JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Warm Water Treatment in Combination with Modified Atmosphere Packaging Reduces Undesirable Effects of Irradiation on the Quality of Fresh-Cut Iceberg Lettuce

XUETONG FAN,*,† PETER M. A. TOIVONEN,‡ KATHLEEN T. RAJKOWSKI,† AND KIMBERLY J. B. SOKORAI†

Eastern Regional Research Center, Agricultural Research Service, U.S. Department of Agriculture, 600 East Mermaid Lane, Wyndmoor, Pennsylvania 19038, and Pacific Agri-Food Research Centre, Agriculture and Agri-Food Canada, Summerland, British Columbia, Canada V0H 1Z0

Fresh-cut iceberg lettuce dipped in either 5 or 47 °C water for 2 min was packaged in modified atmosphere film bags and then exposed to 0, 0.5, 1, or 2 kGy γ-radiation. Dipping cut lettuce in 47 °C water for 2 min prior to irradiation reduced antioxidant and phenolic accumulations induced by irradiation. Irradiation at 2 kGy increased cellular leakage and sogginess of cut lettuce dipped in both temperatures. Samples irradiated at 0.5 and 1 kGy had similar firmness and vitamin C and antioxidant contents as the controls after 14 and 21 days of storage except 1 kGy samples dipped at 47 °C had lower antioxidant contents than controls at 14 days of storage. Lettuce dipped at 47 °C and irradiated at 0.5 and 1 kGy had better overall visual quality and less tissue browning than corresponding irradiated samples dipped at 5 °C. These results suggest lettuce treated with warm water and irradiated at 0.5 or 1 kGy had the best sensory quality without significant loss in texture, vitamin C, or total antioxidants.

KEYWORDS: Irradiation; lettuce; warm water treatment; quality; antioxidants

INTRODUCTION

Consumption of fresh-cut vegetables in the United States has increased every year in the past decade. However, there is a concern for the microbial safety of fresh-cut vegetables. Fresh-cut vegetables, including lettuce, have high levels of microorganisms (*1*). Although the percentage of fresh-cut vegetables contaminated with food-borne human pathogens is very low, several outbreaks of food-borne illness have been found to be associated with the consumption of fresh vegetables (*2*, *3*). Psychrotropic bacteria, such as *Listeria monocytogenes*, are known to grow at low temperature even under modified atmosphere packaging (*4*). Various disinfectants used in commercial processing lines, such as chlorine, have only limited effect (∼1 log reduction) on microbial populations (*5*).

Ionizing irradiation is a nonthermal technology that effectively eliminates food-borne pathogens in various foods, including fresh vegetables. Langerak (*6*) showed that radiation at 1 kGy resulted in reductions of bacterial populations while doubling the shelf life of cut endive. A dose of 0.19 kGy radiation combined with chlorination significantly reduced microbial populations of cut lettuce (*7*). Farkas and others (*8*) showed that 1 kGy radiation reduced loads of spoilage bacteria, improved microbiological shelf life, and extended sensorial keeping quality of precut peppers and carrots. Prakash and others (*9*) found that a dose of 0.35 kGy γ-radiation decreased aerobic counts by 1.5 logs on cut romaine lettuce, and the difference was maintained for the 22 days of storage at 4 °C. A 10% loss in firmness was observed by the radiation dose, but no other sensory attributes were affected. Prakash and others (*10*) also found that 1 kGy radiation eliminated *L. monocytogenes* and *Escherichia coli* inoculated on diced celery while extending shelf life by 1 week. Although the low doses of irradiation can inactivate some radiation-sensitive pathogens, to achieve a 5 log reduction of radiation-resistant bacteria, higher doses (>1 kGy) of radiation are required. At those doses, irradiation may induce undesirable changes in quality, such as softening, browning, and loss of vitamin C. Therefore, to achieve the 5 log reduction, irradiation is likely to be used in combination with other pathogen-reducing techniques.

Mild heat treatment has been used for many years as a nonchemical method to control fungal rots in various fruits and vegetables (*11*, *12*). Recently, it has been shown that the treatment also reduces populations of bacteria in lettuce. Delaquis and others (*13*) demonstrated that microbial population was reduced by 3 logs in lettuce washed in chlorinated water at 47 °C and by 1 log at 4 °C. Li and others (*14*) showed that treatment at 50 °C water, with or without chlorine, reduced the population of mesophilic aerobic microflora by 1.7−2.0 logs. However, treatment of lettuce with 20 ppm (μg mL^{-1}) of

* Author to whom correspondence should be addressed [telephone (215) 836-3785; fax (215) 233-6445; e-mail xfan@arserrc.gov].
† U.S. Department of Agriculture.
‡ Agriculture and Agri-Food Canada.

