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Effect of Low-Dose Radiation on Microbiological, Chemical, and Sensory Characteristics of Chicken Meat Stored Aerobically at 4°C

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ABSTRACT

The effect of γ-radiation (0.5, 1, and 2 kGy) on the shelf life of fresh skinless chicken breast fillets stored aerobically at 4°C was evaluated. Microbiological, chemical, and sensorial changes occurring in chicken samples were monitored for 21 days. Irradiation reduced populations of bacteria, i.e., total viable bacteria, *Brochothrix thermosphacta,* lactic acid bacteria (LAB), and the effect was more pronounced at the highest dose (2 kGy). Pseudomonads, yeasts and molds, and *Enterobacteriaceae* were highly sensitive to γ-radiation and were completely eliminated at all doses. Of the chemical indicators of spoilage, thiobarbituric values for nonirradiated and irradiated aerobically packaged chicken samples were in general low (<1 mg of malonaldehyde per kg of muscle) during refrigerated storage for 21 days. With regard to volatile amines, both trimethylamine nitrogen (TMA-N) and total volatile basic nitrogen (TVB-N) values for nonirradiated aerobically packaged chicken increased steeply, with final values of ca. 20.3 and 58.5 mg N/100 g of muscle, respectively. Irradiated aerobically packaged chicken samples had significantly lower TMA-N and TVB-N values ($P < 0.05$) of ca. 2.2 to 3.6 and 30.5 to 37.1 mg N/100 g of muscle, respectively, during refrigerated storage for 21 days. Of the biogenic amines monitored, only putrescine and cadaverine were detected in significant concentrations in both nonirradiated and irradiated chicken samples, whereas histamine formation was noted only in nonirradiated samples throughout storage. On the basis of sensorial evaluation, low-dose irradiation (0.5 and 1.0 kGy) in combination with aerobic packaging extended the shelf life of fresh chicken fillets by ca. 4 to 5 days, whereas irradiation at 2.0 kGy extended the shelf life by more than 15 days compared with that of nonirradiated chicken.

Spoilage of fresh poultry products is an economic burden to the producer and in some cases may present a health hazard because poultry meat may harbor pathogenic microorganisms *(10).* Consequently, development of methods to increase shelf life and overall safety and quality is a major task of the poultry processing industry. Several preservation approaches have been investigated, including modified atmosphere packaging and vacuum packaging alone or in combination with other procedures such as treatment with acids *(22),* EDTA-nisin *(8),* phosphates *(19),* essential oils *(6),* high hydrostatic pressure *(27),* and irradiation *(32).*

Irradiation is one of the preservation technologies used to ensure the microbiological safety of meat products. Current regulations allow up to 3 kGy to be used for irradiation of poultry meat in the United States *(42).*

Relatively few studies have been published on the effects of ionizing radiation and packaging of poultry meat. Hashim et al. *(15)* irradiated fresh and frozen chicken at doses of 1.66 and 2.86 kGy and determined the effects of processing on the sensory attributes of both raw and cooked irradiated meat. They found that raw irradiated chicken had a more intense fresh chicken flavor compared with nonirradiated samples. Cooked irradiated frozen dark meat had more chicken flavor and cooked irradiated refrigerated dark meat was more tender than the controls. Kanatt et al. *(23)* irradiated minced chicken at 2.5 kGy and stored it at 0 to 3°C for up to 4 weeks. The irradiated meat was microbiologically safe and its sensory qualities were acceptable for up to 4 weeks in the nonfrozen state, whereas the nonirradiated minced chicken had a shelf life of approximately 1 week. Thayer and Boyd *(40)* irradiated ground turkey with 0, 1.5, and 2.0 kGy at 5°C, and meat was then packaged either in air-permeable pouches or under atmospheres containing 30 or 53% CO_2, 19% O_2, and 51 or 24% N_2 and stored at 7°C for up to 28 days. A dose of 2.5 kGy extended the time for the aerobic plate counts (APCs) to reach 10^7 CFU/g from 4 to 19 days compared with that for nonirradiated turkey in air-permeable pouches. The effects of irradiation and packaging of fresh meat and poultry were reviewed by Lee et al. *(25),* who concluded that more information is needed to ensure the appropriate use of both irradiation and packaging (under modified atmosphere, vacuum, and air) of meat and poultry. The aim of this work was to study the effect of ionizing radiation on the shelf life of fresh chicken meat fillets.

