Available online at www.sciencedirect.com
SCIENCE DIRECT®

Postharvest Biology and Technology 33 (2004) 93–100

Postharvest Biology and Technology

www.elsevier.com/locate/postharvbio

Application of radio frequency treatments to control insects in in-shell walnuts

E.J. Mitcham [a,*], R.H. Veltman [a], X. Feng [a,1], E. de Castro [a], J.A. Johnson [b], T.L. Simpson [a], W.V. Biasi [a], S. Wang [c], J. Tang [c]

[a] *Department of Pomology, University of California, 1035 Wickson Hall, One Shields Avenue, Davis, CA 95616-8683, USA*
[b] *USDA-ARS Horticultural Crops Research Laboratory, 9611 S. Riverbend Avenue, Parlier, CA 93648, USA*
[c] *Department of Biological Systems Engineering, Washington State University, P.O. Box 646120, Pullman, WA 99164-6120, USA*

Received 22 April 2003; accepted 12 January 2004

Abstract

Codling moth (*Cydia pomonella* [L.]), navel orangeworm (*Amyelois transitella* [Walker]), and Indianmeal moth (*Plodia interpunctella* [Hübner]) are common insect pests in walnuts (*Juglans regia* [L.]). Currently, exported in-shell walnuts are disinfested using methyl bromide fumigation. Restrictions on methyl bromide use have increased interest in developing alternative postharvest treatments. Radio frequency (RF) heating is such an alternative. Our tests have shown that heating walnuts with radio frequency energy to temperatures lethal to these important insect pests has no negative effects on walnut quality, and may even reduce the susceptibility of walnuts to becoming rancid in storage. Radio frequency treatments provided acceptable rates of heating (5–6 °C min^{-1}) for in-shell walnuts to lethal temperatures. Heating walnuts to 55 °C or higher resulted in 100% mortality of fifth instar navel orangeworm, which is the most resistant of the three insect pests. Moisture content of walnuts is an important factor affecting heating rates during radio frequency treatments. The relationship between average moisture content and average heating rate was linear, and the variability in moisture content and heating rates was higher with a higher average moisture content. Radio frequency treatments reduce the moisture content of walnuts. A combined system of radio frequency heating with hot air has the potential to accelerate or even replace batch drying of walnuts in the future.

Keywords: Walnut; Navel orangeworm; Heat; Disinfestations; Postharvest

1. Introduction

Methyl bromide (MeBr) fumigation is the current treatment applied to most in-shell walnuts to meet quarantine and phytosanitary requirements before shipment to domestic and international markets. The three most economically significant pests in walnuts are codling moth (*Cydia pomonella* [L.]), navel orangeworm (*Amyelois transitella* [Walker]), and Indianmeal moth (*Plodia interpunctella* [Hübner]). Under the Montreal Protocol of the United Nations, MeBr will be banned from use for purposes other than pre-shipment and quarantine by 2005 (Anonymous, 2001). Increased MeBr restrictions have increased the

* Corresponding author. Tel.: +1-530-752-7512; fax: +1-530-752-8502.
E-mail address: ejmitcham@ucdavis.edu (E.J. Mitcham).
[1] Permanent address: College of Food Science, Southwest Agricultural University, Chongqing 400716, PR China.

0925-5214/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.postharvbio.2004.01.004

cost of the fumigant, and will reduce its availability in the future. Sulfuryl fluoride may soon be registered for postharvest disinfestation of walnuts; however, there is an interest in developing a non-chemical alternative.

Alternative disinfestation treatments for walnuts include irradiation (Thayer and Harlan, 1983), cold storage (Moffitt and Burditt, 1989), controlled atmospheres (Toba and Moffitt, 1991) and heat treatments. Food irradiators are costly and there is concern over public acceptance of irradiated food. Cold storage and controlled atmosphere also require substantial capital investment and lengthy treatment times. This could make them unsuitable for the vital European holiday market, for which treatment times need to be less than 24 h.

