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Development of a saline water immersion technique with RF energy as a postharvest treatment against codling moth in cherries☆

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Abstract

'Sweetheart' sweet cherries (*Prunus avium* L.) immersed in 0.15% saline water were treated with radio frequency (RF) energy. The dielectric and ionic conductivity properties of the immersion water and that of fruit were matched to obtain a relatively uniform temperature distribution within and among fruits during RF heating. With immersion in saline water of 0.15% NaCl, the mean temperature of the water and that of the cherries differed by ≤ 0.6 °C, while the maximum temperature variation within and among fruits determined within 1 min after RF treatment completion was $< \pm 1.0$ °C of the set temperatures of 48 and 50 °C. The saline water immersion technique helped overcome the markedly high temperature differential problem within and among fruits, normally associated with treatments in air (without immersion) during RF heating. More than 99% mortality of the 200–400 codling moth larvae or 589–624 eggs was obtained at 50 °C when treated for between 7 and 10 min (heating 2–5 min and holding 5 min). Most quality parameters analyzed were better, or are comparable with methyl bromide fumigated fruit. Saline–water-immersion treatment in RF may be used to overcome the problem of slow conventional hot air or water heating, as well as the non-uniformity of temperature associated with electromagnetic heating in air, for developing alternative quarantine treatment for fruits.

Keywords: Quarantine; Heat treatment; Radio frequency; Microwave; Saline water immersion; Codling moth; Fruits; Cherries

1. Introduction

Insect pest infestation of commodities is a major problem in the production, storage, marketing and export of agricultural commodities. Many importing countries often require inspection certificates for absence of targeted live pests in a

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shipment after a pre-approved postharvest 'sanitation' treatment. Codling moth (*Cydia pomonella* L.) is a major quarantine pest of pome fruits, stone fruits and nuts entering Japan (Johnstone, 1967). Methyl bromide (MeBr) is currently used to fumigate these commodities to meet import quarantine security requirements. There is, however, heightened concern about the health and environmental risks associated with the use of MeBr and many other fumigants (Lacey and Chauvin, 1999). Thus, development of alternative treatments for disinfestation of fruits is urgently needed.

Different heat treatment methods using hot air, hot water, or microwaves have been studied as potential postharvest quarantine treatment alternatives to MeBr fumigation of fresh commodities for export (Sharp et al., 1991; Armstrong et al., 1995; Neven and Mitcham, 1996; Neven et al., 1996; Ikediala et al., 1999). Heat treatment can be an effective control against quarantine pests of certain commodities and is the basis of many approved phytosanitary protocols for tropical fruits such as papayas, mangoes and banana roots (Hansen, 1992). Many hurdles, however, remain to be overcome in order for heat treatments to become acceptable for heat-sensitive fresh commodities or fruits such as apples and cherries against codling moth. At doses lethal to the target insects, many of those treatment methods may have deleterious effects on the fruit quality mainly due to prolonged treatment times (Shellie and Mangan, 1996; Smith and Lay-Lee, 2000). Furthermore, some of the heat application methods resulted in non-uniform heating in fruits, or drying of cherry fruit stems, causing a reduction in general quality (such as firmness, fruit color, pitting, bruising, etc.) attributes (Ikediala et al., 1999). Heat transfer to the inner sections of foods during conventional heating is limited by the low thermal conductivity of food materials, thus necessitating prolonged heating in many cases. However, short treatment times are preferred not only from the perspective of quality, but also from the viewpoint of commercial applications. Yokoyama and Miller (1987) stressed the need for short exposure periods in order for this treatment to be incorporated in packinghouse handling procedures. The need to solve similar problems and achieve fast and effective thermal processing in food processing applications has resulted in the increased use of microwaves and radio frequency (RF) energies to heat foods. The concept of a high-temperature/short-time process has been used in commercial pasteurization and sterilisation of foods to improve quality retention (Lund, 1977). This concept was suggested for further research investigation for developing novel thermal quarantine treatments for fresh commodities (Ikediala et al., 2000a; Tang et al., 2000).

Headlee and Burdette (1929) demonstrated the possibility of exploiting electromagnetic energy for insect control. Since then, considerable research work has been conducted on the feasibility of RF and microwave energy for quarantine treatment against grain weevils (Nelson and Charity, 1972; Andreuccetti et al., 1994; Halverson et al., 1996). Hallman and Sharp (1994) and Nelson (1996) summarized research on the application of RF and microwave heat treatments to control pests in many postharvest crops and suggested combining RF or microwave energy with other treatment methods. Although some of the reported research results showed promise for control of certain pests, none has found practical application. Nelson (1991) observed that RF treatment for stored-grain insect control had been thoroughly explored but had yet to become practical or adopted by the industry because this treatment was more expensive than chemical controls in the past. Some other reported attempts at using RF or microwave treatments were not encouraging, mainly because the researchers did not fully understand and use the unique features of the RF and microwave heating characteristics. Orsat et al. (1999) emphasized the need for extensive research to establish product-RF field behaviour to promote the industrial use of this technology.