MATERIALS AND METHODS

Chicken sample preparation and storage conditions. Chicken fillets (skinless breast) were obtained from a local poultry processing plant and transported to the laboratory in insulated polystyrene boxes on ice within 60 min of when the raw chicken

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meat was processed. Chicken fillets (one ca. 250-g fillet per pouch) were then placed in 75-μm-thick three-layer (low-density polyethylene–polyamide–low-density polyethylene) barrier pouches with an oxygen permeability of 52.2 ml/m^2-day-atm and a water vapor permeability of 2.4 g/m^2/day (25°C and 0% relative humidity). The pouches were sealed aerobically with a model N48 vacuum sealer (Boss GmbH, Tuttlingen, Germany). Chicken samples were divided into four groups (nonirradiated control samples and samples to be irradiated at 0.5, 1.0, and 2.0 kGy). The nonirradiated control samples were stored aerobically under refrigeration (4°C), and the rest of the aerobically packaged samples were immediately transported to the irradiation facility on ice. After irradiation, 12 randomly chosen chicken samples (3 per treatment) were removed for microbiological, chemical, and sensory analyses. Samples were maintained aerobically at 4 ± 0.5°C and retrieved after 1, 5, 8, 11, 14, 17, and 21 days of storage.

Irradiation. Samples were irradiated at the EL.VIO.NI, S.A. plant (Mandra, Attica, Greece) with a cobalt-60 radiation source at a dosage of 1 kGy/h. The strength of the source was 150 kCi. Dosimetry was performed using polymethyl methacrylate dosimeters (PMMA Instruments, Harwell, UK). The absorbance signal was measured with a Camspec M 201 UV spectrophotometer at 640 nm. The applied doses were 0.5, 1.0, and 2.0 kGy; actual doses were within 10% of the target dose. To minimize variation in radiation dose absorption, the boxes in each experiment were turned 180° halfway through the irradiation process. Chicken samples were covered with ice to keep them at 4 ± 0.5°C during irradiation.

Microbiological analysis. Chicken meat (25 g) was transferred aseptically to a stomacher bag (Seward Medical, London, UK), 225 ml of 0.1% peptone water was added, and the mixture was homogenized for 60 s with a stomacher (Lab Blender 400, Seward Medical). Samples (0.1 ml) of serial dilutions of chicken homogenates were spread on the surface of the appropriate media in petri dishes for determination of APCs on plate count agar (1.05463, Merck, Darmstadt, Germany) and incubated at 30°C for 3 days. Pseudomonads were cultured on cetrimide fusidin cephaloridine agar (CM 0559, supplemented with selective supplement SR 0103, Oxoid, Basingstoke, UK) incubated at 20°C for 2 days *(30). Brochothrix thermosphacta* was cultured on streptomycin sulfate–thallous acetate–cycloheximide (actidione) agar prepared from basic ingredients in the laboratory and incubated at 20°C for 3 days *(11).* For members of the family *Enterobacteriaceae,* a 1.0-ml sample was inoculated into 10 ml of molten (45°C) violet red bile glucose agar (CM 0485, Oxoid). After the agar had set, a 10-ml overlay of molten medium was added, and the culture was incubated at 30°C for 24 h, after which the large colonies with purple halos were counted *(31).* Lactic acid bacteria (LAB) were cultured on deMan Rogosa Sharpe medium (CM 0361, Oxoid) incubated at 25°C for 5 days. Yeasts and molds were cultured on rose bengal chloramphenicol agar (1.00467, Merck) incubated at 25°C for 5 days in the dark. Three replicates of at least three appropriate dilutions of each culture were evaluated for colonies. All plates were examined visually for typical colony types and morphological characteristics associated with each growth medium. The selectivity of each medium was checked routinely by Gram staining and microscopic examination of smears prepared from randomly selected colonies from all cultures.

pH. The pH value was determined with a pH meter equipped with a stab type probe (type 691, Metrohm, Herisau, Switzerland). Chicken samples were homogenized thoroughly with 10 ml of distilled water, and the homogenate was used for pH determinations.

Chemical analysis. Trimethylamine nitrogen (TMA-N) concentration (milligrams per 100 g of chicken muscle) was determined according to the method proposed by Dyer *(4),* and total volatile basic nitrogen (TVB-N) concentration (milligrams per 100 g of chicken muscle) was determined according to the method of Malle and Poumeyrol *(29).* Thiobarbituric acid (TBA) concentration (milligrams of malonaldehyde [MA] per kilogram of chicken muscle) was determined according to the method proposed by Pearson *(36).*

High-pressure liquid chromatographic analysis of BAs. The extraction, separation, and quantification of biogenic amines (BAs) were carried out with the procedure described by Paleologos et al. *(35).*

Sensory evaluation. Each skinless chicken fillet (ca. 100 g) was cooked in a microwave oven at high power (700 W) for 4 min, including time of defrosting. A panel of seven judges experienced in poultry evaluation was used for sensory analysis. All panelists who evaluated the sensory attributes of cooked chicken had previously participated in training sessions to become familiar with the sensory characteristics of cooked chicken. Panelists were asked to evaluate taste, odor, and appearance of the cooked samples. Panelists also were presented with a freshly thawed chicken sample that had been stored at −30°C throughout the experiment and cooked as described; this serving was the reference sample. Acceptability as a composite of odor, taste, and appearance was estimated using a scale of 0 to 9, where 9 represented excellent, 8 represented very good, 7 represented good, 6 represented acceptable, and <6 represented poor (development of off-odor or off-taste); a score of 6 was taken as the lower limit of acceptability. The product was defined as unacceptable after the development of off-odor or off-taste.