Industrial radio frequency (RF) heating operating between 10 and 100 MHz has been successfully used in the food processing and textile industries. It involves direct interactions between dielectric materials, such as fruits and nuts, with electromagnetic waves to generate heat. This avoids heating limitations caused by airspaces or bulkiness of the product as in conventional surface heating with air or water. Because of their dielectric properties, RF may also heat insects faster than the surrounding nut (Wang et al., 2003). RF is classified as "non-ionizing" radiation because these frequencies produce insufficient energy to ionize water molecules, unlike higher levels of energy such as X-rays and gamma rays that can alter molecular structures. It is therefore regarded as a safe treatment that will be acceptable for consumers. RF treatments also meet organic labeling standards. The challenge with RF treatments has been lack of heating uniformity, which is particularly difficult for products with limited heat tolerance.

In developing a postharvest treatment for walnuts, tests must be done on the most tolerant life stage and species of the target insects. To determine the most tolerant species and life stage, insect mortality data must be developed over a range of temperatures. Washington State University has developed a thermal block heating system to heat insects at various rates and to a range of different temperatures (Wang et al., 2002). The experiments done by Wang et al. led to a "thermal death curve" for the different life stages of codling moth, navel orangeworm, and Indianmeal moth. These data were used to establish the optimal temperatures for insect control with RF.

Quarantine treatments against insects commonly require Probit 9 mortality (99.9986%) while also minimizing or avoiding damage to the product. It is, therefore, important to examine the effect on walnut quality of treatment times and temperatures that control the target pests. Quality factors for walnuts include texture, kernel color, moisture content, rancidity and flavor. The development of rancidity can be indicated by peroxide values (PV) and free fatty acids (FA).

Understanding the factors that control heating uniformity in walnuts with RF is critical to translating laboratory experiments to commercial applications. The minimum walnut temperature must be sufficient to kill insect pests while the maximum temperature is below the limit of heat tolerance. Factors requiring further examination are heating variability within the RF field and the variability in moisture content between batches of nuts and individual nuts.

Results are discussed in terms of the potential of RF heating as a pre-shipment treatment for in-shell walnuts.

2. Materials and methods

2.1. Equipment and heating rate variability

The postharvest laboratory of the Pomology Department at UCDavis is equipped with a 27 MHz, 12 kW batch RF machine (Strayfield International Limited, Workingham, UK). Some initial tests were conducted to map the uniformity of the RF field within this machine. Knowledge on the uniformity of the electromagnetic field in the RF unit is important to distinguish between aberrations in heating uniformity caused by the machine itself and those caused by product characteristics. Two types of initial tests were conducted to investigate the heating uniformity of the RF machine. First, the heating rate of tap water in several glass jars (4-l) that were equally distributed over the lower electrode of the RF machine was determined. Second, we investigated if rotating the sample container of nuts during RF treatment affected the heating variability. A simple mechanism was developed (two ropes attached to the sample container) to manually rotate the container. Nuts from the same batch were heated in the RF machine with and without application of the rotation device, and heating rates of and temperature variability between individual nuts were compared. In these experiments a standardized nut heating protocol (see Section 2.2) was used.

2.2. Nut heating protocols

Walnuts (*Juglans regia* L. cv Hartley) were obtained from a local walnut processing plant and stored at 0 °C in 23 kg raffia bags until experimentation. About 2.5 kg of nuts (ca. 500 nuts) were heated in a cylindrical polyethylene sample container with a diameter of 33.5 cm and a height of 20 cm until the coldest of eight walnuts of which the kernel temperature was monitored reached target temperatures of 47–55 °C. In every experiment the target temperature was the minimum temperature. The container was filled completely in all experiments. During operation, the standard settings of the RF unit were: a minimum gap of 20.5 cm between the upper and the lower electrode and maximum power of 12 kW. The A_{initial} can be defined as the heating power (amps) just after starting the RF machine.

