with a lighter magenta color after air shipment than sea shipment, indicating that the fruit continued to ripen and senesce during storage.

Although sea shipment resulted in significantly higher berry browning than air shipment, heating fruit to target tem-

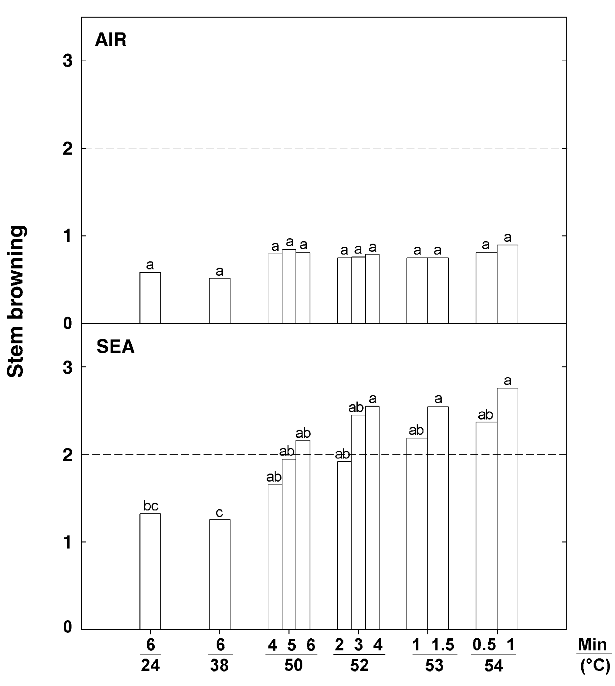

Fig. 2. Mean values for cherry stem browning following simulated air and sea shipment. Mean separation was performed using Tukey–Kramer adjustment. Different letters indicate significant differences within air and sea shipment ($\alpha = 0.05$). Values are from three replicates with 25 fruit per replicate. Fruit were evaluated with a scale of 0 = none, 1 = 1–25%, 2 = 26–50%, 3 = 51–75%, 4 = 76–100% brown. Values beyond 2 are considered unmarketable.

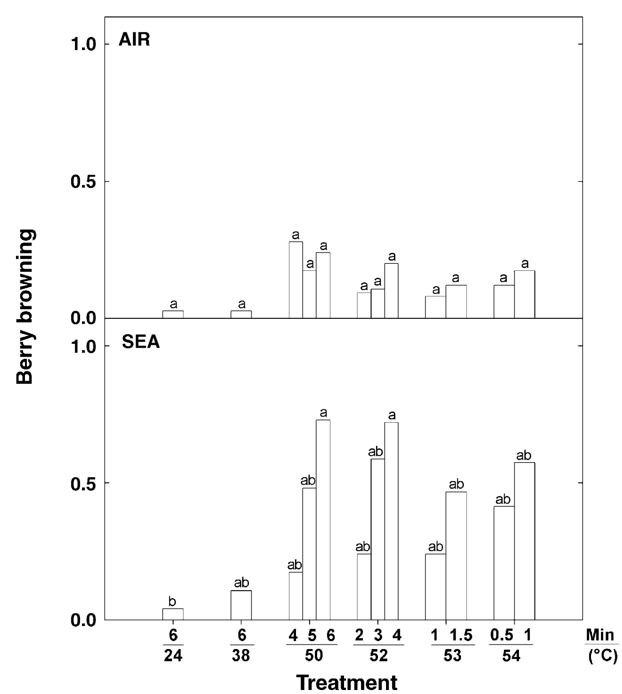

Fig. 3. Mean values for berry browning following simulated air and sea shipment. Mean separation was performed using Tukey–Kramer adjustment. Different letters indicate significant differences within air and sea shipment ($\alpha = 0.05$). Values are from three replicates with 25 fruit per replicate. Fruit were evaluated under a scale of 0 = none; 1 = slight; 2 = moderate; 3 = severe. Values beyond 1.5 are considered unmarketable.