Statistical analysis. Experiments were conducted twice on different occasions with different chicken samples. Triplicate samples were analyzed per replicate. Data from each replication were averaged, log transformed, and subjected to analysis of variance with Statgraphics software (Statistical Graphics Corp., Rockville, Md.). Means and standard deviations (SDs) were calculated, and when F values were significant at $P < 0.05$, mean differences were separated by the least significant difference procedure *(38).*

RESULTS AND DISCUSSION

Microbiological analyses. The changes in APCs and counts for LAB, *B. thermosphacta,* and *Enterobacteriaceae* from nonirradiated (control) and irradiated (0.5, 1.0, and 2.0 kGy) fresh chicken fillets stored aerobically during refrigerated storage are shown in Table 1. After ca. 5 days, APCs for nonirradiated chicken reached 7 log CFU/g, which was taken as an index of incipient spoilage. Irradiated samples reached the same APCs after 10 to 11 (0.5 kGy) and 11 to 12 (1 kGy) days, respectively (Table 1). Samples irradiated at 2 kGy did not reach these APCs throughout the entire experiment (21 days). Thayer et al. *(41)* reported that mesophilic bacteria in mechanically deboned chicken meat irradiated at 1.5 kGy required more than 2 weeks of refrigerated storage to reach 10^7 CFU/g, whereas samples that received a 3.0-kGy dose never reached this population. In another study, Mahrour et al. *(28)* found that marinade treatment and irradiation had an

TABLE 1. *Counts of aerobic bacteria, lactic acid bacteria,* Brochothrix thermosphacta, *and* Enterobacteriaceae *from nonirradiated (control) and irradiated (0.5, 1.0, and 2.0 kGy) chicken fillets stored aerobically at 4°C*[a]

Bacteria	Storage time (days)	Bacterial counts (log CFU/g) after irradiation at:			
		0 kGy	0.5 kGy	1.0 kGy	2.0 kGy
Aerobic	1	4.29 ± 0.32	3.72 ± 0.17	3.08 ± 0.24	2.52 ± 0.32
	5	7.15 ± 0.59	4.53 ± 0.35	3.51 ± 0.40	3.32 ± 0.43
	8	8.93 ± 0.64	5.86 ± 0.62	5.16 ± 0.47	3.54 ± 0.32
	11	9.28 ± 0.71	7.56 ± 0.66	6.67 ± 0.59	4.83 ± 0.55
	14	9.17 ± 0.54	7.72 ± 0.52	7.65 ± 0.53	5.27 ± 0.49
	17	9.38 ± 0.48	7.98 ± 0.46	8.03 ± 0.62	5.51 ± 0.61
	21	9.29 ± 0.61	8.13 ± 0.76	7.92 ± 0.64	5.61 ± 0.71
Lactic acid	1	2.73 ± 0.28	2.37 ± 0.18	1.97 ± 0.38	1.35 ± 0.24
	5	3.25 ± 0.43	2.46 ± 0.54	2.16 ± 0.42	1.83 ± 0.33
	8	3.85 ± 0.61	3.25 ± 0.41	3.13 ± 0.54	2.54 ± 0.38
	11	4.65 ± 0.54	3.82 ± 0.55	3.57 ± 0.29	3.42 ± 0.49
	14	5.59 ± 0.72	5.66 ± 0.62	4.71 ± 0.65	4.01 ± 0.56
	17	7.63 ± 0.45	7.72 ± 0.48	6.66 ± 0.69	5.38 ± 0.40
	21	8.08 ± 0.57	7.87 ± 0.29	6.94 ± 0.42	5.69 ± 0.61
B. thermosphacta	1	3.99 ± 0.34	<2[b]	<2	<2
	5	6.40 ± 0.46	4.31 ± 0.45	2.95 ± 0.48	<2
	8	7.77 ± 0.55	4.96 ± 0.56	3.85 ± 0.34	2.43 ± 0.42
	11	8.52 ± 0.41	5.65 ± 0.47	4.95 ± 0.45	3.02 ± 0.32
	14	8.65 ± 0.65	6.05 ± 0.65	5.34 ± 0.53	4.42 ± 0.35
	17	8.36 ± 0.58	6.97 ± 0.33	6.45 ± 0.71	5.54 ± 0.35
	21	8.46 ± 0.71	7.02 ± 0.50	6.97 ± 0.61	5.56 ± 0.21
Enterobacteriaceae	1	3.56 ± 0.34	<1[c]	<1	<1
	5	5.84 ± 0.45	1.43 ± 0.34	<1	<1
	8	6.99 ± 0.18	2.13 ± 0.65	<1	<1
	11	7.48 ± 0.61	3.65 ± 0.44	1.47 ± 0.56	<1
	14	7.52 ± 0.39	3.71 ± 0.59	2.15 ± 0.44	<1
	17	7.57 ± 0.72	5.94 ± 0.39	2.48 ± 0.52	<1
	21	7.88 ± 0.34	6.21 ± 0.25	2.62 ± 0.71	<1