During RF heating, the kernel temperatures of the nuts were monitored using eight fiber-optic probes (Fiso Technologies Inc., Quebec, Canada). To position the probe in a kernel, a walnut was partially cracked, and a small hole was drilled into the kernel. To give a reliable value, the probe must fit tightly in the kernel. Four probes were randomly placed in walnuts located in the lower part of the container; the remaining probes were placed in walnuts in the top layer.

2.3. Determination of the moisture content

To determine the moisture content, 20 walnuts were cracked and the kernel and the shell of each nut were separated. The kernel was cut into small pieces to facilitate water loss. The initial weight of the kernels and shells was determined before the nuts were placed in a 60 °C oven. The weights of the kernels and shells were monitored daily until they became constant. The percentage water loss (weight loss) was determined as a percent of the fresh weight. Industrial laboratories normally do not distinguish between kernel and shell moisture content. To make the results comparable to industrial values, total moisture contents were calculated by dividing total water content (shell plus kernel) by total initial weight (shell plus kernel).

2.4. Effect of moisture content on heating rate

The moisture content of in-shell walnuts was adjusted by immersing them in tap water for about 8 h. After immersion, the nuts were dried by spreading them out in harvest bins and placing them in a 25 °C room. After 4 days the nuts were transferred to a 35 °C room to accelerate the drying process. Moisture contents were determined, and then nuts were heated in the RF unit on days 1, 2, 4, 7 and 16. In another test, the moisture content of walnuts was increased by storing them overnight at 20 °C and a relative humidity of 90–95%.

2.5. Walnut quality

To determine the upper limit of walnut tolerance to heating, walnuts were heated with RF to 55 or 75 °C. Control nuts were not heated. Accelerated storage life tests were conducted in which walnuts were stored for 10 or 20 days at 35 °C to simulate storage at 4 °C for 1 or 2 years, respectively, or for 5 or 10 days at 45 °C to simulate storage at 10 °C for 1 or 2 years, respectively (Taoukis et al., 1997), or samples were analyzed directly after RF treatment without storage. After heating plus storage, samples were stored at 0 °C until oil analyses. Oil was pressed from the walnuts at room temperature using a Carver Laboratory Press; model K (Fred S. Carver Inc., Summit, NJ, USA), and milliequivalents of peroxide (PV; AOCS, 1998a) and percent free fatty acid values (FA; based on oleic acid; AOCS, 1998b) of the oil were determined in triplicate for every treatment and storage period.

A limited taste test was conducted during a demonstration of RF technology for the walnut industry. It was a blind test in which treated walnuts from the above experiment were randomly divided into five groups of three samples each: A, B or C (control, 55 or 75 °C). The five groups included walnuts not stored and walnuts stored 1 and 2 years at 4 and 1 and 2 years at 10 °C. Panellists were asked to rate each of the samples (A, B and C) of each group in terms of flavor, appearance and texture by placing a vertical line on a 10 cm bar to indicate their degree of liking for each sample and quality factor.

2.6. Treatment of infested walnuts with RF energy

Wang et al. (2002) found that navel orangeworm is more heat tolerant than Indianmeal moth and codling moth, and that the fifth instar navel orangeworm is the most heat tolerant life stage. Therefore, we selected fifth instar navel orangeworm as a target pest in our infested studies. Walnuts were infested at the USDA-ARS laboratory in Parlier, California. A non-diapausing fifth instar larva was placed in a walnut through a pre-drilled hole in the shell. The holes were sealed with adhesive clay to prevent insects from escaping from the walnuts. A portion (224) of the infested nuts was not heat-treated, and served as a control. The remaining infested nuts (891) were mixed randomly with about 1100 uninfested nuts from the same batch and with the same moisture content. Upon arrival from the USDA laboratory, the walnuts were held at room temperature until RF treatment. The infested and uninfested nuts were divided into four lots, and treated with RF until the lowest temperature of 8 monitored nuts reached 47, 50, 53, or 55 °C. After treatment, the infested walnuts were stored at room temperature for 4 days. The shells were then cracked and the insects were removed. Insects were counted and mortality was evaluated; moribund and living insects were held at room temperature and observed for a further 2 weeks. Live insects included active larvae, larvae that were in a cocoon and starting to pupate, and pupae. After 2 weeks, the dead larvae and pupae were checked under a microscope for internal movement.