Under ideal conditions, RF and microwaves allow rapid heating throughout a food material without temperature gradients, provided the electric field is uniform and the sample is sufficiently homogeneous. In composite or heterogeneous materials, each component may heat at a rate dependent on its dielectric and thermal properties

(Nelson, 1991). In research on the effects of different variables on the effectiveness of RF and microwave exposures for controlling insects in infested agricultural commodities, information on the dielectric properties of the host material and pest is needed to estimate possible non-uniformity or preferential heating. Non-uniform heating in RF and microwave-treated fruits can influence the effectiveness of their application in insect control (Ikediala et al., 1999). Many methods for improving temperature uniformity in RF and microwave applications have been suggested, including appropriate power level, choice of frequency, and surface cooling (Bengtsson et al., 1970; Decareau, 1985; Virtanen et al., 1997). Bengtsson et al. (1970) attempted the use of water immersion in RF pasteurization of cured ham as a method of evening out electric field and improving the temperature distribution in ham.

Full immersion of fruits in water may not only help reduce the non-uniform distribution of the electric fields but also alter the core focussing in fruits as a result of the dielectric constant differences between water and fruit. By matching the dielectric and ionic conductivity properties of the fruit and immersion water, we theorized that it might be possible to obtain uniform temperature increases in both core and fruit surface.

The objective of this research was to evaluate the feasibility of combining an immersion technique with RF energy as a potential postharvest treatment against internal feeding insect pests in fruits. This paper reports the research findings and the effect of short-time RF-ionized water immersion treatments on the mortality of codling moth in cherries, and on the quality of the treated fruit.

2. Materials and methods

2.1. Selection of energy source

The US Federal Communications Commission (FCC) approved frequencies for Industrial, Scientific and Medical (ISM) application include 13.56, 27.12, and 40.68 MHz for RF, and 915 and 2450 MHz for microwave heating. RF and microwaves differ in aspects such as system design and penetration depth. The depth of penetration (D_p) at which the power of the incident wave is reduced to 1/e ($\sim$37%), increases with decreasing frequency as described by von Hippel (1954)

$$D_p = \frac{c}{4\pi f}\left[\frac{1}{2}\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)\right]^{-1/2} \quad (1)$$

where c is the speed of light in free space (3×10^8 m/s), f is the frequency (Hz), ε' is the dielectric constant, and ε'' is the dielectric loss factor. The penetration depths in apple computed from dielectric properties data reported by Ikediala et al. (2000b) are about 20.0, 4.4 and 1.4 cm at 27, 915 and 2450 MHz, respectively, and for cherries are about 9.8, 3.1, and 1.0 cm at the three frequencies. Therefore, there is generally no penetration depth limitations associated with RF heating of fruits in anticipated commercial applications in which single or multi-layer produce would be treated in continuous systems. In addition, earlier results on dielectric properties of apples, cherries and codling moth larvae (Ikediala et al., 2000b; Tang et al., 2000) suggested the possibility of obtaining preferential heating of codling moth larvae in cherries in the RF frequency range. In this study, we, therefore, selected RF as the energy source for thermal treatment.

2.2. Radio frequency (RF) heating system

A 6 kW, 27 MHz pilot-scale RF system (COMBI 6-S, Strayfield-Fastran Ltd., Wokingham, UK) was used for our studies. The RF system comprised a transformer, rectifier, electronic oscillator, an inductance-capacitance pair (tank circuit), and the work circuit made up of the applicator and the material to be treated (Fig. 1). The applicator was of the throughfield type with two parallel plate electrodes. The parallel plate electrodes, with sample placed on the lower electrode (tray base), acted as the capacitor in the work circuit. Height of the top electrode was adjustable to change the effective capacitance and the amount of RF power coupled to the sample. In general, the system was tuned in such a manner that a reduction in distance between the electrodes allowed the coupling of more power into the sample, thus enhancing the heating efficiency. However, the gap needed to be controlled above a critical minimum value to prevent arcing.

2.3. Determination of dielectric properties and ionic conductivity of materials

The dielectric and conductivity properties of a material determine penetration depth and heating rates, and knowledge of such data is important in developing dielectric heating applications (Bengtsson et al., 1970). Dielectric and conductivity property values of agricultural and biological materials are influenced by frequency, temperature, salt content, and moisture content. At RF frequencies of practical importance in food processing (RF 1–100 MHz), ionic conduction is the dominant loss mechanism (Ryynänen, 1995):

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega} \quad (2)$$

where subscripts 'd' and 'σ' stand for contributions due to dipole rotation and ionic conduction, respectively, σ is the ionic conductivity, ω is the angular frequency ($2\pi f$), and ε_0 is the permittivity of free space or vacuum ($\approx$ 8.854 pF/m).

