Impact of Antimicrobial ingredients and Irradiation on the Survival of *Listeria monocytogenes* and the Quality of Ready-to-Eat Turkey Ham

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ABSTRACT Irradiation is an effective technology in eliminating *Listeria monocytogenes*, but it induces quality changes in meat products at or above specific radiation doses. To minimize irradiation-induced quality changes, only low irradiation doses are recommended. However, low-dose irradiation provides a chance for some pathogens to survive and proliferate during prolonged storage. To solve this problem, antimicrobial ingredients [2% sodium lactate (SL), 0.1% sodium diacetate (SDA), 0.1% potassium benzoate (PB)] and low-dose irradiation were combined and tested for their effects on the growth of *L. monocytogenes* and meat quality. The $\log_{10}$ reductions of *L. monocytogenes* in hams following exposure to 1.0 to 2.5 kGy of irradiation ranged from 2.0 to 5.0. The D_{10} values were 0.52 kGy for control ham or ham with PB, SL, or PB + SL; 0.49 kGy for ham with SL+SDA; and 0.48 kGy for ham with PB + SL + SDA (PSS). Addition of SL + SDA or PB + SL in combination with 1.0 kGy of irradiation was effective in suppressing the growth of *L. monocytogenes* for about 6 wk when stored at 4°C, whereas 2.0 kGy of irradiation was listeriostatic. Ham irradiated with 1 kGy in combination with PSS was listeriostatic throughout storage. SL increased firmness of turkey hams, and sensory panelists noted that the saltiness was a little higher in products containing SL, but its overall impact on quality was minimal. Amounts of benzene were detected in irradiated hams with PB, showing PB was not fit as an antimicrobial ingredient for irradiated foods. In conclusion, 2% SL and 0.1% SDA in combination with low-dose irradiation were effective in ensuring the safety of ready-to-eat meat products against *L. monocytogenes*.

(*Key words*: *Listeria monocytogenes*, e-beam irradiation, antimicrobial ingredient, ready-to-eat turkey ham, meat quality)

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INTRODUCTION

Ready-to-eat (RTE) meat products are the most popular meat products in the United States. However, RTE meat products are occasionally contaminated with *Listeria monocytogenes* mostly due to postprocessing contamination. Of the random samples collected and analyzed by the Food Safety and Inspection Service between January 1 and September 30, 2003, 0.75% of RTE meats tested were positive for *L. monocytogenes* (Food Safety and Inspection Service, 2003). Due to its ability to grow at refrigerated temperature and its resistance to salt and nitrite (Lou and Yousef, 1999; Tompkin, 2002;), any *L. monocytogenes* in cured or noncured RTE meat products, which usually have long shelf-life and are consumed directly without further heating, could proliferate to a threatening level during refrigerated storage. Because of its high mortality rate (~25%, Mead et al., 1999) and economic impact due to products recall (Food Safety and Inspection Service, 2003), *L. monocytogenes* is a major food safety issue for processed meat industry. Currently, the USDA has a "zero tolerance" policy for *L. monocytogenes* in RTE meat products. The ubiquitous nature of *L. monocytogenes* (Beresford et al., 2001) and its ability to grow at refrigerated temperature makes thermal processing and refrigerated storage insufficient to provide a safety margin for processed meat products. To ensure microbiological safety, therefore, additional precautions are needed. Postpackage decontamination and formulation of meat products with antimicrobial additives are common approaches to control *L. monocytogenes* postprocessing contamination (Bedie et al., 2001; Muriana et al., 2002; Samelis et al., 2002).

Irradiation, one of several postpackage decontamination technologies, is an effective way of destroying vegetative foodborne pathogens, including *L. monocytogenes* (Patterson et al., 1993; Thayer, 1995; Thayer and Boyd, 2000). Gamma irradiation requires a radioactive source that makes it inconvenient to use, but electron beam (e-beam)

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Abbreviation Key: PB = potassium benzoate; PSS = PB + SL + SDA; RTE = ready-to-eat; SDA = sodium diacetate; SL = sodium lactate; TSBYE = tryptic soy broth supplemented with 0.6% yeast extract.

irradiation uses accelerated electrons generated by high-energy electrical power and is easier to control. Because e-beam irradiation can be turned off when not in use, it is safer than gamma irradiation. However, only a few studies have been conducted on the effectiveness of e-beam irradiation in eliminating *L. monocytogenes* in RTE meats (Foong et al., 2004).