[a] Values are the mean (±SD) from three samples taken from each of two different experiments ($n = 2 \times 3 = 6$).
[b] Limit of detection for *B. thermosphacta* is 2 log CFU/g.
[c] Limit of detection for the *Enterobacteriaceae* is 1 log CFU/g.

additive effect and reduced the microbial load in chicken legs. The results of the present study indicate that the shelf life of irradiated aerobically packaged chicken meat may be substantially extended, as indicated by APCs.

Results obtained for pseudomonads, yeasts, and molds (not shown) and LAB, *B. thermosphacta,* and *Enterobacteriaceae* revealed significantly higher counts ($P < 0.05$) for nonirradiated than for irradiated (0.5, 1.0, and 2.0 kGy) samples during the entire refrigerated storage period (Table 1).

Of the psychrotrophic bacteria, pseudomonads have been implicated in the spoilage of poultry and processed poultry products *(21)* and were dominant in nonirradiated chicken stored aerobically, in agreement with results for nonirradiated pork packed under air *(13). Pseudomonas* spp. reached ca. 9 log CFU/g by the end of the aerobic storage period and were more numerous than the other bacteria in the microflora of skinless chicken meat because of their faster growth rates and their greater affinity for oxygen *(12).* No pseudomonads were detected (limit of detection, 2 log CFU/g) in irradiated (0.5, 1.0, and 2.0 kGy) chicken samples during the entire aerobic storage period (results not shown). Similarly, pseudomonad numbers in irradiated (1.75 kGy) pork packed under air were significantly reduced *(13).* The elimination of pseudomonads by low-dose radiation can be beneficial given that volatile metabolic products of LAB and/or *B. thermosphacta* are relatively less offensive than the off-odors produced by pseudomonads *(33).* Similarly, *Pseudomonas* spp. were not detected in irradiated (1.5 and 3.0 kGy) mechanically deboned chicken meat after 2 weeks of storage under vacuum *(41).* The specific behavior of pseudomonads may be attributed to the high sensitivity of this bacterial group to irradiation *(16).*

The initial population of yeasts and molds in nonirradiated chicken samples was ca. 2.8 log CFU/g under aerobic packaging conditions, in agreement with mean initial populations on fresh chicken breast (2.96 log CFU/g) *(20).* Populations of yeasts and of specific yeast species in fresh poultry and processed poultry products have been determined in only a few studies, and thus the contribution of these microorganisms to spoilage is difficult to determine *(9).* However, in the present study growth of yeasts and molds in aerobically packaged chicken samples was sub-

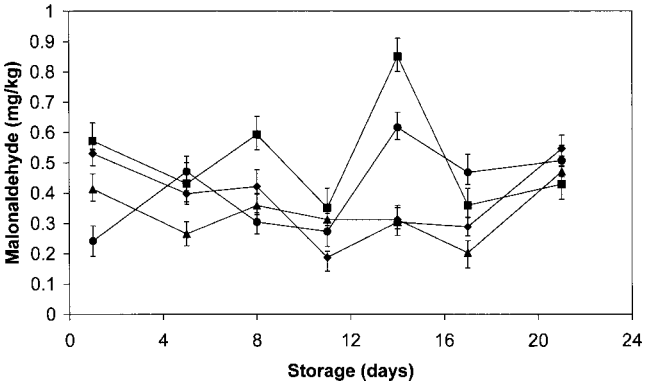

FIGURE 1. *Changes in TBA (thiobarbituric acid) of nonirradiated (control, ●) and irradiated (0.5 kGy, ▲; 1.0 kGy, ♦; 2.0 kGy, ■) chicken fillets stored aerobically at 4°C. Each value is the mean (±SD) of three samples taken from each of two different experiments (*n = 2 × 3 = 6*).*