Dielectric properties and ionic conductivity of cherries and ionized water at 27 MHz RF were also needed to determine the matching parameter of these materials. The dielectric constant and loss factor of cherries, codling moth larvae, and water solutions with different concentrations of salts

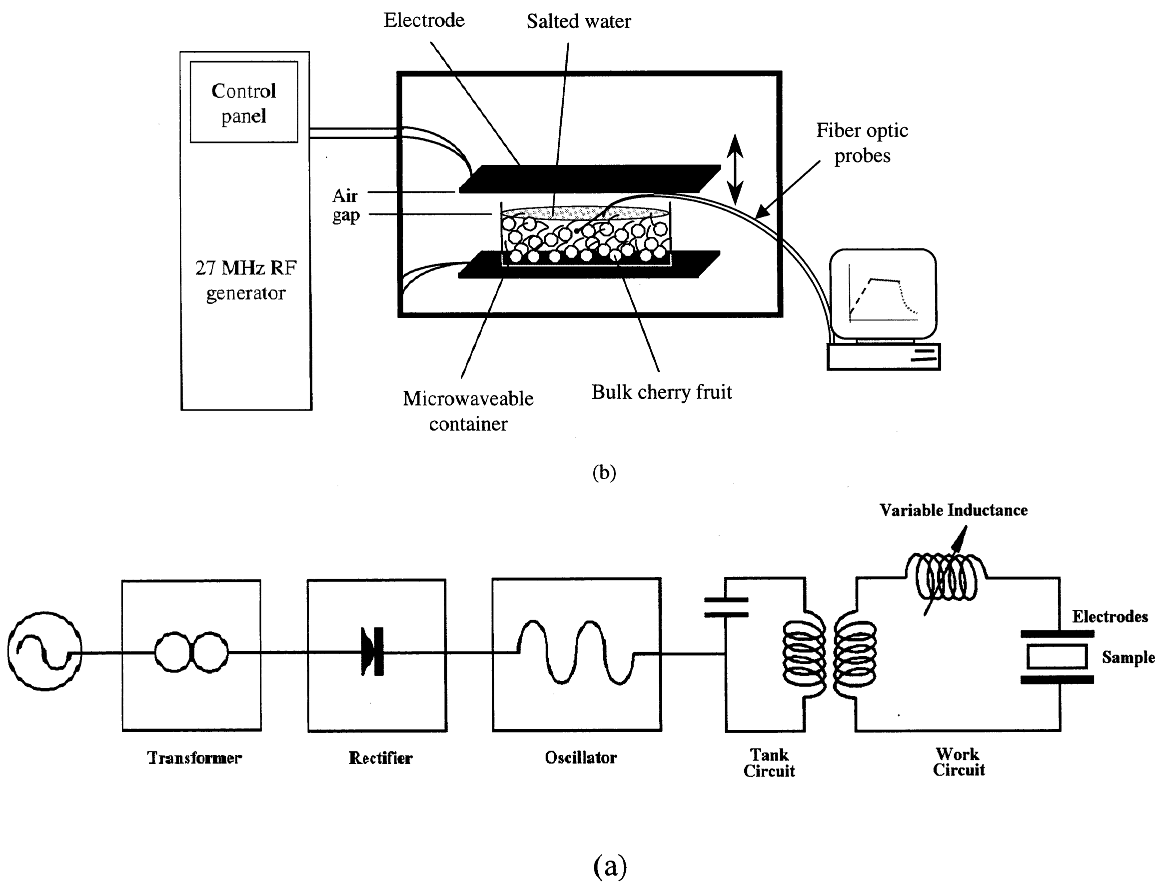

Fig. 1. Schematic diagram of a RF system (a); and a cross-sectional view of the RF applicator with cherries immersed in water during RF treatments (b).

(sodium chloride and anhydrous calcium chloride) were determined as a function of frequency between 0.3 and 3000 MHz, using the HP Dielectric Probe Kit (Model 85070B, Hewlett-Packard Corp., Santa Clara, CA). This system consisted of an open-ended semi-rigid coaxial probe connected to a HP 8752C Network Analyzer (Hewlett-Packard Corp., Santa Clara, CA). Care was taken during measurements to prevent air bubbles on the tip of the probe when immersed in the saline water.

The electrical conductivities of the above materials were also determined, using a benchtop conductivity meter (CON 500, Cole-Parmer Instruments Co., Vernon Hills, IL). These parameters were measured in replicates at room temperature.

2.4. Determination of suitable treatment conditions

We decided to treat fruit while immersed in a solution. The need to immerse fruit in water arose from attempts to treat both the insects residing outside fruit, as well as to reduce the core focusing of the electromagnetic energy in cherries observed in an earlier study (Ikediala et al., 1999). In that study, we observed severe core heating when fruit was heated in air. However, when fruit was heated while immersed in 1.0% saline solution, surface heating of the fruit occurred. Based on the values of the dielectric loss factor and ionic conductivity of the fruit, adding 0.10–0.20% salt to tap water (conductivity from 2.3 to 4.0 mS/cm) provided the desired matching in such a way that temperature of the immersion solution and fruit increased at a similar rate during RF heating. A 0.15% NaCl solution in tap water was used in experiments described in this study. During RF treatment, the gap between electrodes was set to 89–117 mm so that maximum power coupling was obtained without arcing. About 1.3 kW RF power was coupled when treating 100 cherries (size range 8–12 g per fruit) immersed in the saline water in 2.4-l microwaveable plastic containers. This yielded a specific power of about 0.5 kW/kg. In the RF treatment, sample temperatures were measured using three fiber optic probes (Photonetics Inc., MetriCor Div., Wakefield, MA), with one placed in the submersion water and the other two in randomly selected fruits close to the cherry pit and surface. The response time of these probes in water is 0.8 s, with an accuracy of ± 0.5 °C. RF heating was terminated when the water temperature reached a predetermined value. The time period to raise the sample and immersion saline water temperature from 21 °C to reach 48 to 52 °C ranged from 2 to 5 min. At the end of the RF treatment, the temperatures of six to ten randomly selected fruit, and the immersion water were measured within 1 min, using a type T thermocouple thermometer (Barnant 115, Barnant Co., Barrington, IL) to determine the temperature distribution among cherries.