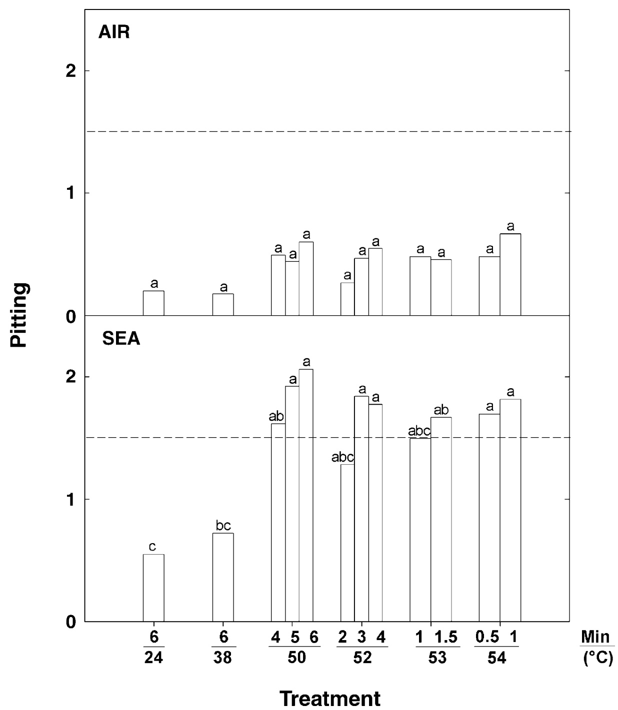

Fig. 4. Mean values for cherry pitting following simulated air and sea shipment. Mean separation was performed using Tukey–Kramer adjustment. Different letters indicate significant differences within air and sea shipment ($\alpha = 0.05$). Values are from three replicates with 25 fruit per replicate. Fruit were evaluated under a scale of 0 = none; 1 = slight; 2 = moderate; 3 = severe. Values beyond 1.5 are considered unmarketable.

peratures and holding for the shortest exposure times (50 °C for 4 min, 52 °C for 2 min, 53 °C for 1 min and 54 °C for 0.5 min) resulted in less berry browning regardless of the shipment used (Fig. 3). The highest level of berry browning was obtained when the fruit were heated to 50 °C for 6 min, but there was no difference with fruit heated to 50 °C for 5 min, 52 °C for 4 min or 54 °C for 1 min (Fig. 3), also suggesting that the longer exposures caused more damage to the fruit. However, berry browning from control or RF treatments, whether air or sea shipped, was very low and well below the limit for marketability (1.5).

Air shipped fruit had a lower level of pitting than sea shipped fruit (Fig. 4). For air shipment, there were no differences between the two controls and the RF-treated fruit (Fig. 4). The treatment that produced the least pitting was RF-heating to 52 °C and holding for 2 min, regardless of shipment type. When fruit were stored for sea shipment, there was significantly less pitting in the control fruit compared with the RF-treated cherries, but there were no differences among the RF-treated cherries (Fig. 4). Following sea shipment, when fruit were held in hot water for the longest exposures (50 °C for all exposures, 52 °C for 3 and 4 min, 53 °C for 1.5 min and 54 °C for 0.5 and 1 min) they had a higher level of pitting, and scored beyond the 1.5 limit for marketability. Feng et al. (2004) also found more pitting when fruit were held in hot water for longer exposure times.

The RF-heated cherries had significantly more skin cracking compared to the control fruit (Table 3). Regardless of shipment, the fruit that were held in hot water after the RF treatment for less than 3 min resulted in less berry cracking. However, despite these differences the RF treatments produced only slight berry cracking. The RF treatments had no significant affects on decay or shrivel (Table 2), the values for each being very low.

The overall condition of RF-treated fruit ranged from 1 to 1.6 on a 0–2 scale, across both shipments, but poor overall quality was mostly observed when fruit were stored for sea shipment (Table 3). Fruit maintained better quality after air shipment, and heating fruit to 52 °C for 2 min produced significantly less damage than other RF treatments (Table 3).