Although effective in controlling microorganisms, irradiation negatively affects the quality of RTE meat even at 2.0 kGy (Zhu et al., 2003, 2004a). Because of this, only low-dosage irradiation would be used by the meat industry to minimize quality changes. With low-dose irradiation, however, some pathogens can survive and proliferate in RTE meats during storage (Sommers et al., 2003; Foong et al., 2004). Thus, it is necessary to use antimicrobial ingredients as an additional hurdle to curb the growth of pathogenic organisms that survived low-dose irradiation. The antimicrobial activities of salts of organic acids such as lactate, acetate, and diacetate are well documented (Blom et al., 1997; Bedie et al., 2001; Stekelenburg and Kant-Muermans, 2001; Glass et al., 2002; Mbandi and Shelef, 2002; Samelis et al., 2002), but there is limited information on the effectiveness of antimicrobial ingredients combined with irradiation in inhibiting the growth of *L. moncytogenes* (Sommers et al., 2003) in RTE meat products. In this study, 0.1% potassium benzoate (PB), 2% sodium lactate (SL), and 0.1% sodium diacetate (SDA) combinations were used as antimicrobial ingredients in turkey ham formulation. The effect of irradiation in combination with antimicrobial ingredients on the survival and growth of *L. monocytogenes* in RTE turkey hams during refrigerated storage was evaluated. The effects of antimicrobial additives and irradiation on the organoleptic quality of RTE turkey hams were also examined to assess the feasibility of using antimicrobial ingredients and irradiation combinations as hurdles to ensure *L. monocytogenes* safety in RTE meats.

MATERIALS AND METHODS

Bacterial Strains and Growth Conditions

Five different *L. monocytogenes* strains (Scott A, H7969, H7596, H7762, and H7962) were used in this experiment. Prior to inoculation, each stock culture was individually grown in a 10-mL of tryptic soy broth[2] supplemented with 0.6% yeast extract[2] (TSBYE) at 35°C for 18 h. Then 1 mL of each strain was transferred individually to 100 mL of TSBYE and incubated at 35°C for another 18 h. Each strain was harvested by centrifugation, washed twice, and resuspended in sterile 0.1% (wt/vol) peptone[2] water. The inoculation cocktail was prepared by mixing equal volumes of each of the 5 strain suspensions, which had approximately the same number of bacteria population.

Preparation of RTE Turkey Meat Products

Oven-roasted turkey hams with different antimicrobial additives were freshly processed in the meat Lab at Iowa State University. Turkey thigh meat was used for hams manufacture. Six antimicrobial additive treatments (Table 1) that included a basic formula without any preservatives (control) or with 0.1% PB, 2% SL, 0.1% PB + 2% SL (PB+SL), 2% SL + 0.1% SDA (SL+SDA), or 0.1% PB + 2% SL + 0.1% SDA (PSS) were mixed with meat and other ingredients and then stuffed into large fibrous casings (ϕ = 11.5 cm). The additional levels of antimicrobial ingredients were chosen based on previous studies (Stekelenburg and Kant-Muermans, 2001; Stekelenburg, 2003; Zhu et al., 2004b).

The hams were heat processed in a smoke house at 84°C until an internal temperature of 74°C was reached, chilled with a 4°C cold-water shower for 10 min, stored at a 4°C cold room for 2 h, and then sliced with an electric slicing machine. RTE turkey hams were sliced to 2 mm thick pieces for microbiological measurements, and 2.0 cm thick pieces for volatile, texture, and sensory evaluation. Sliced samples were vacuum-packaged individually. For volatile analysis and sensory evaluation, only 4 antimicrobial additive treatments (control, PB+SL, SL+SDA, and PSS) were used.

Inoculation of Test Samples

The sliced turkey ham (2 mm thick) was transferred to our microbiology lab and aseptically removed from the original bulk package into nylon-polyethylene bags[3] (3 mil standard barrier, $O_2 < 0.093$ cm^3/100 cm^3 per 24 h at 38°C) with one slice per bag. One side of each sliced turkey ham was surface inoculated with 0.1 mL of *L. monocytogenes* cocktail to approximately 10^6 cfu/cm^2. Inoculated turkey ham samples were manually rubbed for 30 s to distribute the inoculum evenly, then vacuum-sealed with a Multivac A300/16,[4] and kept under refrigeration overnight prior to irradiation.

Irradiation

All samples were irradiated at refrigerated temperature (4°C) using a linear accelerator facility[5] at Iowa State University. The vacuum-packaged, inoculated samples from each additive treatment were divided randomly into 5 groups and irradiated at 0 (control), 1.0, 1.5, 2.0, or 2.5 kGy. Samples irradiated at 0, 1.0, or 2.0 kGy were stored at 4 °C for up to 42 d. The number of *L. monocytogenes* survivors in samples receiving 0, 1.0, 1.5, 2.0, or 2.5 kGy irradiation were analyzed right after irradiation. The number of *L. monocytogenes* in inoculated samples receiving 0, 1.0, or 2.0 kGy irradiation were determined at a 7-d interval. For quality analysis, the vacuum-packaged RTE turkey hams of each additive treatment were randomly divided into 3 groups and irradiated at 0, 1.0, or 2.0 kGy. Volatile analysis was conducted at 0 and 28 d; texture and sensory analysis were conducted 7 d after irradiation. Four replicates were used for each analysis.