2.5. Experimental plan

'Sweetheart' sweet cherries were obtained from commercial sources in Central Washington State. Fruit was infested at the USDA-ARS Yakima Agricultural Research Laboratory, Wapato, WA with 2nd or 3rd instar codling moth at a ratio of 1 larva per fruit. Infested cherries and controls were transported in open coolers to Washington State University (3 h driving distance), Pullman, WA for RF treatments. Before the treatments, cherries were held at room temperature ($\sim$22 °C) overnight. For each test run, 100 fruits were transferred into a 2.4 l plastic container ($19 \times 19 \times 9$ cm) and fully immersed in the saline water. Immature (thinning) apples were used for the tests with eggs because cherries were not available at that time. Although, this was not an ideal situation, the dielectric and conductivity properties of these immature apples and that of cherries were not much different (see Table 1). In addition, the size of the apples was about same or only slightly larger than the cherries. Those apples were exposed to adult moths to lay eggs on, with the number of eggs laid on a fruit varying between 15 and 65. When RF treating fruit with eggs, eight infested immature apples were combined with 92 non-infested cherry fruit in a treatment run. Container and content were placed in the RF field and treated for 2–5 min to achieve 48 or 50 °C final water temperature (Fig. 1b). At the end of RF

Table 1
Dielectric (~27 and 915 MHz) and conductivity properties of lossy materials at room temperature[a]

Dielectrics/materials	$\sigma \times 100$ (S/m)	27MHz RF		915MHz MW	
		ε'	ε''	ε'	ε''
Air	~0	1.0	~0	1.0	~0
Water					
Distilled/de-ionized	$0.5–1.1 \times 10^{-2}$	80.1 ± 0.2	0.03 ± 0.02	78.9 ± 0.02	3.7 ± 0.1
Fresh (fresh tap water,Pullman, WA, USA)	3.25 ± 0.1	79.6 ± 0.2	19.0 ± 0.8	78.8 ± 0.2	4.5 ± 0.0
+0.05% NaCl (common salt)	12.8 ± 0.4	80.3 ± 0.0	75.1 ± 0.5	78.9 ± 0.0	6.4 ± 0.0
+0.10%	22.7 ± 0.4	80.6 ± 0.0	126.6 ± 1.1	79.0 ± 0.0	8.2 ± 0.1
+0.15%	31.8 ± 1.8	81.5 ± 0.2	178.5 ± 0.5	78.7 ± 0.0	9.9 ± 0.0
+0.20%	40.5 ± 0.4	82.1 ± 0.7	226.4 ± 0.9	78.6 ± 0.0	11.5 ± 0.0
+0.25%	49.8 ± 0.0	83.6 ± 0.4	276.0 ± 0.5	78.6 ± 0.0	13.3 ± 0.0
+0.50%	92.2 ± 0.3	88.0 ± 0.0	524.3 ± 1.9	78.1 ± 0.0	21.8 ± 0.1
+1.0%	172 ± 1.5	99.2 ± 0.9	985.8 ± 2.7	77.3 ± 0.0	37.2 ± 0.1
+2.0%	330 ± 4.9	126.1 ± 1.6	1866 ± 2.0	75.7 ± 0.1	67.1 ± 0.0
+0.10% $CaCl_2 \cdot 2H_2O$	17.9 ± 0.3	80.7 ± 0.0	105.6 ± 0.9	78.9 ± 0.0	7.5 ± 0.0
+0.20%	32.6 ± 0.2	81.5 ± 0.4	184.5 ± 0.0	78.6 ± 0.1	10.3 ± 0.0
+1.0%	131 ± 0.5	97.6 ± 0.1	759.3 ± 1.3	77.7 ± 0.0	30.2 ± 0.0
+2.0%	250 ± 2.8	125.0 ± 0.0	1414 ± 0.6	76.6 ± 0.0	52.5 ± 0.0
Sea[b]	400	–	–	–	–
Apples					
McIntosh/Winesap[c]	1.05–1.33	–	–	–	–
Delicious (juice)	18.5 ± 0.5	79.5 ± 0.2	138.9 ± 0.7	74.7 ± 0.0	9.9 ± 0.0
Apples (flesh)	–	64.3 ± 0.7	80.8 ± 5.0	56.9 ± 0.9	8.9 ± 0.4
Immature apple (juice)	43.0 ± 0.9	87.5 ± 0.0	248.9 ± 0.1	77.2 ± 0.2	13.5 ± 0.0
Cherries					
Bing, Rainier (flesh)	–	88.1 ± 4.9	234.9 ± 23.9	69.7 ± 1.4	14.3 ± 1.0
Sweetheart (juice)	42.0 ± 1.2	–	–	–	–
Vegetables pieces[d]	6–10	–	–	–	–
Fruit pieces[d]	5–15	–	–	–	–
Insect					
Codling moth (slurry)	31.0 ± 1.6	125.3 ± 0.4	458.4 ± 34.0	60.3 ± 1.8	22.3 ± 1.1