10.1021/jf020600c
Published on Web 01/23/2003

chlorine at 50 °C did not result in significantly greater reductions in populations of *E. coli* O157:H7 inoculated onto fresh-cut lettuce (*15*). Besides the possible reduction of microbial population by the mild heat treatment, it also extends the shelf life of lettuce by inhibiting the activity of phenylalanine ammonia-lyase (PAL) and by inducing heat shock proteins, resulting in the reduction of phenolics accumulation and tissue browning (*16*, *17*). Furthermore, heat treatment applied either before or after stress can increase the tolerance of plant tissue to stress (*17*, *18*). Ionizing irradiation can be regarded as a stress, exerting most of its effects through free radicals generated from the radiolysis of water. It is unclear whether heat shock can reduce the adverse affect of irradiation on lettuce quality. The objective of this study is to investigate the effect of irradiation in combination with mild heating on the quality of fresh-cut iceberg lettuce.

MATERIALS AND METHODS

Sample Preparation. California-grown cv. Sharpshooter iceberg lettuce was obtained through a local distributor. The lettuce was stored at 3 °C overnight before being processed. Plastic wraps and outer leaves were discarded, and the heads were cored. The leaves were cut with sharp stainless steel knives into pieces of 3 cm square. The pieces were randomized and divided into two lots. One lot of lettuce was treated with warm water (47 °C), and another lot was treated with cold water (5 °C). For treatment at 47 °C, lettuce pieces (~600 g) were placed into a screen basket and then submerged for 2 min in a 100 L water bath at 47 °C. The 47 °C water bath was maintained within 0.5 °C difference during treatment with a 2750 W heater (model MW-1140A-1, Blue M, Blue Island, IL). The lettuce pieces treated at 47 °C were then immediately placed into 5 °C water for 1 min. The lettuce was then drained and spin-dried using hand-operated kitchen spinners (Wilton Industries Inc., Woodridge, IL). For treatment at 5 °C, lettuce was submerged into 5 °C water for 3 min and then spin-dried. The lettuce pieces were then placed into film bags (E-300, Cryovac, Deerfield, IL) with an oxygen transmission rate of 4000 $cm^3/h/m^2$ at 23 °C. There were four bags of cut lettuce for each treatment, and each bag was regarded as a replicate. Each bag contained 150 g of samples. The lettuce in the unsealed bags was stored at 3 °C overnight before being sealed using an impulse sealer. The lettuce was then immediately irradiated at 0, 0.5, 1, or 2 kGy at 4 °C (see below). A dose of 1 kGy involves the absorption of 1 kJ of energy by each kilogram of matter through which the radiation passes. After irradiation, samples were stored at 3 °C. Firmness, vitamin C, color, and sensory evaluation (see below) were measured before irradiation and at 1, 7, 14, and 21 days of storage. Headspace O_2 and CO_2 levels within the packages were also monitored periodically.

Irradiation and Dosimetry. The samples were irradiated using a self-contained cesium-137 γ-radiation source (Lockheed Georgia Co.) with a dose rate of 0.098 kGy/min. Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, by irradiating them within a polypropylene container (4 mm wall) to absorb Compton electrons, and by using the same geometry for sample irradiation during the entire study. During irradiation, temperature in the radiation chamber was controlled by flushing the gas phase of liquid nitrogen into the upper portion of chamber. To eliminate possible effects of nitrogen flushing during irradiation, bags of all treatments were placed in the chamber with nitrogen flushing for the same total period (~21 min). Routine dosimetry was performed using 5-mm-diameter alanine pellets (Bruker, Inc., Billarna, MA). The pellets were placed into 1.2 mL cryogenic vials (Nalgene, Rochester, NY), and the cryogenic vials were placed with the samples prior to irradiation. Alanine pellets were read using a Bruker EMS 104 EPR analyzer and compared with a standard curve. Actual dose was typically within 5% of the targeted doses.

Cellular Leakage. Ten grams of lettuce was placed into 50 mL of deionized water for 2 min at 23 °C with stirring. Electrolyte leakage into the bathing solution was measured using a CON 100 conductivity meter (Oakton, Singapore).

Color Analysis. A Hunter Miniscan XE colorimeter (Hunter Associates Laboratory, Reston, VA) was used to assess lettuce color. The measuring aperture diameter was 36 mm, and D65/10° was the illuminant/viewing geometry. The color meter was calibrated using the standard white and black plates. Two readings were made on lettuce samples from each package. The reading was made on ~20 g samples. Chroma and hue values were calculated from a^* and b^* values (*19*).

Texture. Texture was determined using the TA-XT2i texture analyzer (Texture Technology Corp., Scarsdale, NY) and a Kramer shear press with five blades. A 20 g sample was placed into the press holder, and then the five-blade plunger was moved down at 2 mm/s, to 1 cm below the bottom of the holder. Maximum force was recorded using Texture Expert software (version 1.22, Texture Technology Corp.). Two readings were made on lettuce samples from each package. There were a total of eight measurements for each treatment.

Sensory Evaluation. Each sample was visually rated by four judges according to the scoring system developed by Kader and others (*20*) and Lopez-Galvez and others (*21*). For overall quality, the scale was 1−9, with 9 as excellent and 1 as unusable. Leaf surface browning and edge browning were rated as 1−5 with 1 as no browning and 5 as the severest. The sogginess was rated as 1 (none) to 5 (the severest).