[2]BD, Franklin Lakes, NJ.
[3]Koch Industries, Kansas City, MO.
[4]Sepp Haggenmuller KG, Wolfertschwenden, Germany.
[5]Circe IIIR, Thomson CSF Linac, St. Aubin, France.

TABLE 1. Formulation of oven-roast turkey hams and pH in processed products

Ingredient (%)	Control[1]	PB	SL	PB+SL	SL+SDA	PSS
Meat	90	90	90	90	90	90
Salt	1.5	1.5	1.5	1.5	1.5	1.5
Phosphate (Brifisol)	0.25	0.25	0.25	0.25	0.25	0.25
Transglutaminase	1.0	1.0	1.0	1.0	1.0	1.0
Sodium caseinate	0.5	0.5	0.5	0.5	0.5	0.5
Dextrose	0.5	0.5	0.5	0.5	0.5	0.5
Water	6.25	6.25	5.0	5.0	5.0	5.0
Potassium benzoate	—	0.1	—	0.1	—	0.1
Sodium lactate	—	—	2.0	2.0	2.0	2.0
Sodium diacetate	—	—	—	—	0.1	0.1
Sodium nitrite (ppm)	156	156	156	156	156	156
pH						
Ham	6.66	6.65	6.60	6.65	6.55	6.55

[1]Control = basic formula, PB = 0.1% potassium benzoate, SL = 2% sodium lactate, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate.

Microbiological Analysis

Each package was aseptically opened using an alcohol-sterilized scissors. One hundred milliliters of sterile 0.1% peptone was added to each meat sample (surface area ~100 cm^2) followed by pummeling in a stomacher for 1 min at medium speed. Samples were serially diluted with 0.1% peptone water and surface plated (0.1 mL) in duplicate on modified oxford agar plates[2] to enumerate *L. monocytogenes*. Typical *Listeria* colonies on modified oxford plates were counted after 48 h incubation at 35°C.

Calculation of Radiation D_{10} Values

The D_{10} value, radiation dose (kGy) that results in 90% reduction of viable cells, was determined by plotting the log number of survivors ($\log_{10}$ cfu/cm^2) versus irradiation dose (kGy). Linear regression curves were generated with SAS software (2000). The D_{10} value was calculated as the reciprocal of the absolute value of the slope of the regression line (Mendonca et al., 2004).

Volatile Analysis

Volatiles of samples were analyzed using a Solatek 72 Multimatrix-Vial Autosampler/Sample Concentrator 3100[6] connected to a GC/MS[7] (model 6890/5973) according to the method of Ahn and Lee (2002). One gram of minced turkey ham was placed in a 40-mL sample vial and then placed on a refrigerated (4°C) sample tray. Samples were heated to 40°C and purged with helium gas (40 mL/min) for 11 min. Volatiles were trapped with a Tenax-charcoal-silica trap column at 20°C, desorbed for 2 min at 220°C, concentrated using a cryofocusing unit at –90°C, then desorbed into a GC column for 30 s at 220°C. An HP-624 column (15 m, 250 μm i.d., 1.4 μm nominal), an HP-1 column (60 m, 250 μm i.d., 0.25 μm nominal), and an HP-Wax column (7.5 m, 250 μm i.d., 0.25 μm nominal) were combined using zero-volume connectors and used for volatile analysis. A mass selective detector was used to identify and quantify volatile compounds in irradiated samples. Proper standards of volatiles were used to aid identification. The peak area was reported as the amount of volatiles released. Four replicates were used for each analysis.

Sensory Evaluation

Turkey hams used for sensory evaluation were manufactured, sliced, and irradiated separately. After irradiation, the sliced vacuum-packaged RTE turkey hams free from pathogen were directly transferred to the sensory evaluation lab at Iowa State University. Sensory analysis was only done on samples from the 0 and 1.0 kGy treatments. Ten trained panelists participated in the evaluation of the sensory attributes of RTE turkey hams. During training, panelists were familiarized with the sensory terms, the tasting techniques, and the computer software scoring system. Samples were evaluated for turkey-ham-like aroma, off-aroma, turkey-ham-like flavor, off-flavor, and saltiness. Testing was conducted in partitioned booths and under red fluorescent lights. A linear scale (numerical value of 15 units) was used with descriptive anchors (none and high) at each end of the line. Data were collected by using a computerized sensory system[8] (Compusense*Five*, version 4.0). Before presentation to the sensory panelists, samples were heated in a microwave oven to 60°C as measured by an infrared thermometer and labeled with random 3-digit codes. Two sessions were conducted. In each session, panelists received samples from each of the 8 treatments with serving orders randomized. The measurements made on a given treatment by each panelist in the 2 sessions were averaged and used in the statistical analysis.

Texture Profile Analysis

The RTE turkey hams were immobilized between specially constructed stainless steel plates, a star-shaped,

[6]Takmar-Dohrmann, Cincinnati, OH.
[7]Hewlett-Packard Co., Wilmington, DE.
[8]Version 4.0, Compusense, Inc., Guelph, Ontario, Canada.