[a] All data are the mean and standard deviation of two to four replicates.
[b] Balanis (1989).
[c] Mohsenin (1984).
[d] Metaxas (1996).

heating, samples were held in the immersion water for 2 or 5 min to allow the heat to impart additional insect lethality. We expected 100% kill of 200 codling moth larvae in a sample after holding it at 50 °C for 5 min, based on the thermal-death-time curve developed by Ikediala et al. (2000a). Treated fruit were then hydrocooled in chilled water of 1–3 °C for 12 min. Samples were subsequently held in a cold room at 4 °C for one day, removed and held at 23 °C and 60–70% RH overnight, with a 16:00 light:08:00 dark photoperiod before mortality analyses, following the methods outlined by Yokoyama et al. (1991), Neven et al. (1996), Ikediala et al. (1999), where mortality was assessed as failure of eggs to hatch or larvae to move when prodded 1–2 days after treatment.

For quality studies, freshly harvested cherries were treated with RF in a similar manner to that for infested fruit, but fruit was held after RF heating in the immersion water for longer times, ranging from 5 to 15 min for 48 °C treatment and

2–6 min for 50 °C treatment. We subjected the fruit to longer treatments in testing for quality than for insect mortality to simulate possible commercial applications in which allowance may be given to provide extra security (safety factor) for a designed minimum treatment that should provide 100% insect control. Since insect kill using heat and the fruit quality may be inversely related, it was essential to determine if this window existed in which fruit quality is still maintained. Treated and control fruit were placed in a cold storage room before being transported under refrigerated condition, to the USDA-ARS Tree Fruit Research Laboratory, Wenatchee, WA for quality analyses. To compare the quality of the RF treatments with MeBr fumigated fruit, samples from the same batch for RF treatment were fumigated with MeBr at the USDA-ARS Laboratory, Wapato, WA using the earlier approved treatment schedule of 64 g/m^3 for 2 h at 6 °C (MAFF-Japan, 1978; Drake et al., 1991). To simulate commercial practice, cherries were stored at 1 °C for up to 2 weeks to monitor the impact of storage on the quality of treated fruit. Firmness, percentage soluble solids content (SSC), titratable acidity (TA), fruit and cherry stem colours (Hunter L*,a*,b* values), visual fruit and stem damage, pitting, bruising, and rot were then determined as described by Drake et al. (1991), after 0 and 14 days storage. Insect mortality and fruit quality tests were replicated four and three times, respectively. Controls for insect mortality and quality tests were immersed in the saline water only (no RF treatment) and subjected to similar handling and analyses as RF-treated fruit.

3. Results and discussion

3.1. Heating rates of fruit and immersion saline water in RF system

Temperature in fruit increased linearly with time during RF treatments, and the heating rate depended on the coupled power. Fig. 2 shows a typical temperature-time history of cherries during RF treatment while immersed in 0.15% saline solution. Fruit and immersion water temperatures were raised to 50 °C in 2–5 min, compared with 15 min hot water dip or 37–45 min hot air treatment (Tang et al., 2000). Furthermore, both fruit surface and core temperatures increased sim-

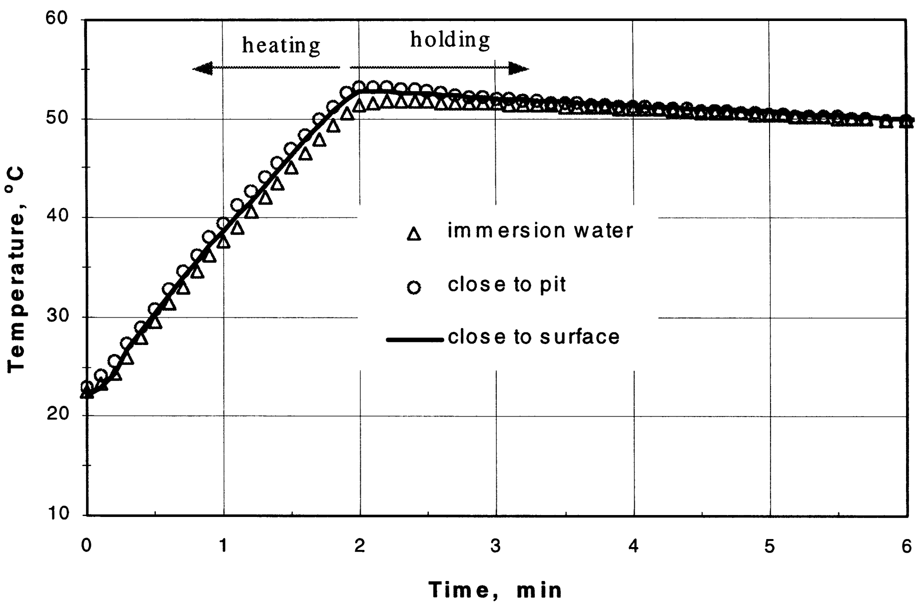

Fig. 2. Typical temperature profile in cherries during saline water (~ 0.15% NaCl) immersion RF treatment.

ilarly with heating time to the final treatment temperature (Fig. 2). This is in contrast to hot water or air treatments, where the fruit surface reached the medium temperature much faster than the centre.