Headspace Analysis. Gases within the sealed packages were periodically sampled to determine the levels of CO_2 and O_2 during storage. To measure the atmosphere, a 0.5 mL headspace was withdrawn using a syringe from the bags by piercing the film with a fine hypodermic needle. The sampling hole was resealed with a patch of electrical tape, and the contents of the bag were used in subsequent quality analysis. The gas samples were then injected into a Gow-Mac series 580 gas chromatograph (Gow-Mac Instrument, Bridgewater, NJ) equipped with a 183 cm CTR I column (Alltech Asoociates, Inc., Deerfield, IL) and a thermal conductivity detector. The CTR I column consists of an outer column (0.64 cm i.d.) packed with an activated molecular sieve and an inner column (0.32 cm i.d.) packed with a porous polymer mixture. The injector, oven, and detector temperatures were held at ambient (23−25 °C). The carrier gas was helium with a flow rate at 120 mL min^{-1}. CO_2 and O_2 levels were calculated in comparison to a standard.

Vitamin C Analysis. Vitamin C [ascorbic acid (AA) plus dehydroascorbic acid] was measured according to the method of Graham and Annette (*22*) with minor modifications. Samples (10 g) were homogenized with 20 mL of 5% (62.5 mM) metaphosphoric acid (MPA) using a homogenizer (Virtishear, Virtis, Gardiner, NY) at a speed setting of 70 for 1 min. The homogenate was filtered through four layers of cheesecloth, and then the filtrate was centrifuged at 11952*g* for 10 min at 5 °C in a Sorvall RC2-B refrigerated centrifuge (Kendro Laboratory Products, Newtown, CT). To reduce dehydroascorbic acid in the supernatant to AA, 1 mL aliquot of supernatant was added to 0.16 mL of 30 mM DL-homocysteine solution and the pH adjusted to 6.5−7.0 by slow addition of 2.6 M dipotassium hydrogen phosphate. After 30 min at 23 °C, the reaction was stopped by the addition of 5% (w/v) MPA. Total volume was adjusted to 2 mL using 5% MPA. The mixture was filtered through a 0.45 μm Acrodisc LC 13 PVDF syringe filter (Gelman Sciences, Ann Arbor, MI). The filtered samples were placed into 2 mL vials and analyzed using a Hewlett-Packard Ti-series 1050 HPLC system (Agilent Technologies, Palo Alto, CA). The HPLC system consists of an autosampler, an integral photodiode array detector, an autoinjector, and a Hewlett-Packard rev. A02. 05 Chemstation. Injection volume was 20 μL. Separation of compounds was achieved with an Aminex HPX-87H organic acids column (300 × 7.8 mm) fitted with a microguard cation H+ eluted with a mobile phase of 5 mM sulfuric acid at a flow rate of 0.5 mL min^{-1}. Column temperature was maintained at 30 °C using a column heater (Bio-Rad Laboratories, Hercules, CA). AA was monitored at 245 nm and calculated from an AA standard.

Antioxidant Analysis. Samples (10 g) were homogenized with 20 mL of 50% ethanol using a homogenizer (Virtishear, Virtis) at a speed setting of 70 for 1 min. The homogenate was filtered through four layers of cheesecloth and then centrifuged at 11952*g* for 10 min at 5 °C in a Sorvall RC2-B refrigerated centrifuge (Kendro Laboratory Products). Antioxidant power in the supernatants was determined using the ferric reducing antioxidant power (FRAP) assay (*23*).

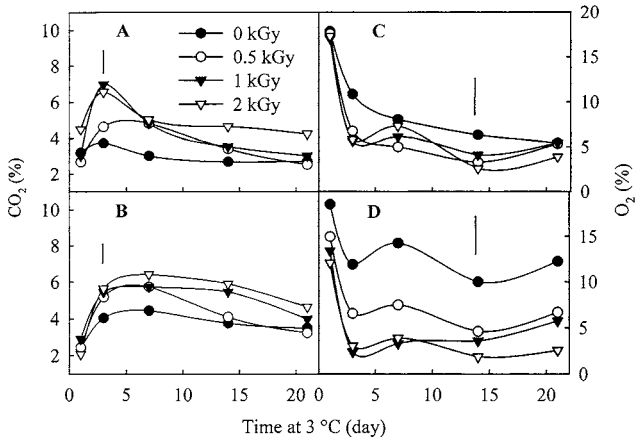

Figure 1. Changes in headspace CO_2 (A, B) and O_2 (C, D) levels in the modified atmospheric packages of fresh-cut iceberg lettuce during storage at 3 °C. Fresh-cut lettuce dipped in water of 5 °C (A, C) or 47 °C (B, D) was irradiated at a dose of 0, 0.5, 1, or 2 kGy. The samples were then stored at 3 °C. Values are means of four replicates. Vertical bars represent the LSD ($P < 0.05$) values.