Data are presented as mean value ± standard deviation or standard error, as appropriate.

3. Results and discussion

3.1. Initial tests on heating variability

We did several initial, preparatory experiments with 32 4-l jars filled with 1.8-l tap water, which were equally distributed over the lower electrode of the RF unit, to test the uniformity of the electromagnetic field. This was to establish if heating variability was caused by a non-uniform electromagnetic field, or by differences in nut physiology, or both. The tests revealed that the center of the electromagnetic field was relatively uniform, and that the temperature distribution patterns after heating the water were reproducible. When the tap water was heated to a target temperature of 40 °C, the temperature variability in 20% of the field (in the center) was 2 °C or less (40–42 °C). More than 50% of the field showed a variation of 6 °C or less. There would be a 2.75 °C difference between water samples in the center of the machine if the water was heated to 55 °C from 20 °C (Δ45 °C) as compared with heating to 40 °C (Δ30 °C). From these tests we concluded that the variability in heating rate, which is inherent to the design of the machine that was used (an asymmetrical, batch type RF unit), was relatively small compared to the variability in heating rate when walnuts were treated. The variability in heating rate caused by non-uniformity of the electromagnetic field was estimated to be 10% or less of the variability found in the experiments with walnuts. Non-uniformity would be much less of an issue in a symmetrical, conveyorized RF system, which would be used in commercial applications.

In a second test, the sample container was rotated during RF heating, avoiding in-shell walnuts being continuously subjected to the same inequalities of the electromagnetic field. However, rotation of the container did not decrease but increased the variability in heating rate between the nuts in the container (S.D. of 1.71 and 0.94 for rotated and non-rotated), and no relationship was found between rotation and the average heating rate (9.0 and 8.8 °C min^{-1} for rotated and non-rotated, respectively). Also, no significant differences were found in temperatures measured in the upper and lower walnut layers during treatment. Factors other than uniformities in the electromagnetic field, such as the moisture content of the walnuts, had a greater effect on the heating rate.

3.2. Walnut heating

The heating time is defined as the time it takes to heat all eight monitored nuts from room temperature to a target temperature. In the experiment presented in Fig. 1, the target temperature was 75 °C and the heating time was 4.2 min. It took 2.8 min to heat the eight monitored nuts to 55 °C (Fig. 1). Walnut kernel moisture content before treatment was 2.9 ± 0.25% and the average heating rate was 13.5 ± 1.3 °C min^{-1}. RF technology would only be meaningful for walnut

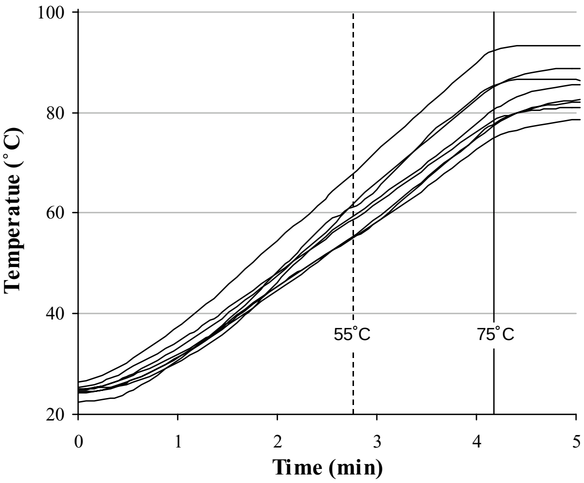

Fig. 1. Time to heat a bed of 500 walnuts to 55 and 75 °C with radio frequency energy. Kernel temperatures of eight walnuts were monitored. The dashed and solid vertical lines mark the point in time (2.8 and 4.2 min, respectively) that all eight kernels reached 55 and 75 °C, respectively.