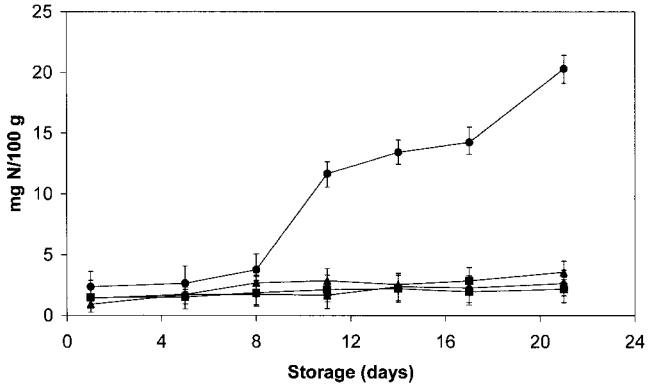

FIGURE 2. *Changes in TMA-N (trimethylamine nitrogen) of nonirradiated (control, ●) and irradiated (0.5 kGy, ▲; 1.0 kGy, ♦; 2.0 kGy, ■) chicken fillets stored aerobically at 4°C. Each value is the mean (±SD) of three samples taken from each of two different experiments (*n = 2 × 3 = 6*).*

stantial, reaching ca. 7.1 log CFU/g after 11 days of storage. Similar to the results for *Pseudomonas* spp., low-dose irradiation (0.5, 1.0, and 2.0 kGy) completely eliminated these species in chicken samples throughout the entire storage period (limit of detection, 2 log CFU/g) (results not shown). Results of the present study are in partial agreement with the findings of Cho et al. *(7),* who reported that a radiation dose greater than 5.0 kGy eliminated the growth of yeasts and molds in chicken. In another study, higher radiation doses of 5.0, 7.5, and 10.0 kGy resulted in formation of black spots on legs and thighs of chicken carcasses by day 12 of storage, and yeast isolation revealed the presence of *Candida, Saccharomyces,* and *Alternaria* species *(1).* The limited information available on identification of yeasts and molds and their association with poultry spoilage suggests that yeasts are active members of the microflora of spoiled poultry *(9).* Knowledge of the presence and number of yeasts and molds in poultry and in processed poultry products would be useful for developing technologies to retard spoilage.

Final populations of facultative anaerobic LAB, *B. thermosphacta,* as well as aerobic bacteria in irradiated aerobically packaged chicken (2 kGy) were quite similar ($<10^6$ CFU/g) (Table 1). The microflora of refrigerated meat (including poultry) under aerobic packaging conditions is dominated by gram-negative bacteria, i.e., *Pseudomonas* spp., whereas under modified atmospheres gram-positive bacteria, mainly LAB and *B. thermosphacta,* play an important role in spoilage of meat and meat products *(17).* Similar results have been reported, confirming growth of LAB and/or *B. thermosphacta* in various types of fresh meat, including pork *(13, 43)* and ground turkey *(40).*

Enterobacteriaceae counts in nonirradiated aerobically packaged chicken exceeded 7 CFU/g after ca. 8 to 9 days of refrigerated storage (Table 1). Respective counts for irradiated chicken samples were lower ($P < 0.05$), and populations always remained <7 log CFU/g, decreasing with increasing radiation dose. *Enterobacteriaceae* were completely eliminated by the highest radiation dose (2 kGy). In another study, *Enterobacteriaceae* were not isolated from irradiated (1.75 kGy) pork stored under various modified atmospheres *(13).* Radiation doses of 1.5 and 2.5 kGy completely eliminated coliforms in ground turkey stored at 7°C under aerobic or modified atmosphere packaging conditions (30 or 53% CO_2) *(40).* Low-dose radiation may have a positive effect on food safety through the suppression of *Enterobacteriaceae,* some of which could be enterovirulent *Escherichia coli.*

Chemical analyses. Changes in pH during storage were not significant ($P > 0.05$). pH values for nonirradiated and irradiated chicken samples were ca. 5.9 to 6.0 (results not shown). The changes in concentrations of TBA, TMA-N, TVB-N, and BAs for control and irradiated chicken during the 21-day storage period under refrigeration are shown in Figures 1 through 3.

TBA values for nonirradiated and irradiated chicken samples varied and in general were low (<1 mg MA/kg muscle) during the entire 21-day storage period (Fig. 1). No substantial differences in TBA values were recorded between nonirradiated and irradiated samples during storage. In related studies of ionizing radiation, contradictory results have been reported for TBA values in nonirradiated