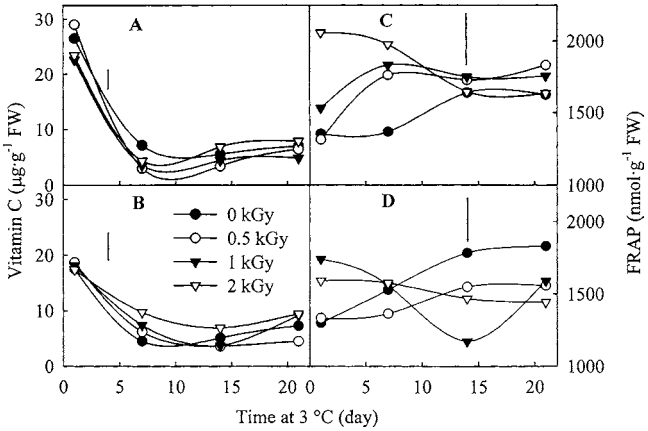

Figure 2. Changes in vitamin C content (A, B) and antioxidant capacity (C, D) of fresh-cut iceberg lettuce during storage at 3 °C. Fresh-cut lettuce dipped in water of 5 °C (A, C) or 47 °C (B, D) was irradiated at a dose of 0, 0.5, 1, or 2 kGy. The samples were then stored at 3 °C. Antioxidant capacity was measured during the ferric reducing antioxidant power (FRAP) assay. Values are means of four replicates. Vertical bars represent the LSD ($P < 0.05$) values.

Phenolics Analysis. Total phenolic content was measured using the Folin−Ciocalteu colorimetric method (*24*, *25*). The extract (0.9 mL) used for the FRAP assay was mixed with 0.1 mL of 50 units/mL ascorbate oxidase and then incubated at 23 °C for 90 min to remove ascorbic acid. Then the ascorbate-free extract (0.1 mL) was mixed with 0.2 mL of Folin−Ciocalteu reagent (Sigma Chemical Co., St. Louis, MO) and incubated for 1 min at 23 °C. Then 3 mL of 5% Na_2CO_3 was added. Absorbances at 765 nm were recorded for the mixtures after 2 h of incubation at 23 °C. Phenolic content was expressed as milligrams per gram of gallic acid equivalent.

Statistical Analysis. Data were subjected to statistical analysis using SAS ver. 6.12 (SAS Institute, Raleigh, NC). The effect of radiation dose, storage time, and dipping temperature as well as interaction between dose, storage time, and temperature were performed using the general linear model (GLM) procedure.

RESULTS AND DISCUSSION

Package Atmosphere. CO_2 levels of all samples increased initially and reached a maximum at day 3 for packages containing lettuce dipped at 5 °C (**Figure 1A**,**B**). The maximums were observed at day 7 for samples dipped at 47 °C. Irradiated samples had sharper increases in CO_2 levels and higher maximums than non-irradiated samples. During most of the storage period, irradiated samples had higher CO_2 levels compared with non-irradiated samples. CO_2 levels were slightly higher in samples dipped at 47 °C than at 5 °C, particularly at 14 and 21 days of storage.

O_2 levels within all packages decreased rapidly during the first 3 days of storage (**Figure 1C**,**D**). Irradiated samples had a faster initial decrease in O_2 levels and were relatively stable thereafter. For non-irradiated lettuce, O_2 levels were lower in samples treated at 47 °C than in those treated at 5 °C. During most of the storage period, irradiated samples had lower O_2 levels, regardless of water treatment temperature. For samples dipped at 5 °C, higher doses of irradiation resulted in lower O_2 levels in the package headspace.

The faster initial changes in headspace O_2 and CO_2 of irradiated samples indicate that respiration may be stimulated by irradiation. Earlier studies have demonstrated that irradiation increases respiration in a number of fresh fruits and vegetables (*26*, 27).

Color and Texture. Generally speaking, chroma values increased while L^* and hue values decreased during storage (data not shown). Irradiation and dipping water temperature had no effect on L or chroma values. The changes in the color parameters indicate that lettuce lost greenness and became darker during storage. On the average, lettuce dipped at 47 °C had small but statistically significantly ($P < 0.05$) lower hue value (98.9 vs 99.9) than that dipped at 5 °C.

Firmness did not show a consistent change in response to storage time or radiation dose during storage except that firmness decreased with increasing radiation doses at 1 day of storage in lettuce dipped at 5 °C (data not shown). Lettuce treated at 47 °C had slightly but significantly ($P < 0.05$) lower firmness (2.0 vs 1.9 kg) than that treated at 5 °C, on average.

Nutritive Values. The vitamin C content of all lettuce samples decreased linearly during storage, but most of the loss occurred during the first week of storage (**Figure 2A**,**B**). Radiation dose had no consistent effect on vitamin C content. At day 1, lettuce dipped at 47 °C, regardless of dose, had a lower vitamin C content than that dipped at 5 °C. At 7 days of storage, vitamin C increased with higher radiation dose in lettuce dipped at 47 °C. After 14 and 21 days of storage, there was no significant difference in vitamin C content among the samples.