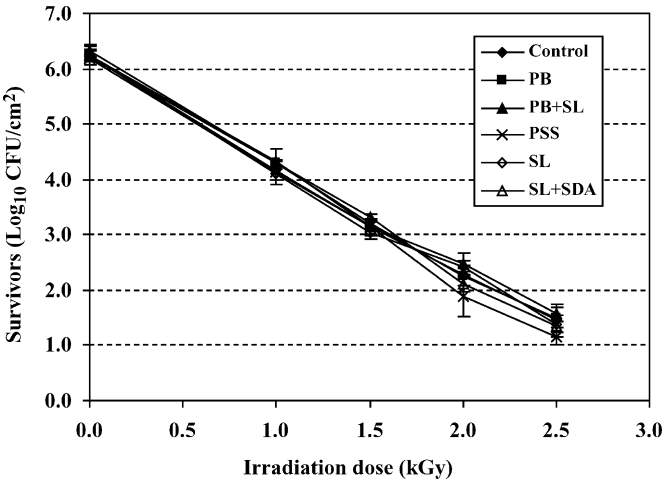

FIGURE 1. Survival of *Listeria monocytogenes* after irradiation of turkey hams with or without antimicrobial ingredients at 0 d of storage. Control = basic formula, PB = 0.1% potassium benzoate, SL = including 2% sodium lactate, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate.

cherry-pitter probe[9] was used to penetrate the slices perpendicularly. Each sample underwent 2 cycles of 50% compression using the above probe fitted to a TA-XT2i Texture Analyzer.[9] Two separate texture profile analyses were done per slice, and 4 slices were used for each treatment. Five textural parameters (i.e., hardness, cohesiveness, springiness, chewiness, and resilience) were obtained from the force-time curve and calculated as described by Bourne (1978).

Statistical Analysis

A factorial design was used in this study. Data were analyzed by the GLM procedure of the Statistical Analysis System (SAS, 2000). The differences in the mean values were compared by the Tukey's multiple comparison, and mean values and standard deviation are reported ($P < 0.05$).

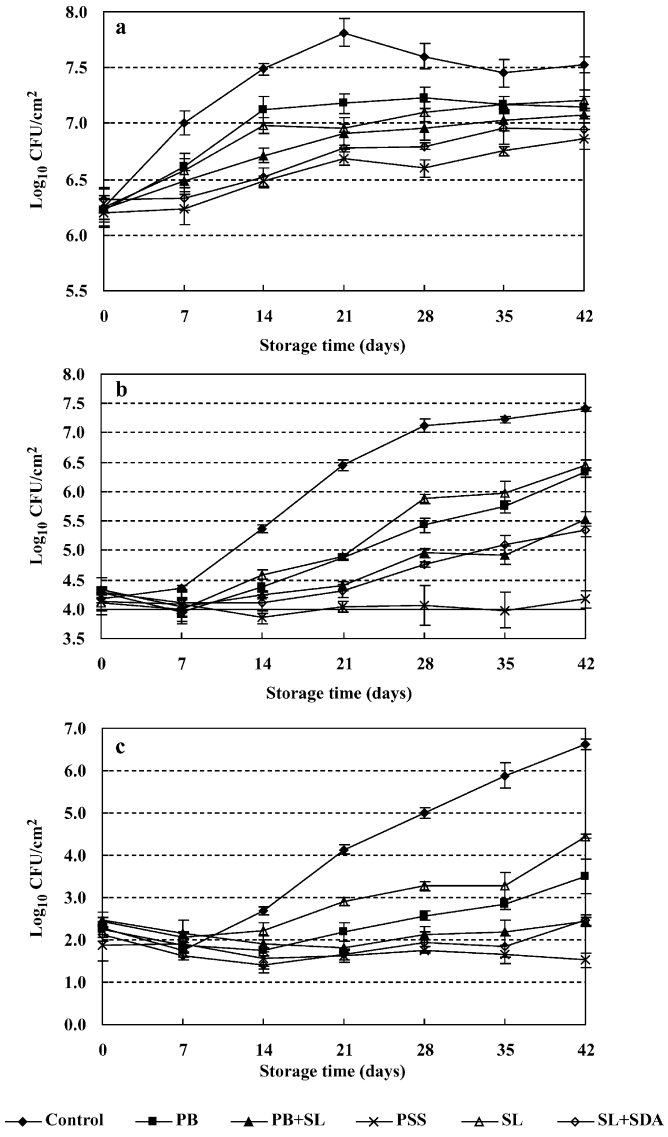

FIGURE 2. Survival and growth of *Listeria monocytogenes* on irradiated vacuum-packaged ham during storage at 4°C. Control = basic formula, PB = 0.1% potassium benzoate, SL = 2% sodium lactate, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate. A) 0 kGy, b) 1.0 kGy, c) 2.0 kGy.