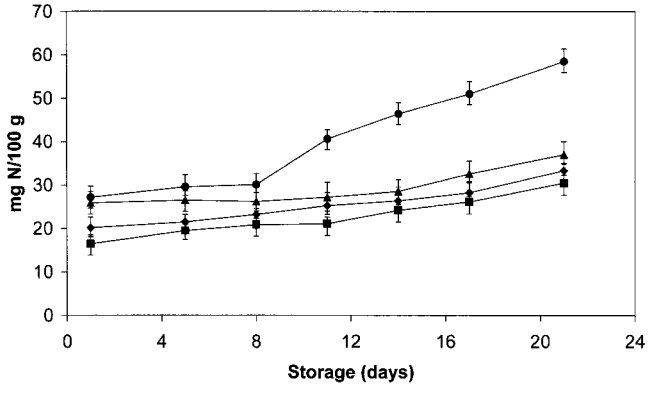

FIGURE 3. *Changes in TVB-N (total volatile basic nitrogen) of nonirradiated (control, ●) and irradiated (0.5 kGy, ▲; 1.0 kGy, ♦; 2.0 kGy, ■) chicken fillets stored aerobically at 4°C. Each value is the mean (±SD) of three samples taken from each of two different experiments (*n = 2 × 3 = 6*).*

TABLE 2. *Concentration of biogenic amines in nonirradiated (control) and irradiated (0.5, 1.0, and 2.0 kGy) chicken fillets stored aerobically at 4°C*[a]

Biogenic amine	Storage time (days)	Concn (mg/kg) after irradiation at:			
		0 kGy	0.5 kGy	1.0 kGy	2.0 kGy
Putrescine	1	28.1 ± 0.8	11.5 ± 0.8	9.8 ± 0.8	7.2 ± 0.5
	5	40.5 ± 1.4	19.8 ± 0.5	14.4 ± 0.7	10.5 ± 0.6
	8	81.2 ± 2.8	42.2 ± 1.4	31.5 ± 1.4	19.6 ± 1.3
	11	160.5 ± 3.5	52.6 ± 1.8	44.5 ± 1.9	25.3 ± 0.9
	14	210.9 ± 5.4	68.6 ± 2.2	59.1 ± 1.6	30.5 ± 1.2
	17	252.6 ± 7.5	76.5 ± 3.4	67.5 ± 1.9	43.2 ± 1.4
	21	300.3 ± 8.7	82.6 ± 3.9	74.9 ± 2.4	65.5 ± 2.1
Cadaverine	1	9.8 ± 0.3	5.2 ± 0.7	3.3 ± 0.2	1.5 ± 0.2
	5	14.8 ± 0.8	8.7 ± 0.9	6.7 ± 0.7	5.3 ± 0.4
	8	30.1 ± 1.6	17.2 ± 0.6	15.9 ± 0.7	9.3 ± 0.6
	11	80.5 ± 3.2	19.6 ± 0.8	16.9 ± 0.9	12.8 ± 0.5
	14	120.5 ± 4.5	25.6 ± 1.2	19.2 ± 0.5	16.4 ± 0.9
	17	160.7 ± 6.4	32.2 ± 1.6	28.3 ± 1.2	25.6 ± 0.6
	21	210.1 ± 7.6	38.2 ± 1.9	35.9 ± 1.1	32.1 ± 1.7
Histamine	1	2.2 ± 0.3	ND	ND	ND
	5	4.1 ± 0.4	ND	ND	ND
	8	6.6 ± 0.6	ND	ND	ND
	11	10.6 ± 0.7	ND	ND	ND
	14	13.3 ± 0.6	ND	ND	ND
	17	19.2 ± 0.9	ND	ND	ND
	21	54.0 ± 1.7	ND	ND	ND

[a] Values are the mean (±SD) from three samples taken from each of two different experiments ($n = 2 \times 3 = 6$). ND, not detected.

and irradiated samples. For cooked turkey meat that had been stored under vacuum or aerobic conditions, Ahn et al. *(2)* reported lower TBA values for irradiated (4.5 kGy) than for nonirradiated turkey samples on day 7 of storage. In contrast, higher TBA values of 5.0 and 6.2 mg MA/kg of muscle were reported for irradiated (3 and 4 kGy, respectively) mechanically deboned chicken after 12 days of storage *(10)*. A TBA value of 4.3 mg MA/kg muscle for irradiated (2.5 kGy) chicken meat after 4 weeks of chilled storage was reported by Kanatt et al. *(24)*. These contradictory findings reveal the complexity of the lipid oxidation characteristics of irradiated poultry meat. However, higher TBA values would be expected for irradiated meat samples given the high oxidizing potential of γ-radiation *(37)*.