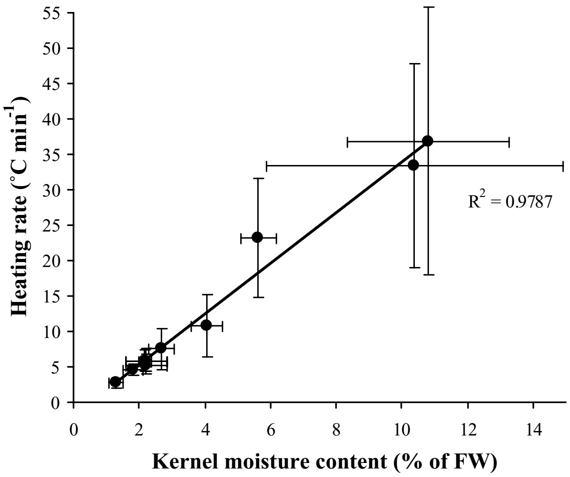

Fig. 2. The linear relationship between the moisture content of walnut kernels given as percent of the total kernel fresh weight ($n = 20$) and the heating rate during radio frequency treatment ($n = 8$). Vertical lines represent standard deviations.

disinfestation if it could kill insects without significantly decreasing walnut quality, taking into account certain safety margins. Every walnut in a batch should be subjected to the target temperature to be sure that all insects are killed. A high variability in heating rate, and thus final temperature, would subject some walnuts to temperatures they do not tolerate. For this reason, variability in heating rate is an important factor, and it should be kept as small as possible.

3.3. Moisture content and heating of walnuts

The relationship between the moisture content and the heating rate of the walnut kernel was linear, and the variation in moisture content was higher at higher average moisture contents (Fig. 2, Table 1). Some walnuts took up more water than others when immersed, however, the differences in moisture content decreased during drying. The initial, large variability in moisture content on days 1 and 2 influenced the variation in heating rate of the walnuts: where there was a

Table 1
Relationship between the percent moisture content (mean ± S.E.) ($n = 20$) of the kernel and the shell, and the heating time to 53 °C, the maximum difference between the coldest and the warmest walnut during treatment, the maximum standard deviation of the walnut kernel temperatures, the heating rate ($n = 8$), and the initial power (in Amps)

	Moisture content (% ± S.D.)			Time (min) to 53 °C	Maximum difference (°C)	Maximum S.D. (°C)	Heating rate (°C min^{-1} ± S.D.)	Power ($A_{initial}$)
	Shell	Kernel	Total					
1	18.7 ± 2.1	10.8 ± 2.5	15.3 ± 2.1	1.41	51.8	29.8	36.9 ± 10.5	1.1
2	15.6 ± 2.4	10.4 ± 4.5	13.3 ± 3.2	1.48	29.5	11.9	33.4 ± 8.0	0.8
3	14.9 ± 1.2	5.6 ± 0.5	9.9 ± 0.7	1.52	32.7	14.0	23.2 ± 4.7	0.9
4	11.8 ± 0.5	4.1 ± 0.5	8.5 ± 0.5	3.61	25.0	8.8	10.8 ± 2.5	0.5
5	8.3 ± 1.0	2.7 ± 0.4	5.3 ± 0.6	4.97	19.8	6.9	7.6 ± 1.6	0.5
6	5.4 ± 0.7	1.8 ± 0.3	3.8 ± 0.5	6.6	11.7	4.1	4.6 ± 0.5	0.4
7	3.8 ± 0.2	1.3 ± 0.2	2.8 ± 0.3	13.46	22.1	7.2	2.8 ± 0.4	0.3