The linear temperature increase with time as shown in Fig. 2 is expected since the thermal energy is generated volumetrically through the conversion of RF energy to heat and:

$$\Delta T = \frac{P_{\text{abs}}}{C_{\text{p}}\rho}\Delta t \qquad (3)$$

where C_{p} is the specific heat of the sample (J/kg °C); ρ is the sample density (kg/m^3); and Δt is the RF heating time (s). The absorbed power P_{abs} (W/m^3) was related to the electric field intensity E (V/m) and dielectric loss factor according to:

$$P_{\text{abs}} = 5.563 \times 10^{-11} f \varepsilon'' E^2 \qquad (4)$$

The electric power intensity, E, in the sample during the RF treatment depended on the electrode gap, the amount of fruit treated (including the quantity of water used), and the percent salt in the immersion water. In our experiments, we observed increased heating rates in fruit when using the water immersion technique compared with treatment in air for the same gap of plate electrodes. This suggests that the total power coupled into the sample increased and may be attributed to better tuning and load matching.

Conversion of electrical energy into thermal energy is proportional to the value of the dielectric loss factor for a fixed electric intensity as shown in Eq. (4). The dielectric loss factor, on the other hand, depends upon ionic conductivity, which in turn is influenced by salt content according to Eq. (2), Table 1 lists dielectric and conductivity properties for cherries, codling moth larvae and selected saline solutions at 27 MHz RF and 915 MHz microwave energy. As expected, the higher the salt content (conductivity), the higher the dielectric loss factor and thus the amount of RF power coupled and the rate of heating.

3.2. Effect of immersion water and saline concentration on heating uniformity

From preliminary tests, we observed that fruits treated with RF (or 915 MHz microwave) in air (without immersion in water) suffered thermal damage (burn) at the points of contact with the container or with other fruit. This could be the result of over-heating caused by a concentration of electric fields around those contact areas. When fruit was, however, immersed in water (de-ionized or ionized), this problem was eliminated. To prevent damage to our fibre optic sensors because of arcing and fruit burning when heating with RF in air, we could not gather similar temperature profile data.

Core-focused heating was also observed when fruit was treated in air or when immersed in de-ionized water. Similar observations were made by Ikediala et al. (1999) who reported cherry pit temperatures about 10 °C above the surface temperature when heating in a 915 MHz microwave cavity. When heating fruit in de-ionized water using RF energy, the temperature of the de-ionized water increased only a few degrees, while that of the fruit increased by over 30 °C. That is, the de-ionized immersion water did not absorb much of the energy. At the other extreme, when fruit was immersed in a 1% salt water, most of the RF energy was absorbed by the water, raising its temperature by over 30 °C, while the fruit core temperature increased by a only few degrees. This latter phenomenon created surface heating of fruit, a condition analogous to conventional hot water treatment of the fruits. We thus exploited the use of appropriate saline solution as the immersion medium to overcome the marked temperature differential within and among fruit.

The data presented in Table 1 was used to select appropriate immersion saline solutions that matched with the electrical properties of cherries to ensure uniform heating. Stogryn (1971) derived expressions for the ionic conductivity of NaCl solution at given temperature, T (°C) and normality, N as:

$$\sigma(T,N) = \sigma(25,N)\{1.000 - 1.962 \times 10^{-2}\Delta + 8.08 \times 10^{-5}\Delta^2 - N\Delta[3.020 \times 10^{-5} + 3.922 \times 10^{-5}\Delta + N(1.721 \times 10^{-5}\Delta - 6.584 \times 10^{-6}\Delta)]\} \qquad (5)$$

Table 2
Total number of codling moth and percent survival, by life stage, treated with 27 MHz radio frequency

Treatment, holding (°C, min)	Eggs[a]			II-Instar			III-Instar		
	Treated[b]	Hatch[b]	% Survival	Treated[b]	Alive[b]	% Survival	Treated[b]	Alive[b]	% Survival
Control	248	183	73.8	120	99	82.5 ± 5.3	130	113	86.9
48, 2	600	74	12.3 ± 1.6	400	101	25.3 ± 13.4	292	77	26.4 ± 15.5
48, 5	596	22	3.7 ± 1.7	400	10	2.5 ± 5.0	292	5	1.7 ± 4.8
50, 2	589	60	10.2 ± 5.1	200	0	0.0	292	4	1.3 ± 1.9
50, 5	642	2	0.3 ± 0.4	200	0	0.0	292	0	0.0

[a] Treatments were done with immature apples, because cherry fruits were of poor quality and could not endure the 2 weeks holding period for all eggs to hatch.