A different pattern was noted for changes in TMA-N and TVB-N values for nonirradiated and irradiated chicken samples (Figs. 2 and 3). Both TMA-N and TVB-N values for irradiated (0.5, 1, and 2.0 kGy) chicken samples were lower ($P < 0.05$) than those for nonirradiated samples stored aerobically (Figs. 2 and 3). Both TMA-N and TVB-N values for nonirradiated chicken increased steeply after 8 to 9 days of storage, with final TMA-N and TVB-N values of ca. 20.3 and 58.5 mg N/100 g of muscle, respectively. Irradiated (0.5, 1, and 2 kGy) samples had significantly lower TMA-N and TVB-N values ($P < 0.05$) of ca. 2.2 to 3.6 and 30.5 to 37.0 mg N/100 g of muscle, respectively, during the 21 days of refrigerated storage (Figs. 2 and 3). Limited information is available on production of volatile amines in meat, including chicken. Al-Bachir and Mehio *(3)* reported lower TVB-N values in irradiated luncheon meat than in nonirradiated controls after 10 weeks of storage. In another study of the formation of BAs in chicken breast and thigh after slaughter, TVB-N values of ca. 34.5 to 46.6 mg N/100 g of muscle were recorded on day 15 of refrigerated storage, in agreement with our results obtained for aerobically packaged chicken, i.e., 40.6 mg N/100 g of muscle on day 11 of storage (Fig. 3). Volatile amines such as TMA-N and TVB-N have been used to assess the extent of spoilage in marine fish, and upper TMA-N and TVB-N limits of 1 and 30 to 35 mg N/100 g of muscle, respectively, have been suggested for determination of freshness *(18)*. With regard to meat quality, TVB-N limit values of ca. 20 and 26 mg N/100 g of muscle for beef and pork (corresponding to 8 and 10 days of refrigerated storage, respectively) have been proposed as indicators of meat quality *(5)*.

BAs evaluated in this study were putrescine, cadaverine, spermine, spermidine, tyramine, and histamine (Table 2). Of all BAs, only the diamines putrescine and cadaverine were detected in significant concentrations in both nonirradiated and irradiated chicken samples, whereas histamine formation was noted only in nonirradiated samples during storage. Putrescine was the main amine formed followed by cadaverine, and initial (day 1) values of ca. 28.1 and 9.8 mg/kg of muscle were recorded for nonirradiated aerobically packaged samples, respectively, with final values of 300.3 and 210.1 mg/kg of muscle, respectively (Table 2). Respective concentrations of these BAs for irradiated chicken samples were significantly lower ($P < 0.05$) than those for nonirradiated samples throughout the entire stor-

TABLE 3. *Values for odor, taste, and appearance of nonirradiated (control) and irradiated (0.5, 1.0, and 2.0 kGy) chicken fillets stored aerobically at 4°C*[a]

Sensory attribute	Storage time (days)	Sensory value after irradiation at:			
		0 kGy	0.5 kGy	1.0 kGy	2.0 kGy
Odor	1	9.0 ± 0.3	8.4 ± 0.6	8.2 ± 0.4	7.6 ± 0.6
	5	5.2 ± 0.7	8.5 ± 0.6	8.1 ± 0.5	7.8 ± 0.5
	8	3.6 ± 0.4	7.4 ± 0.3	7.4 ± 0.3	7.9 ± 0.2
	11	2.7 ± 0.1	4.4 ± 0.5	5.0 ± 0.8	7.4 ± 0.8
	14	2.3 ± 0.5	3.5 ± 0.2	4.1 ± 0.6	6.9 ± 0.4
	17	1.7 ± 0.4	3.1 ± 0.6	3.8 ± 0.2	6.8 ± 0.9
	21	1.4 ± 0.6	2.6 ± 0.4	3.3 ± 0.4	6.6 ± 0.7
Taste	1	8.9 ± 0.4	8.2 ± 0.4	7.8 ± 0.4	7.3 ± 0.7
	5	6.0 ± 0.6	8.6 ± 0.6	8.4 ± 0.6	8.4 ± 0.4
	8	NA	7.6 ± 0.4	7.7 ± 0.3	7.6 ± 0.3
	11	NA	NA	NA	7.1 ± 0.7
	14	NA	NA	NA	6.6 ± 0.2
	17	NA	NA	NA	6.4 ± 0.4
	21	NA	NA	NA	6.1 ± 0.6
Appearance	1	8.8 ± 0.7	8.8 ± 0.3	8.7 ± 0.4	8.7 ± 0.7
	5	8.7 ± 0.3	8.7 ± 0.4	8.6 ± 0.6	8.7 ± 0.5
	8	8.4 ± 0.4	8.6 ± 0.5	8.6 ± 0.8	8.6 ± 0.4
	11	7.8 ± 0.5	8.3 ± 0.6	8.3 ± 0.5	8.5 ± 0.6
	14	7.2 ± 0.7	8.1 ± 0.7	8.0 ± 0.4	8.4 ± 0.9
	17	6.5 ± 0.8	7.8 ± 0.9	7.7 ± 0.5	8.2 ± 0.8
	21	5.8 ± 0.9	7.2 ± 0.2	7.3 ± 0.7	7.9 ± 0.6