At 1 and 7 days of storage, antioxidant content increased with higher radiation doses in lettuce dipped at 5 °C, whereas irradiation had little effect on the antioxidant level of lettuce dipped at 47 °C (**Figure 2C**,**D**). The antioxidant content of all non-irradiated lettuce samples as well as those dipped at 5 °C and irradiated at 0.5 kGy increased linearly during the 21 days of storage, whereas that of lettuce dipped at 5 °C and irradiated at 2 kGy decreased during storage. After 14 and 21 days of storage, antioxidant content did not differ among irradiated and non-irradiated lettuce dipped at 5 °C, whereas antioxidant content decreased with higher radiation doses in lettuce dipped at 47 °C. Lettuce dipped at 47 °C and irradiated at 0.5 or 1 kGy had an antioxidant content similar to that of non-irradiated samples after 21 days of storage.

Compared to antioxidants, phenolics of lettuce had similar changes in response to water dipping, irradiation, and storage (data not shown). The increase in phenolic content induced by irradiation was less pronounced in lettuce dipped at 47 °C than at 5 °C at 1 and 7 days of storage.

Our results show that the increased antioxidant content induced by irradiation was negated by the 47 °C water dip

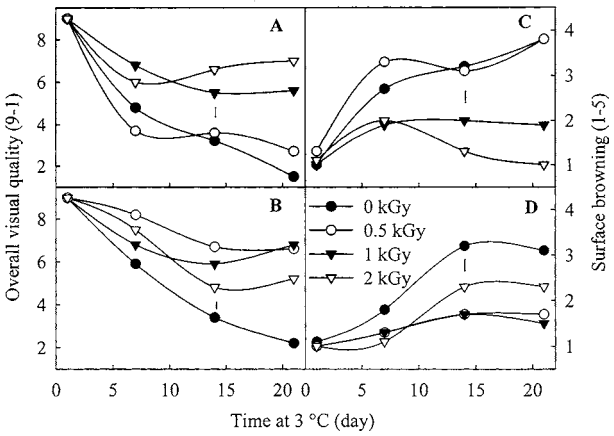

Figure 3. Changes in overall visual quality (A, B) and surface browning (C, D) of fresh-cut iceberg lettuce during storage at 3 °C. Fresh-cut lettuce dipped in water of 5 °C (A, C) or 47 °C (B, D) was irradiated at a dose of 0, 0.5, 1, or 2 kGy. The samples were then stored at 3 °C. Values are means of four replicates. Vertical bars represent the LSD ($P < 0.05$) values.

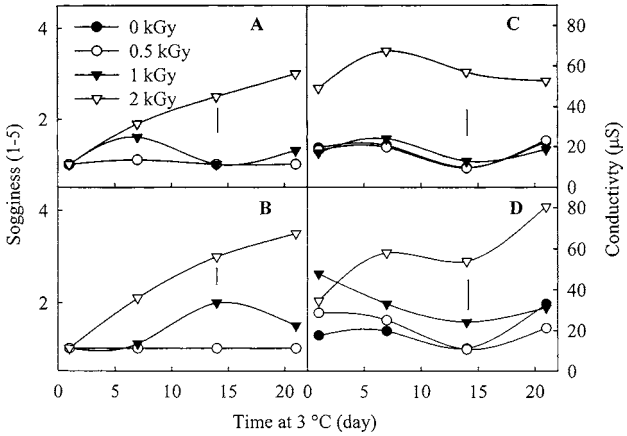

Figure 4. Changes in sogginess (A, B) and cellular leakage (C, D) of fresh-cut iceberg lettuce during storage at 3 °C. Fresh-cut lettuce dipped in water of 5 °C (A, C) or 47 °C (B, D) was irradiated at a dose of 0, 0.5, 1, or 2 kGy. The samples were then stored at 3 °C. Values are means of four replicates. Vertical bars represent the LSD ($P < 0.05$) values. Sogginess scores overlap for the 0 and 0.5 kGy samples.

treatment, and phenolic content induced by 2 kGy radiation was higher in lettuce dipped at 5 °C than at 47 °C at 1 day of storage (data not shown). These results indicate warm water dipping reduces the lettuce's ability to synthesize phenolics and antioxidants. Heat shock has been shown to shift the normal protein synthesis to synthesize heat shock protein (*17*, *28*). PAL, the key enzyme for the synthesis of phenolics, is reduced by heat shock (*16*). Our results suggest that irradiation induces phenolics synthesis, but the heat shock before irradiation reduces the radiation-induced synthesis of phenolics.

Free radicals generated during irradiation may act as stress signals and may trigger stress responses in lettuce, resulting in increased antioxidant synthesis. It appears that irradiation stimulated the synthesis of phenolics but not that of vitamin C, although both phenolics and vitamin C are antioxidants. Phenolic compounds are the major component of antioxidants in plant tissues (*29*). γ-Radiation induces accumulation of 4-(3-methyl-2-butenoxy)isonitrosoacetophenone in citrus fruit. This compound exhibits both antioxidant and antifungal activities (*30*). The increased antioxidant values due to irradiation have also been observed in fruit juice (*31*) and alfalfa sprouts (*32*).