RESULTS AND DISCUSSION

Irradiation Sensitivity of L. monocytogenes

Figure 1 shows survival curves of five-strain *L. monocytogenes* cocktail in turkey hams with single or combined antimicrobial ingredients following e-beam irradiation. Log_{10} reductions of *L. monocytogenes* in hams following 1.0 to 2.5 kGy irradiation ranged from 2.0 to 5.0.

With linear regression of the log_{10} colony-forming units per square centimeter reduction following e-beam irradiation, the calculated D_{10} value for control, PB-, SL- and PB+SL-added ham was about 0.52 kGy, whereas those for the hams containing SL+SDA and PSS were approximately 0.49 and 0.48, respectively, which was consistent with previous reports. Foong et al. (2004) reported no apparent difference in the D_{10} values of smoked turkey with or without lactate. Sommers et al. (2003) reported that adding SDA and PL increased the sensitivity of *L. monocytogenes* to gamma irradiation. The D_{10} value was 0.56 kGy for bologna without SDA and PL, 0.53 kGy for bologna containing 0.07% SDA+1% PL, and 0.46 kGy for bologna containing 0.15% SDA+2% PL. The D_{10} values in this study were higher than those of Foong et al. (2004) who reported that the D_{10} values for commercial frankfurters, bologna, turkey ham, and roast beef ranged from 0.42 to 0.44 kGy. The main reason for those differences could be due to the differences in RTE formulation, *L. monocytogenes* strains,

[9]Texture Technology Corp., New York.

TABLE 2. Selected volatiles of turkey hams with or without antimicrobial ingredients

		0 Days				28 Days			
	Treatment[1]	0 kGy	1 kGy	2 kGy	SEM	0 kGy	1 kGy	2 kGy	SEM
Hexane	Control	34^{bz}	510^{a}	153^{by}	41	0^{by}	234^{a}	193^{ay}	55
	PB+SL	330^{y}	376	512^{x}	52	0^{by}	142^{b}	532^{ax}	107
	SL+SDA	601^{x}	506	242^{xy}	134	0^{cy}	262^{b}	738^{ax}	50
	PSS	511^{x}	491	387^{xy}	42	133^{bx}	131^{b}	623^{ax}	27
	SEM	37	103	78		6	64	96	
3-Methyl butanal	Control	125^{c}	354^{b}	658^{ay}	15	133^{cx}	569^{b}	777^{ay}	11
	PB+SL	49^{c}	315^{b}	$1,175^{ax}$	28	115^{cy}	498^{b}	$1,945^{ax}$	68
	SL+SDA	48^{c}	358^{b}	$1,137^{ax}$	25	127^{cx}	835^{b}	$2,097^{ax}$	182
	PSS	87^{c}	350^{b}	586^{ay}	12	132^{cx}	388^{b}	$1,766^{ax}$	31
	SEM	20	15	27		3	136	102	
Benzene	Control	0	0^{y}	0^{z}	0	0	0^{y}	0^{y}	0
	PB+SL	0^{c}	649^{bx}	$2,885^{ax}$	16	0^{c}	$1,021^{bx}$	$3,353^{ax}$	180
	SL+SDA	0	0^{y}	0^{z}	0	0	0^{y}	0^{y}	0
	PSS	0^{c}	664^{bx}	$1,426^{ay}$	29	0^{c}	749^{bx}	$2,973^{ax}$	58
	SEM	0	28	31		0	105	127	
1-Heptene	Control	0^{b}	218^{a}	287^{ay}	24	0^{c}	164^{b}	226^{ay}	9
	PB+SL	0^{c}	155^{b}	631^{ax}	44	0^{c}	239^{b}	$1,183^{ax}$	62
	SL+SDA	0^{b}	136^{b}	478^{axy}	57	0^{b}	355^{b}	$1,244^{ax}$	119
	PSS	0^{c}	154^{b}	335^{ay}	13	0^{c}	161^{b}	996^{ax}	10
	SEM	0	22	63		0	66	96	
Dimethyl disulfide	Control	263^{c}	$2,285^{b}$	$3,967^{axy}$	223	907^{c}	$3,838^{b}$	$6,311^{az}$	141
	PB+SL	317^{c}	$2,092^{b}$	$5,421^{ax}$	158	861^{c}	$5,139^{b}$	$17,244^{ax}$	891
	SL+SDA	589^{b}	$2,525^{ab}$	$2,960^{ay}$	572	715^{c}	$6,477^{b}$	$14,353^{ax}$	1,289
	PSS	278^{b}	$1,791^{a}$	$2,116^{ay}$	197	576^{c}	$4,223^{b}$	$10,894^{ay}$	111
	SEM	101	232	516		85	920	1,006	
Total volatiles	Control	$38,498^{cy}$	$47,549^{by}$	$49,266^{ay}$	2,220	$40,945^{b}$	$41,029^{by}$	$47,718^{ay}$	1,040
	PB+SL	$43,028^{by}$	$43,970^{by}$	$71,931^{ax}$	1,184	$37,571^{b}$	$52,956^{bxy}$	$138,385^{ax}$	7,060
	SL+SDA	$53,114^{x}$	$59,275^{x}$	$58,847^{y}$	3,496	$37,238^{c}$	$63,737^{bx}$	$145,641^{ax}$	5,996
	PSS	$49,817^{cx}$	$42,283^{by}$	$56,813^{ay}$	1,712	$37,787^{c}$	$50,698^{bxy}$	$132,418^{ax}$	1,782
	SEM	2,202	1,527	2,988		889	4,561	6,778	