[b] About 200–400 codling moth larvae or 589–624 eggs were treated at each level in two to four replicates with 120–248 in the controls (one or two replicates). Data points are the mean and standard deviation.

where

$$\sigma(25,N) = N[10.394 - 2.3776N + 0.68258N^2 - 0.13538N^3 + 1.0086 \times 10^{-2}N^4] \quad (6)$$

and $\Delta = 25 - T$. At 25 °C, results from the above equations agreed well with the data obtained in Table 1 for conductivity of NaCl. From Table 1, a 0.20% NaCl solution in tap water (conductivity ~ 0.41 S/m and loss factor ~ 226) provided dielectric properties that matched very closely that of cherries (conductivity ~ 0.42 S/m and loss factor ~ 234) at 27 MHz. In experimental treatments, however, a 0.15% solution was used, which yielded desired temperature uniformity in both immersion water and fruit. It is also more desirable to use less saline water from the perspective of commercial application.

When fruits were treated by RF to a 50 °C target temperature, mean temperatures of the immersion water and that of the cherries differed by ≤ 0.6 °C (Fig. 2), while the maximum temperature variation within and among fruit determined within 1 min after RF treatment was $< \pm 1.0$ °C of set temperature, with standard deviation (S.D.) about the mean ranging from ± 0.4 to ± 1.4 °C (five to eight replicates). There was no noticeable temperature difference among small versus large cherries, a major problem encountered by Ikediala et al. (1999) when cherries were treated without water immersion. The RF saline water immersion treatment overcame the problem of a markedly large temperature differential within and among fruits, associated with a RF or microwave treatment in air (without immersion) condition. Apart from the near-matching of the dielectric loss factors which may be responsible for the uniform heating rate, given uniform electric field intensity, the small difference in dielectric constant (Table 1) between 0.15% salt water and cherries may have reduced core-focussing of the energy.

3.3. Codling moth mortality

Tables 2 summarizes mortality data obtained for different life stages of codling moth after RF treatments that raised fruit temperatures to 48 or 50 °C and after holding times of 2 or 5 min. Mortality increased with temperature and holding time, but appears to depend more on holding time due probably to the short time required to raise the fruit and immersion water temperature from 48 to 50 °C. About 100% insect kill (0% survival) was achieved for all insect stages tested (except for the eggs) at 50 °C and 5 min hold. This agreed with the thermal death time curve developed for 5th instar codling moth by Ikediala et al. (2000a). The slightly lower mortality obtained for eggs may be attributed in part to the use of immature apples. We had assumed that since the eggs were on the surface of the fruit, kill would mainly come from the hot immersion wa-

Table 3
Comparison of ‘Sweetheart’ cherry quality parameters after treatment with methyl bromide (MeBr) and RF immersion technique[a]

Treatment	Firmness (N)	SSC (%)	TA (%)	Fruit colour (a)	Stem colour (a)[b]	Visual fruit damage[c]	Visual stem damage[c]	Pitting[d]	Bruising[d]
0 day									
Control	7.2	23.4	0.67	7.1	−0.3	1.0	1.0	1.7	0.3
MeBr	6.9	22.8	0.70	5.5	1.8	1.0	1.5	1.0	2.0
48 °C, 5 min	7.3	22.6	0.64	4.2	−1.8	1.0	1.0	2.7	5.7
10 min	6.5	22.6	0.63	4.7	−0.7	1.3	1.1	4.7	6.3
15 min	7.2	22.9	0.59	2.6	−0.2	1.2	1.0	5.3	10.0
50 °C, 2 min	6.2	23.1	0.62	2.6	−0.7	1.0	1.5	9.0	12.7
4 min	6.5	22.0	0.58	6.6	−1.4	1.0	1.2	7.7	11.3
6 min	7.5	22.8	0.63	8.2	−1.7	1.0	1.5	8.7	9.3
S.D. range	0.4–0.8	0.1–0.7	0.01–0.03	0.2–3.7	0.1–1.4	0.0–0.3	0.0–0.1	1.5–3.1	0.6–3.1
14 day									
Control	6.4	23.4	0.53	7.4	−0.8	3.2	2.1	21.7	6.3
MeBr	5.7	23.1	0.57	5.1	3.5	3.4	3.6	19.3	8.0
48 °C, 5 min	5.5	22.8	0.50	4.1	−0.5	3.4	2.2	24.0	6.3
10 min	5.3	21.9	0.50	4.4	−0.9	3.5	2.5	24.7	3.7
15 min	5.3	22.9	0.47	3.1	−0.3	3.5	2.7	23.3	6.7
50 °C, 2 min	5.2	23.3	0.48	3.0	0.4	3.5	2.7	23.7	5.7
4 min	5.3	22.8	0.52	3.7	−0.7	3.3	2.6	23.0	3.0
6 min	5.4	22.3	0.51	3.7	1.3	3.6	2.8	24.0	4.3
S.D. range	0.1–0.6	0.2–1.2	0.01–0.05	0.1–0.6	0.2–1.4	0.0–0.3	0.0–0.3	0.6–2.0	0.6–6.7

[a] S.D. range is the range of standard deviation (S.D.) about the mean for data in the column for the storage period.
[b] Indicates greenness. The more negative the value, the greener the colour.
[c] Rated scale for scores (1, none; 2, slight; 3, moderate; 4, severe).
[d] Number is relative to 30 fruits examined. All data points are the mean of three replicates.

ter. However, there appeared to be a slight adhesion problem (tiny air pockets on fruit) such that complete wetting of the fruit by the immersion water was not obtained. From thermal death time kinetics (unpublished data) obtained for codling moth (two egg stages, and 1st–5th instar), we found that the eggs were less tolerant to heat treatment than the later larval stages. We are unable to infer that the dielectric property of the immature apple and cherry fruits played any marked role in the RF heating and difference in mortality since these were similar.