Sensory Evaluation and Cellular Leakage. The overall visual quality of lettuce deteriorated during storage (**Figure 3A**,**B**). The decrease in visual quality was slower in irradiated samples. After 21 days of storage, non-irradiated lettuce was mostly unusable. Irradiated lettuce had better overall quality than non-irradiated lettuce dipped at either 47 or 5 °C. On average, lettuce samples dipped at 47 °C had better quality than those dipped at 5 °C. Overall quality generally increased with higher radiation dose. After 21 days of storage, lettuce dipped at 5 °C and irradiated at 2 kGy and lettuce treated at 47 °C and irradiated at 0.5 or 1 kGy had better quality than the rest of the lettuce samples.

Surface browning increased during storage (**Figure 3C**,**D**). Surface browning generally decreased with higher radiation doses at 7, 14, and 21 days of storage, regardless of dipping water temperature. After 21 days of storage, lettuce dipped at 47 °C and irradiated at 1 or 2 kGy as well as that dipped at 5 °C and irradiated at 2 kGy had the least surface browning. At 0.5 kGy, lettuce dipped at 47 °C had consistently less surface browning than samples dipped at 5 °C. Edge browning displayed a trend very similar to that of surface browning in response to radiation, dipping water temperature, and storage time (data not shown). The overall quality had negative correlation with browning on surface or edge, in agreement with an earlier study (*21*). Li and others (*14*), however, found that treatment at 50 °C reduced browning but did not improve overall quality.

Sogginess increased during storage (**Figure 4A**,**B**). Lettuce irradiated at 2 kGy had higher sogginess scores during most of the storage period regardless of dipping temperature. Lettuce dipped at 47 °C and irradiated at 2 kGy had the highest sogginess scores. Lettuce irradiated at 0.5 or 1 kGy had no significantly different in sogginess compared to controls after 21 days of storage.

The cellular leakage of lettuce dipped at 5 °C did not change consistently during storage for non-irradiated lettuce (**Figure 4C**,**D**). Lettuce irradiated at 2 kGy had higher leakage than the respective control samples treated at the same temperatures during the entire storage period. The leakage of lettuce dipped at 47 °C and irradiated at 0.5 or 1 kGy decreased during storage, whereas the leakage of lettuce dipped at 47 °C and irradiated at 2 kGy increased during storage. The decrease in the leakage during storage suggests lettuce irradiated at 0.5 or 1 kGy recovered partially from injuries due to irradiation. The increase in leakage of lettuce irradiated at 2 kGy during storage indicates that the damage was severe and beyond repair. Lettuce samples dipped at 47 °C had higher cellular leakage than those dipped at 5 °C measured immediately after dipping (day 0). Although lettuce dipped at 47 °C and irradiated at 1 kGy had higher leakage that non-irradiated samples at 1 day of storage, there was no difference in the electrolyte leakage between the two treatments at 7, 14, or 21 days of storage.

Traditionally, membrane permeability of plant tissues was measured by assessing conductivity changes of bathing water or solution after 1−3 h of incubation and reported as the percentage of total electrolytes in given time. In the present study, the incubation time for measurement of leakage was only 2 min and total electrolytes were not measured. The measurement used in the present study represents solutes (ions) already leaking out of tissues. Our results indicate both cellular leakage and sogginess increased as radiation dose increased. The sogginess may be due to the leakage of fluid from cell and may be regarded as flaccidity or loss of turgidity. Our results also show that although firmness was lower in some irradiated samples at day 1, the difference disappeared as storage prolonged. El Assi and others (*33*) found that firmness loss in tomato pericarp tissues due to irradiation was apparent within

24 h following irradiation; however, by 7 days after treatment, firmness of pericarp treated at 0.7 kGy was comparable with that of pericarp from control fruit. Water content and cell turgidity may play an important role in tissue turgidity and firmness. Loss of cell turgidity and increased cell leakage may reduce firmness. However, tissues after low-dose irradiation can re-absorb fluid from intercellular space (*34*), which may result in the partial recovery of firmness.

Recently, Li and others (*14*) showed that heat treatment (50 °C, 1.5 min) initially reduced population of psychrotropic microorganisms and mesophilic aerobic microorganisms occurring naturally on iceberg lettuce. However, microorganisms grew more quickly during subsequent storage. After 14 days of storage at 5 °C, there was no difference between the treatments. They also found that dipping lettuce at 50 °C did not result in significantly greater reductions in populations of *E. coli* O157:H7 compared to treatments at 20 °C. Loaiza-Velarde and others (*16*) found that warm water treatment (1−2 min) decreased lettuce tissue browning. The efficacy increased as water temperature increased from 45 to 55 °C. However, tissue damage increased with higher dipping water temperature. The sensitivity of produce to heat injury varied with preharvest weather and growing conditions, cultivar, rate of heating, and subsequent storage (*35*). We used 47 °C for the current experiment because we have found that a dipping temperature of 50 °C resulted in severe injury to lettuce tissue (data not shown).