[a–c]Means within a row with different number differ significantly ($P < 0.05$); n = 4.

[x–z]Means within a column with different number differ significantly ($P < 0.05$).

[1]Control = basic formula, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate.

and plating medium (Patterson, 1989; Tarte et al., 1996; Gürsel and Gürakan, 1997).

Antimicrobial Ingredients and Growth of L. monocytogenes After Irradiation

Figure 2a shows the growth of *L. monocytogenes* in nonirradiated hams with single or combined antimicrobial ingredients during refrigerated storage (4°C). Single or combined antimicrobial ingredients delayed the growth of *L. monocytogenes* in ham products. In control ham, *L. monocytogenes* reached the peak number after 21 d of refrigerated storage, whereas in hams containing 2 or 3 combined antimicrobial ingredients, *L. monocytogenes* increased less than 1 log after 42 d of refrigerated storage (Figure 2a). Although the growth of *L. monocytogenes* in turkey hams with SL+SDA was slower than that of PB+SL, the difference was not significant. The combination of PB+SL+SDA was more effective in controlling the growth of *L. monocytogenes* than PB+SL. The synergistic inhibitory effect of lactate and diacetate combination on growth of pathogenic organisms is well documented (Bedie et al., 2001; Glass et al., 2002; Mbandi and Shelef, 2002; Samelis, et al., 2002; Stekelenburg, 2003). Samelis et al. (2002) reported that SL (1.8%; 3% of a 60% commercial solution) used in combination with 0.25% sodium acetate, SDA, or glucono-δ-lactone inhibited the growth of *L. monocytogenes* in frankfurters during refrigerated storage. Cured smoked wieners formulated with ≥1% lactate plus ≥0.1% diacetate inhibited the growth of *L. monocytogenes* for 60 d at 4.5°C (Glass et al., 2002). In turkey slurries formulated with 2.5% lactate and ≥0.1% diacetate, the growth of *L. monocytogenes* was inhibited for 42 d at 4°C (Schlyter et al., 1993). Because inclusion of high level (>0.1%) of SDA in the formulation had a negative effect on the odor and taste of the final processed products (Stekelenburg and Kant-Muermans, 2001), only 0.1% diacetate was included in the turkey ham formulation in this study.

As shown in Figure 2 (b and c), an extended lag phase was observed in turkey hams irradiated at 1.0 and 2.0 kGy and stored at 4°C, especially for those hams with combined antimicrobial ingredients. The increased lag phase was associated with irradiation dose, and addition of antimicrobial ingredients in turkey formulation greatly increased lag phase at each irradiation dose. During lag phase, surviving pathogens are believed to repair injuries caused by irradiation, and the organisms presumably needed more time to repair irradiation damages when 2 or 3 antimicrobial ingredients were presented.

TABLE 3. Sensory scores[1] of turkey hams with different antimicrobial ingredients

Irradiation	Control[2]	PB+SL	SL+SDA	PSS	SEM
Ham-like aroma					
0 kGy	4.4[a]	4.8[a]	4.1[a]	5.3[ax]	0.6
1.0 kGy	3.8[a]	3.7[a]	3.6[a]	3.0[ay]	0.6
SEM	0.5	0.6	0.7	0.5	
Off-aroma					
0 kGy	5.8[a]	4.1[a]	5.9[a]	4.1[a]	0.9
1.0 kGy	6.3[a]	6.5[a]	6.9[a]	5.9[a]	0.9
SEM	0.9	0.8	0.9	0.8	
Ham-like flavor					
0 kGy	5.7[a]	5.9[a]	4.5[a]	6.1[a]	0.6
1.0 kGy	4.6[a]	4.7[a]	4.1[a]	4.8[a]	0.6
SEM	0.6	0.6	0.6	0.6	
Off-flavor					
0 kGy	3.6[a]	3.1[a]	5.3[a]	3.0[a]	0.8
1.0 kGy	4.7[a]	3.8[a]	5.7[a]	4.5[a]	0.8
SEM	0.7	0.8	0.8	0.7	
Saltiness					
0 kGy	5.5[b]	7.1[ab]	9.0[a]	6.8[ab]	0.6
1.0 kGy	5.8[b]	6.5[ab]	8.3[a]	7.7[ab]	0.6
SEM	0.6	0.7	0.6	0.6	

[a,b]Means within a row with no common number differ significantly ($P < 0.05$).