3.2. Infested cherry experiment

RF-heated cherries had greater than 90% total larval mortality while control mortality was less than 15% (Table 4).

Table 4
Fifth-instar codling moth mortality after radio frequency heating within cherry fruit.

Treatment		Total mortality (%)	Mortality inside cherry (%)	Mortality outside cherry (%)
Temperature (°C)	Time (min)			
24	6	14.0c[a]	6.7c	33.8b
38	6	12.9c	5.1c	19.9c
50	4	89.7b	81.3b	97.9a
	5	100.0a	100.0a	100.0a
	6	100.0a	100.0a	100.0a
52	2	99.3a	98.0a	100.0a
	3	99.3a	99.0a	100.0a
	4	100.0a	100.0a	100.0a
53	1	100.0a	100.0a	100.0a
	1.5	100.0a	100.0a	100.0a
54	0.5	100.0a	100.0a	100.0a
	1	100.0a	100.0a	100.0a

[a] Mean separation using Tukey–Kramer adjustment. Different letters (a–c) indicate significant differences ($\alpha = 0.05$) within columns.

Infested fruit that were heated to 50 °C for 5 or 6 min, 52 °C for 4 min or 53 and 54 °C at all exposure times resulted in 100% larval mortality. Heating the infested fruit to the lower temperatures (50 and 52 °C, for the shortest exposure times, 4 and 2–3 min, respectively) resulted in less than 100% mortality, showing the importance of holding the fruit at the target temperature for an accurate holding period to assure larval mortality. Because of the small size of cherry fruit, it was easy for larvae to move out of the fruit very fast in an effort to escape the elevated fruit temperatures during treatment. These larvae were found outside of the fruit in the hot water, but inside the silk bag. The movement of the larvae to the surface of the cherries was also a problem during microwave heat treatments (Ikediala et al., 1999). The larvae found outside the cherries were exposed directly to a heated water environment within the RF field, resulting in 100% larval mortality, except when water was heated to 50 °C for 4 min (Table 4), emphasizing the importance of RF-heating to the target temperature and holding time necessary to achieve 100% mortality (Table 1). However, achieving a 100% mortality rate provides for phytosanitary control, but does not guarantee Probit 9 security. To achieve Probit 9 security would likely require a slightly longer exposure time or higher temperatures.

4. Conclusions

Stem browning and pitting were the quality attributes most affected by RF-heating of Bing sweet cherries. When RF-treated fruit were stored to simulate sea shipment, stem browning and pitting were unacceptable and greatly affected the overall condition of the cherries. On the contrary, when fruit were stored for air shipment quality was acceptable for all attributes, with only slight damage. Regardless of the shipment period, heating cherries to 52 °C for 2 min caused the least pitting and resulted in acceptable amounts of stem browning.

Complete codling moth mortality was higher following treatment at the higher temperatures (53 and 54 °C) with shorter exposure times (0.5–1.5 min) than for treatments at lower temperatures (50 and 52 °C) with longer exposure times (2–4 min). Equivalent efficacy was achieved following treatment for the longest exposure times at the lower temperatures, and all durations at the higher temperatures. The higher mortality of the insects outside the cherries indicates that even if insects escaped from the cherry flesh during treatment, they would still be killed in the hot saline water. In addition, the shorter heat treatment with RF appears to be better tolerated by the cherries than the standard hot water treatments.

RF-heating treatments that may provide Probit 9 security, 52 °C with a holding time of 4 min and 54 °C for 1 min, resulted in poor fruit quality when cherries were stored for sea shipment, but quality was acceptable after air shipment. However, the specific heating requirements for Probit 9 control of codling moth larvae must be experimentally determined. All RF-treated fruit had acceptable quality following simulated air shipment indicating that the correct temperature and exposure combination during RF-heating may provide a potential alternative to methyl bromide quarantine treatments when fruit are air shipped and marketed promptly.

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