Although irradiation at 1 and 2 kGy increased phenolic content of lettuce at 1 and 7 days of storage (data not shown), the lettuce had less browning. The reduction in browning and improvement in overall visual quality were probably due to high CO_2 and low O_2 levels in the packages, which resulted from an irradiation-induced increase in respiration rate. High CO_2 and low O_2 levels have been shown to inhibit browning of fresh-cut lettuce (*36*).

Our results suggested that irradiation had little effect on firmness or Hunter color parameters but increased antioxidant and phenolic contents. Dipping lettuce in 47 °C water reduced irradiation-induced phenolics and antioxidants, but treatment with warm water also increased the sensitivity of lettuce to irradiation, as evidenced by electrolyte leakage and sogginess, particularly at 2 kGy. Irradiation at 0.5 or 1 kGy in combination with warm water treatment had the least browning and best overall visual quality without consistent losses in firmness, vitamin C content, or antioxidant content. Overall, our results suggest that warm water treatment in combination with low-dose (0.5 or 1 kGy) radiation, which has been shown by others to reduce microbial populations on lettuce, can also help maintain the sensory quality of fresh-cut lettuce packaged in modified-atmosphere bags.

ACKNOWLEDGMENT

We thank Robert Richardson, Sara Beltz, and Michael Ryan Ott for technical assistance.

LITERATURE CITED

(1) Barriga, M. I.; Trachy, G.; Willemot, C.; Simard, R. E. Microbial changes in shredded iceberg lettuce stored under controlled atmospheres. *J. Food Sci.* **1991**, *56*, 1586−1588, 1599.

(2) Beuchat, L. R. Pathogenic microorganisms associated with fresh produce. *J. Food Prot.* **1996**, *59*, 204−216.

(3) Wachtel, M. R.; Charkowski, A. O. Cross-contamination of lettuce with *Escherichia coli* O157:H7. *J. Food Prot.* **2002**, *65*, 465−470.

(4) Beuchat, L. R.; Brackett, R. E. Survival and growth of *Listeria monocytogenes* on lettuce as influenced by shredding, chlorine treatment, modified atmosphere packaging and temperature. *J. Food Sci.* **1990**, *55*, 755−757, 870.

(5) Zhang, S.; Farber, J. M. The effects of various disinfectants against *Listeria monocytogenes* on fresh-cut vegetables. *Food Microbiol.* **1996**, *13*, 311−321.

(6) Langerak, D. I. The influence of irradiation and packaging on the quality of prepacked vegetables. *Ann. Nutr. Aliment.* **1978**, *32*, 569−586.

(7) Hagenmaier, R. D.; Baker, R. A. Low-dose irradiation of cut iceberg lettuce in modified atmosphere packaging. *J. Agric. Food Chem.* **1997**, *45*, 2864−2868.

(8) Farkas, J.; Saray, T.; Mohacsi-Farkas, C.; Horti, C.; Andrassy, E. Effects of low-dose γ-irradiation on shelf life and microbiological safety of precut/prepared vegetables. *Adv. Food Sci.* **1997**, *19*, 111−119.

(9) Prakash, A.; Guner, A. R.; Caporaso, F.; Foley, D. M. Effects of low-dose γ-irradiation on the shelf life and quality characteristics of cut romaine lettuce packaged under modified atmosphere. *J. Food Sci.* **2000**, *65*, 549−553.

(10) Prakash, A.; Inthajak, P.; Huibregtse, H.; Caporaso, F.; Foley, D. M. Effects of low-dose γ-irradiation and conventional treatments on shelf life and quality characteristics of diced celery. *J. Food Sci.* **2000**, *65*, 1070−1075.

(11) Couey, H. M. Heat treatment for control of postharvest diseases and insect pests of fruits. *HortScience* **1989**, *24*, 198−202.

(12) Lurie, S. Postharvest heat treatments of horticultural crops. *Hortic. Rev.* **1998**, *22*, 91−121.

(13) Delaquis, P. J.; Stewart, S.; Toivonen, P. M. A.; Moyls, A. L. Effect of warm, chlorinated water on the microbial flora of shredded iceberg lettuce. *Food Res. Int.* **1999**, *32*, 7−14.

(14) Li, Y.; Brackett, R. E.; Shewfelt, R. L.; Beuchat, L. R. Changes in appearance and natural microflora on iceberg lettuce treated in warm, chlorinated water and then stored at refrigeration temperature. *Food Microbiol.* **2001**, *18*, 299−308.

(15) Li, Y.; Brackett, R. E.; Chen, J.; Beuchat, L. R. Survival and growth of *Escherichia coli* O157:H7 inoculated onto cut lettuce before and after heating in chlorinated water, followed by storage at 5 or 15 C. *J. Food Prot.* **2001**, *64*, 305−309.