S.D.: standard deviation; A: Amps; numbers 1, 2, 4, 6 and 7 refer to tests in which walnuts were dried for 1, 2, 4, 7 and 16 days, respectively, after emersion in tap water. Number 3 refers to a test with walnuts which were stored overnight in humidified air. Number 5 refers to a test with walnuts just after they had been removed from storage at 0 °C.

larger variability in moisture content the variability in heating rate was larger as well. In commercial operations, in-shell walnuts are cleaned by washing them in 2.8–3% sodium hypochlorite or 6–8% hydrogen peroxide solution at room temperature. The 8-h immersion of the nuts in our study did not represent the 2-min commercial washing in sodium hypochlorite solution, but was only meant to evaluate the effects of extreme moisture contents on RF heating to determine the relationship between heating rate and moisture content.

The results shown in Fig. 2 demonstrate the importance of controlling the moisture content of in-shell walnuts to ensure uniform RF heating. The effects of commercial washing in bleach or peroxide solution on RF heating require further testing. In some operations, it may be preferable to apply the RF treatment after washing and bleaching and before drying of the in-shell walnuts. RF could then be employed to accomplish most of the re-drying, which could save considerable time and result in product with a more even moisture content. A second advantage of applying RF just after washing the nuts is the higher heating rate during RF treatment because of the increased moisture content.

Wang et al. (2001) found the total moisture content to be 10.0 ± 0.8% after 2 min of simulated washing under laboratory conditions. After washing, walnuts must be re-dried to reduce the moisture content to at least 7% to avoid mould development in storage, according to commercial practice. Wang et al. (2001) found that the moisture content of walnuts was reduced from 10.0% to an acceptable 5.6% for storage when they were subjected to a procedure in which walnuts were RF heated to 55 °C together with forced hot air at 53–55 °C. This type of process may offer options for on-line drying instead of batch-wise drying of walnuts in the future. The hot air process could be adjusted in such a way that over-drying and loss of saleable weight is prevented.

The current standard commercial practices of fumigation with methyl bromide plus venting (about 6 h), washing for 2 min in sodium hypochlorite or hydrogen peroxide, and drying of walnuts with 52 °C hot air (4–6 h) are time consuming processes. Combining RF and hot air into a single online treatment system could make batch drying of the walnuts superfluous in the future, and a significant amount of time could be saved.

Table 2
Oil quality of walnuts (mean ± S.E.) in terms of peroxide value and free fatty acid content after radio frequency heating to 55 or 75 °C followed by a simulated storage life of 1 or 2 years at 4 or 10 °C

Storage life		Simulation		Peroxide value (meq kg^{-1})			Free fatty acids (%)		
Time (years)	Temperature (°C)	Time (days)	Temperature (°C)	Control	55 °C	75 °C	Control	55 °C	75 °C
No storage		No storage		0.70 ± 0.12	0.76 ± 0.17	0.84 ± 0.24	0.13 ± 0.01	0.13 ± 0.00	0.14 ± 0.02
1	4	10	35	1.08 ± 0.21	1.03 ± 0.09	0.98 ± 0.23	0.23 ± 0.04	0.17 ± 0.03	0.14 ± 0.01
2	4	20	35	1.43 ± 0.10	1.25 ± 0.15	1.35 ± 0.18	0.20 ± 0.01	0.19 ± 0.01	0.16 ± 0.02
1	10	5	45	1.23 ± 0.35	1.23 ± 0.43	1.08 ± 0.42	0.19 ± 0.01	0.19 ± 0.03	0.20 ± 0.05
2	10	10	45	1.86 ± 0.09	1.87 ± 0.25	1.56 ± 0.16	0.29 ± 0.03	0.22 ± 0.02	0.19 ± 0.02