Mortality from our current RF treatment for codling moth larvae was significantly higher than those observed by Ikediala et al. (1999), where 915 MHz microwave treatment at 50 and 55 °C and a 2 min holding time reportedly obtained only 9–98% codling moth kill in ‘Bing’ and ‘Rainier’ cherries. The authors noted that the low mortality and wide variation in those data were due to non-uniformity of heating among fruit, the core focusing of heat in fruit, and the inability to treat insects outside fruit. Since the core temperature rose faster than the surface, it was difficult to kill insects outside fruits without damage to quality of the internal flesh. It is worth pointing out that this non-uniform temperature due to size variation among cherries and core-focussed heating in the fruit was eliminated by the saline water immersion technique, which also largely contributed to the increased insect mortality and efficacy of the treatment temperature-time combinations.

In the present study, insects outside the fruit were treated in the immersion water to an extent equal to those inside the fruit because the internal temperature of fruit was similar to that outside fruit (immersion saline water). The coupled water immersion of cherries with RF also enabled the treatment of egg-infested fruit. This was also difficult with treatment in air because the air environment in RF or microwaves cavities is not heated due to its very low dielectric properties (Table 1).

The thermal-death-time curve obtained using a conduction-heating block and presented by Ikediala et al. (2000a) suggests that 5 min holding at 48 °C only resulted in less than 50% mortality. For infested sweet cherries treated with forced hot air, Neven and Mitcham (1996) reported that 99% mortality required 124 min at 45 °C and 72 min at 47 °C. Comparing the present results (e.g. > 90% mortality after holding for 5 min at 48 °C) with those of Ikediala et al. (2000a) and Neven and Mitcham (1996), we speculate that preferential heating of the insects compared with fruit and the immersion water may partly explain the high mortality rate at 48 °C in this study. This may be due to the fact that the dielectric loss factor for codling moth was 458 (Table 1), a value 2–2.5 times that of cherries and saline water at the RF frequency. From Eq. (4), and the fact that different components of a composite material may heat at a rate depending on their dielectric and thermal properties (Nelson, 1991), more RF energy may have coupled to the insects than the fruit. However, the amount of this power is very difficult to verify experimentally.

3.4. Treatment effects on cherry quality

The effect of RF and water immersion treatment on important quality parameters of ‘Sweetheart’ sweet cherry was compared with the control and MeBr-fumigated fruit (Table 3). For most quality parameters, the RF-treated fruits were similar or slightly better than that of the MeBr treatment, while the control was better than both the MeBr and RF-treated fruits. Soluble solids content (SSC) and incidence of rots were unchanged after 14 days in storage (data for fruit rots not shown), while there appeared to be no defined pattern of change with fruit and stem colours, and the incidence of bruising. Bruising seemed higher in RF-treated fruit, lower in the control and MeBr-fumigated fruit at 0 day storage, but similar or lower after 14 days in storage. Neven and Drake (2000) found similar results for CATTS-treated, irradiated, and MeBr fumigated cherries and attributed this to increased handling. RF-treated cherry stems had the same color as the control, while the stems of fumigated fruit turned dark brown. Ikediala et al. (1999) reported drying and a reduction in the greenness of cherry stems following a 915 MHz microwave treatment in air. Drake et al. (1991) noted that the stem condition greatly influenced consumer perception of the overall cherry quality.

Firmness and titratable acidity (TA) decreased slightly between 0 and 14 days storage, while pitting and visual fruit and stem damage increased with storage time for all treated and control fruit. Incidence of pitting was generally high and appeared to be slightly more prevalent in the RF-treated fruits immediately after RF-treatments. A similar trend was observed for bruising on the first day of treatment. This trend was, however, reversed after 14 days in storage, and may be attributed to extra handling before and after RF treatments, and the presence of salt in the immersion water. Thus, the saline water immersion may have provided added benefit by preventing cherries from osmotically absorbing water during the treatment period, and may also have aided in maintaining certain quality parameters. Lurie and Klein (1992) and Alonso et al. (1997) showed that $CaCl_2$ and thermal pretreatments of apples and cherries improved storability and may also prevent freezing-induced loss of firmness.

4. Conclusion

When cherries were immersed in ionized (0.15% NaCl salt in water) solution and treated with RF energy for total (heating and holding) treatment times of 7–10 min (for insect mortality tests) at 50 °C or 10–20 min (for fruit quality tests) at 48 and 50 °C, we achieved 100% codling moth larvae mortality in cherries with little or no quality reduction. The saline water immersion technique overcame the markedly large temperature differential problem associated with RF treatments of fruits in air. Cherry overall quality parameters were either better than or comparable to MeBr-fumigated fruit, suggesting that fruit were tolerant of short time exposure to temperatures up to 50 °C. Treating fruit in immersion water of selected salt concentration and RF may be used to develop an effective alternative quarantine method for fruit. Large scale and confirmatory tests are needed to enable the establishment of a quarantine protocol for cherries using RF and this immersion technique.

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