(16) Loaiza-Velarde, J. G.; Tomas-Barbera, F. A.; Saltveit, M. E. Effect of intensity and duration of heat shock treatments on wound-induced phenolics metabolism in iceberg lettuce. *J. Am. Soc. Hortic. Sci.* **1997**, *122*, 872−977.

(17) Saltveit, M. E. Wound induced changes in phenolics metabolism and tissue browning are altered by heat shock. *Postharvest Biol. Technol.* **2000**, *21*, 61−69.

(18) Loaiza-Velarde, J. G.; Saltveit, M. E. Heat shocks applied either before or after wounding reduce browning of lettuce leaf tissue. *J. Am. Soc. Hortic. Sci.* **2001**, *126*, 227−234.

(19) McGuire, R. G. Reporting of objective color measurement. *HortScience* **1992**, *27*, 1254−1255.

(20) Kader, A. A.; Lipton, W. J.; Morris, L. L. Systems for scoring quality of harvested lettuce. *HortScience* **1973**, *8*, 408−409.

(21) Lopez-Galvez, G.; Saltveit, M. E.; Cantwell, M. The visual quality of minimally processed lettuces stored in air or controlled atmosphere with emphasis on romaine and iceberg types. *Postharvest Biol. Technol.* **1996**, *8*, 179−190.

(22) Graham, W. D.; Annette, D. Determination of ascorbic and dehydroascorbic acid in potatoes (*Solanum tuberosum*) and strawberries using ion-exclusion chromatography. *J Chromatogr.* **1992**, *594*, 187−194.

(23) Benzie, I. F. F.; Strain, J. J. Ferric reducing/antioxidant power assay: Direct measure of total antioxidant activity of biological fluids and modified version for simultaneous measurement of total antioxidant power and ascorbic acid concentration. *Methods Enzymol.* **1996**, *299*, 15−27.

(24) Gao, X.; Bjork, L.; Trajkovski, V.; Uggla, M. Evaluation of antioxidant activities of rosehip ethanol extracts in different test systems. *J. Sci. Food Agric.* **2000**, *80*, 2021−2027.

(25) Singleton, V. L.; Orthofer, R.; Lamuela-Raventos, R. M. Analysis of total phenols and other oxidation substrates and antioxidants by means of Folin−Ciocalteu reagent. *Methods Enzymol.* **1999**, *299*, 152−178.

(26) Couture, R.; Makhlouf, J.; Cheqour, F.; Willemot, C. Production of CO_2 and C_2H_4 after γ-irradiation of strawberry fruit. *J. Food Qual.* **1990**, *13*, 385−393.

(27) Maxie, E. C.; Abdel-Kader, A. Food irradiation—Physiology of fruits as related to feasibility of the technology. *Adv. Food Res.* **1966**, *15*, 105−145.

(28) Vierling, E. The roles of heat shock proteins in plants. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1991**, *42*, 579−620.

(29) Cao, G.; Sofic, E.; Prior, R. L. Antioxidant capacity of tea and common vegetables. *J. Agric. Food Chem.* **1996**, *44*, 3426−3431.

(30) Dubery, I. A.; Louw, A. E.; van Heerden, F. R. Synthesis and evaluation of 4-(3-methyl-2-butenoxy) isonitrosoacetophenone, a radiation-induced stress metabolite in citrus. *Phytochemistry* **1999**, *50*, 983−989.

(31) Fan, X.; Thayer, D. W. γ-radiation influences browning, antioxidant activity and malondialdehyde level of apple juice. *J. Agric. Food Chem.* **2002**, *50*, 710−715.

(32) Fan, X.; Thayer, D. W. Quality of irradiated alfalfa sprouts. *J. Food Prot.* **2001**, *64*, 1574−1578.

(33) El Assi, N.; Huber, D. J.; Brecht, J. K. Irradiation-induced changes in tomato fruit and pericarp firmness, electrolyte efflux, and cell wall enzyme activity as influenced by ripening stage. *J. Am. Soc. Hortic. Sci.* **1997**, *122*, 100−106.

(34) Skou, J. P. Changes in the permeability of carrot tissues due to γ-irradiation and other physical and chemical treatments. *Physiol. Plant.* **1963**, *16*, 423−441.

(35) Paull, R. E.; Chen, N. J. Heat treatment and fruit ripening. *Postharvest Biol. Technol.* **2000**, *21*, 21−37.

(36) Gorny, J. R. A summary of CA and MA recommendation for selected fresh-cut fruits and vegetables. In *Seventh International Controlled Atmosphere Research Conference. CA '97 Vol. 5: Fresh-Cut Fruits and Vegetables and MAP*; Gorny, J. R., Ed.; University of California: Davis, CA, 1997; pp 34−66.

Received for review May 28, 2002. Revised manuscript received October 23, 2002. Accepted October 29, 2002. Mention of brand or firm name does not constitute an endorsement by the U.S. Department of Agriculture above others of a similar nature mentioned

JF020600C