3.4. Quality evaluation of walnuts

For the walnut industry, two factors are important in the development of alternative disinfestation methods: the insects must be killed, and nut quality must not be adversely affected. To kill all insects, each walnut must reach the target temperature. However, heating variability causes some nuts to get much hotter than the target temperature. Therefore, we determined how much heat can be applied to the walnuts without loss of quality. Nuts were heated in RF to 55 or 75 °C followed by a simulated storage life period of 1 and 2 years at 4 and 10 °C (Table 2). The experiments showed an increase in PV values and FA percentages with increasing storage duration and temperature. RF treatment to target temperatures of 55 or 75 °C did not increase PV and FA values above the control except that immediately after the RF treatment PV values were increased. Generally, treated kernels had slightly decreased values compared to the untreated control. This trend, however, was not significant, but is in agreement with observations reported by Wang et al. (2001, 2002). In another experiment we found that peroxide and FA values were not affected when nuts were heated to target temperatures between 70 and 80 °C (data not shown).

Walnuts are considered significantly rancid by commercial laboratories when PV values exceed 1 meq kg^{-1} or FA values exceed 0.6%. PV and FA values were already relatively high at the start of this experiment (Table 2), because nuts had been stored for more than 4 months at room temperature prior to treatment. Control values presented by Wang et al. (2002), for instance, are much lower compared to control values in Table 2. Taste tests did not suggest any taste aberrations of the nuts that were heated to 75 °C. In a blind test, panellists were not able to distinguish these nuts from untreated, control nuts. This result would indicate that the final temperature of in-shell walnuts could be 20–25 °C higher than the 55 °C target temperature and still not alter quality.

3.5. Insect mortality in walnuts

Previous work by Wang et al. (2002) demonstrated that the navel orangeworm is more heat tolerant than the codling moth or the Indianmeal moth. For this study, we used walnuts infested with fifth instar navel orangeworm, knowing that treatments effective in killing this species and life stage would also be effective in controlling the other major pests. Kernel temperatures of walnuts treated with RF energy increased linearly from about 23 °C to target temperatures of 47, 50, 53 and 55 °C. The heating times for the four final temperatures were 5.2, 5.1, 6.5 and 7.3 min, respectively (Table 3). Heating rates were relatively low because of the low moisture content of the walnuts (Table 3).

Evaluation of infested walnuts indicated that some of the navel orangeworms escaped during shipment, leaving an empty nut (Table 4). However, evaluation of the control nuts indicated that none of the larvae remaining in the nuts died during shipment. Insect mortality reached 32, 77, 99 and 100% following RF heating to 47, 50, 53 and 55 °C, respectively. The average kernel temperature at the end of these treatments was 50.4, 53.4, 60.6 and 62.9 °C, respectively, while the lowest of the eight temperatures monitored reached the set point temperature.

Table 3
Moisture content (mean ± S.E.) of in-shell walnuts before heating and heating characteristics of walnuts in insect mortality study

Treatment	Moisture content (%)			Time (minute to target temperature)	Heating rate (°C min^{-1})	Power ($A_{initial}$)
	Shell	Kernel	Total			
Control	6.8 ± 0.8	2.2 ± 0.6	4.7 ± 0.8	–	–	–
47 °C	6.8 ± 0.8	2.2 ± 0.6	4.7 ± 0.8	5.2	5.2 ± 0.7	0.4
50 °C	6.8 ± 0.8	2.2 ± 0.6	4.7 ± 0.8	5.1	5.8 ± 0.9	0.4
53 °C	6.8 ± 0.8	2.2 ± 0.6	4.7 ± 0.8	6.5	5.8 ± 1.7	0.4
55 °C	6.9 ± 0.4	2.2 ± 0.2	4.9 ± 0.3	7.3	5.9 ± 1.5	0.4

A: Amps.