[x,y]Means within a column with different number differ significantly ($P < 0.05$); n = 10.

[1]A linear scale (numerical value of 15 units) was used with descriptive anchors at each end of the line, where 0 = none and 15 = very strong.

[2]Control = basic formula, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate.

TABLE 4. Texture analysis data for turkey hams with different antimicrobial ingredients

Attribute and irradiation	Control[1]	PB	SL	PB+SL	SL+SDA	PSS	SEM
Hardness							
0 kGy	2.031[c,2]	2.071[bc]	2.336[abxy]	2.178[abcx]	2.386[ax]	2.293[abc]	0.064
1.0 kGy	1.960[b]	2.184[b]	2.541[ax]	2.676[ay]	2.706[y]	2.489[a]	0.058
2.0 kGy	2.030[c]	2.057[bc]	2.224[bcy]	2.556[ay]	2.299[bx]	2.284[b]	0.059
SEM	0.050	0.061	0.060	0.072	0.054	0.061	
Springiness							
0 kGy	0.806[b]	0.816[ab]	0.823[abxy]	0.832[a]	0.836[axy]	0.824[ab]	0.005
1.0 kGy	0.808[c]	0.816[abc]	0.813[bcx]	0.831[ab]	0.821[abcx]	0.836[a]	0.005
2.0 kGy	0.798[b]	0.824[a]	0.835[ay]	0.829[a]	0.840[ay]	0.843[a]	0.006
SEM	0.006	0.005	0.005	0.005	0.005	0.006	
Cohesiveness							
0 kGy	0.565[a]	0.572[a]	0.585[a]	0.567[a]	0.580[ax]	0.593[a]	0.008
1.0 kGy	0.597[a]	0.580[a]	0.583[a]	0.581[a]	0.590[axy]	0.598[a]	0.007
2.0 kGy	0.588[ab]	0.593[ab]	0.607[ab]	0.580[b]	0.615[ay]	0.600[ab]	0.007
SEM	0.009	0.006	0.008	0.006	0.008	0.008	
Chewiness							
0 kGy	0.925[b]	0.965[b]	1.124[a]	1.025[abx]	1.153[ax]	1.119[ax]	0.033
1.0 kGy	0.943[b]	1.032[b]	1.206[a]	1.289[ay]	1.309[ay]	1.242[ay]	0.029
2.0 kGy	0.953[c]	1.004[bc]	1.128[ab]	1.227[ay]	1.190[ax]	1.154[axy]	0.035
SEM	0.025	0.031	0.036	0.034	0.033	0.035	
Resilience							
0 kGy	0.223[a]	0.225[a]	0.235[axy]	0.220[a]	0.229[ax]	0.239[a]	0.006
1.0 kGy	0.234[a]	0.221[a]	0.218[ax]	0.223[a]	0.225[ax]	0.238[a]	0.006
2.0 kGy	0.228[a]	0.231[ab]	0.243[aby]	0.226[b]	0.259[ay]	0.247[ab]	0.007
SEM	0.008	0.006	0.006	0.006	0.006	0.007	

[a–c]Means within a row with different number differ significantly ($P < 0.05$).

[x–z]Means within a column with different number differ significantly ($P < 0.05$); n = 4.

[1]Control = basic formula, PB = 0.1% potassium benzoate, SL = 2% sodium lactate, PB+SL = 0.1% potassium benzoate and 2% sodium lactate, SL+SDA = 2% sodium lactate and 0.1% sodium diacetate, PSS = 0.1% potassium benzoate, 2% sodium lactate, and 0.1% sodium diacetate.

[2]Unit: hardness, kg; springiness, the height that the food recovers during the time that elapses between the end of the first pressure and the start of the second pressure; cohesiveness, the ratio of the positive force area during the second compression to that during the first compression; gumminess, hardness × cohesiveness; chewiness, hardness × cohesiveness × springiness.

For control hams without antimicrobial ingredients, 1.0 and 2.0 kGy delayed the lag phase for 7 and 14 d, respectively. This finding was consistent with the results of Foong et al. (2004) who reported irradiation of commercial turkey hams at 2.0 kGy and storage at 4°C increased the lag phase of *L. monocytogenes* for 2 wk. For turkey hams formulated with 2 antimicrobial ingredients such as 2% SL plus 0.1% SDA and 2% SL plus 0.1% PB, the lag phase increased to 21 d in hams irradiated with 1.0 kGy (Figure 2b), and *L. monocytogenes* stayed in lag phase throughout the storage in hams irradiated with 2.0 kGy (Figure 2c). In hams with 3 combined antimicrobial ingredients, 0.1% PB plus 2% SL plus 0.1% SDA, *L. monocytogenes* stayed in the lag phase during the whole refrigerated storage in hams irradiated at 1.0 or 2.0 kGy (Figure 2, b and c).