Table 4
Mortality of fifth instar navel orangeworm larvae following radio frequency heating to various temperatures

Treatment	Live	Dead	Pupae	Empty nut	Total[c]	Mortality (%)
Control	209	0	41	15	224	0
47 °C	110	51	2	12	173	32
50 °C	40[a]	137	0	10	192	77
53 °C	2[b]	185	0	6	193	99
55 °C	0	329	0	4	333	100

[a] Five of the larvae that lived were moribund and after 14 days they were all dead (not included in mortality).
[b] Fourteen days after treatment one of the two larvae was dead (not included in mortality).
[c] Total was calculated by combining nuts with live and dead insects and empty nuts.

4. Conclusions

RF heating killed fifth instar navel orangeworm larvae in in-shell walnuts when a target temperature of 55 °C is applied. After treatment and simulated storage, PV and FA values were not affected indicating that there was no significant effect of heating on the development of rancidity.

Our laboratory experiments involved heating only 500 walnuts at one time, while our 12 kW unit could heat larger quantities. For commercial use, it is estimated that 162 kW would be required to heat 4.54 tonnes (metric) of walnuts per hour. A slower throughput would require less capacity. The approximate capital costs for such equipment would be US$ 200,000. Walnuts would pass on a conveyor through one or more RF units with nut mixing between the units. While RF heating shows considerable promise as a safe disinfestation method for walnuts, additional work is needed in the following areas.

1. Confirmation of the temperature that kills 100% of the fifth instar navel orangeworm larvae in large scale tests. It should be further investigated to what extent killing rates depend on heating rates.
2. A complete analysis of the use of RF combined with hot air for drying of in-shell walnuts after a washing step.
3. Translation of the experimental set-up to a practical application.

Acknowledgments

This research was supported by grants from USDA IFAFS (00-52103-9656), USDA-CSREES (01-51102-11324) and California Walnut Marketing Board.

References

Anonymous, 2001. Summary and major provisions of the EPA process for exempting quarantine and pre-shipment applications of methyl bromide. Interim final rule. Federal Register, 19 July 2001, pp. 37752–37769.

AOCS, 1998a. AOCS official method Cd 8–53: peroxide value acetic acid–chloroform method. In: Official Methods and Recommended Practices of the American Oil Chemists, pp. 1–2.

AOCS, 1998b. AOCS official method Cd 5a-40: free fatty acids. In: Official Methods and Recommended Practices of the American Oil Chemists, pp. 1–2.

Moffitt, H.R., Burditt, A.K., 1989. Effect of low temperatures on three embryonic stages of the codling moth (Lepidoptera: Tortricidae). J. Entomol. 82, 1379–1381.

Taoukis, P.S., Labuza, T.P., Sagus, I.S., 1997. Kinetics of food deterioration and shelf-life prediction. In: Valentas, K.J., Rotstein, E., Singh, R.P. (Eds.), Handbook of Food Engineering Practice. CRC Press, Boca Raton, FL, p. 374.

Thayer, D.W., Harlan, J.W., 1983. Status of the USDA food irradiation programs. Food Technol. 37, 46–47.

Toba, H.H., Moffitt, H.R., 1991. Controlled atmosphere storage and quarantine treatment for non-diapausing codling moth larvae in apples. J. Entomol. 84, 1316–1319.

Wang, S., Tang, J., Ikediala, J.N., 2001. Combined radio frequency and hot air treatments for insect control and drying of in-shell walnuts. ASAE Meeting Presentation, Paper No. 016170. Sacramento, CA, USA, 30 July–1 August 2001.

Wang, S., Tang, J., Johnson, J.A., Mitcham, E., Hansen, J.D., Cavalieri, R.P., Bower, J., Biasi, B., 2002. Process protocols based on radio frequency energy to control field and storage pests in in-shell walnuts. Postharvest Biol. Technol. 26, 265–273.

Wang, S., Tang, J., Cavalieri, R.P., Davis, D., 2003. Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments. Trans. ASAE 46, 1175–1182.