After the lag phase, the surviving pathogens started to proliferate in control hams irradiated at 1.0 kGy and peaked at 7.2 $\log_{10}$ cfu/cm^2 after 28 d of refrigerated storage, which indicated that low-dose (1.0 kGy) irradiation alone could not provide safety margin for RTE turkey ham. However, irradiation with 1.0 kGy in combination with 2% SL + 0.1% SDA or 0.1% PB + 2% SL inhibited the growth of *L. monocytogenes* for about 6 wk at 4°C (Figure 2b), and 2.0 kGy irradiation in combination with 2% SL + 0.1% SDA or 0.1% PB + 2% SL was listeriostatic (Figure 2c). Hams that received 1.0 or 2.0 kGy irradiation and 0.1% PB + 2% SL + 0.1% SDA were listeriostatic throughout storage (Figure 2, b and c). Sommers et al. (2003) reported that gamma radiation at 3.0 kGy prevents proliferation of *L. monocytogenes* in bologna containing 0.07% SDA + 1% PL and in bologna containing 0.15% SDA + 2% PL over 8 wk of storage at 9°C.

Antimicrobial Ingredients, Irradiation, and Quality of Turkey Hams

A total 43 volatiles were identified by GC-MS. Because volatiles generated by irradiation have been extensively discussed in former publications, we list (Table 2) only the amount of 5 selected representative volatiles that were induced by irradiation and have been reported previously (Du et al., 2002; Lee et al., 2003; Zhu et al., 2003). Irradiation increased the amounts of hexane, 3-methyl butanal, 1-heptene, dimethyl disulfide, and total volatile contents in turkey ham, which was consistent with our previous reports (Du et al., 2002; Lee et al., 2003).

Addition of antimicrobial ingredients had no effect on the volatiles of hams with or without irradiation, except for hams containing PB (Table 2). Irradiation greatly increased the amount of benzene detected in volatiles in hams containing PB. This finding was in agreement with our previous report on turkey breast rolls (Zhu et al., 2004b). Because benzene has negative effect on health (Mehlman 2002; Bogadi-Sare et al., 2003), PB+SL and PSS may not be good antimicrobial combinations for food that receives irradiation, despite their effectiveness in inhibiting the growth of *L. monocytogenes*. It is estimated that chronic inhalation of air containing 0.004 ppm or more benzene will cause adverse health effects (ATSDR, 1997).

The effect of antimicrobial ingredients on the organoleptic quality of irradiated hams was evaluated by a trained sensory panel (Table 3). The microbial experiment showed that 1.0 kGy of irradiation plus combined antimicrobial ingredients was effective in inhibiting the growth of *L. monocytogenes* (Figure 2b). Therefore, irradiation with 2.0 kGy was not included in sensory evaluation. For hams receiving 1.0 kGy of irradiation or nonirradiated control, the trained sensory panelists did not detect any significant differences in aroma, off-aroma, flavor, or off-flavor. However, the saltiness of hams containing antimicrobial ingredients was significantly higher than that of control (ham without antimicrobial additives). This result indicated that salt level in formulation should be reduced slightly for hams formulated with antimicrobial ingredients. In a previous study with ground chicken, Jensen et al. (2001) reported that 3% SL caused an increase in saltiness and bitterness that could be masked by the addition of 1% sucrose.

Table 4 depicts the texture profile data of turkey hams with or without antimicrobial additives before and after irradiation. For all hams containing SL, the hardness was largely greater than for the rest of hams. The chewiness of products containing SL was also increased (Table 4). This result could be due to the improved protein gelation during cooking, because 2% SL addition increased the ion content and improved protein solubility and water-binding capacity of the meat. Stekelenburg and Kant-Muermans (2001) reported that the firmness of the ham products formulated with 3.3% SL and 0.1% SDA was slightly tough, which is consistent with our results. If the increase in hardness and chewiness is undesirable in some products, slightly reduction of phosphate or binders, such as transglutaminase, in formulation should solve the problems (Lee and Park, 2003).

In summary, irradiation was very effective in reducing *L. monocytogenes* in RTE turkey hams, but surviving *L. monocytogenes* could proliferate during subsequent storage. Antimicrobial ingredient combinations (PB+SL, SL+SDA, and PSS) could be used in addition to low-dose irradiation of RTE meat to inhibit the growth of surviving pathogens during prolonged refrigerated storage. Sensory properties of turkey hams were not significantly affected by antimicrobial additives combined with 1.0 kGy of irradiation. Because a significant amount of benzene was detected in volatiles of hams containing PB, addition of PB as an antimicrobial agent to irradiated foods is not recommended. The SL+SDA in combination with 1.0 or 2.0 kGy of irradiation, thus, is recommended to ensure safety and quality of RTE ham.

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