[a] Values are the mean (±SD) sensory score (9, excellent; <6, poor) from three samples taken from each of two different experiments ($n = 2 \times 3 = 6$). NA, not analyzed.

age period. High concentrations of putrescine and cadaverine in nonirradiated aerobically packaged chicken meat may be attributed to high populations of *Pseudomonas* spp. With regard to the effect of irradiation on formation of BAs, previous research has indicated that high energy γ-radiation has a strong bactericidal effect on various species, including *Pseudomonas* spp., and thus on microbial enzymatic activity responsible for the formation of BAs *(16).* Production of histamine was only noted in nonirradiated chicken meat stored aerobically, and histamine concentrations of ca. 54.0 mg/kg of muscle were recorded on day 21 of storage. Irradiation suppressed formation of histamine in chicken samples during the entire storage period. Histamine concentrations of ca. 50 mg/kg can potentiate toxicity in sensitive individuals *(39).* With regard to other BAs evaluated in the present study (spermine, spermidine, and tyramine), low-dose irradiation had almost no effect on their formation (results not shown). Concentrations of spermine, spermidine, and tyramine in nonirradiated aerobically packaged chicken samples were ca. 36.6 to 53.3, 4.0 to 7.9, and 0.2 to 6.4 mg/kg of muscle, respectively, during the entire refrigerated storage period, whereas respective concentrations of ca. 27.0 to 64.4, 6.5 to 12.4, and 0.1 to 6.1 mg/kg of muscle were recorded for irradiated samples. To date, limited data are available on formation of BAs and the effects of preservation technologies such as ionizing radiation and high hydrostatic pressure *(34).*

Sensory evaluation. Sensory scores for odor, taste, and appearance of cooked nonirradiated (control) and irradiated chicken decreased with time of refrigerated storage (Table 3). A score of 6 was considered the lower limit of acceptability corresponding to initial development of off-odor or off-taste. Odor, taste, and appearance had similar patterns of decreasing acceptability (Table 3). All irradiated samples received higher sensory scores ($P < 0.05$) than did their nonirradiated counterparts as judged by these sensory attributes. This trend was apparent after day 8 and continued throughout the entire period of refrigerated storage. The limit of acceptability of odor was reached after 4 to 5 days for the nonirradiated samples and after 9 to 10 days for irradiated (0.5 and 1 kGy) samples. The limit of acceptability was not reached for irradiated (2.0 kGy) chicken samples even after 21 days of storage. Sensory scores for taste were not recorded for chicken samples that had exceeded the microbiological limit of 7 log CFU/g because these samples were judged unfit to taste (Table 3). As for odor, the limit of acceptability for taste was not reached for samples irradiated at 2.0 kGy even after 21 days of storage. Appearance scores for both nonirradiated and irradiated chicken (Table 3) decreased at a slower rate than did scores for odor and taste. The limit of acceptability for appearance was reached only after ca. 20 days for the nonirradiated samples and was due to the apparent growth of yeasts and molds.

In other studies involving irradiation (1.66 to 2.86 kGy) of chicken meat *(15),* the product continued to have a fresh ''chickeny'' flavor until the end of the storage period, and no other sensory attributes were affected by ir-

radiation, in agreement with present findings. Lescano et al. *(26)* found that the sensory quality of chicken breast samples (based on taste evaluation) was not affected and the product was considered acceptable up to day 22 of storage. Abu-Tarboush et al. *(1)* also concluded that radiation doses of 2.5 to 10 kGy had little effect on the sensory acceptability (odor, taste, texture, and appearance) of both raw and cooked chicken (breast and thigh).

Sensory analysis data for cooked chicken based on odor were correlated with microbiological (APC) data (Tables 1 and 3) obtained for nonirradiated samples and samples irradiated at 0.5 and 2.0 kGy but not with data for samples irradiated at 1 kGy. The discrepancy observed between sensory and microbiological data was ca. 2 days only for the 1-kGy samples. A similar discrepancy between sensory and microbiological data has been reported *(14)* and was attributed to differences in populations of total and specific spoilage microorganisms.

Based on odor scores, a shelf life of ca. 8 and 9 days was achieved for chicken samples irradiated at 0.5 and 1.0 kGy, respectively. These radiation doses extended the shelf life of fresh skinless chicken by ca. 4 to 5 days compared with the control samples (nonirradiated aerobically stored), whereas the radiation dose of 2 kGy extended chicken shelf life by more than 15 days ($P < 0.05$). Similarly, a dose of 2.5 kGy seemed adequate to extend the shelf life of chicken by 12 days *(1)*, whereas radiation doses of 3.0 and 4.0 kGy maintained the acceptable quality of refrigerated mechanically deboned chicken meat (evaluated by sensory, chemical, and microbiological analysis) for 10 and 6 days, respectively, as compared with 4 days for nonirradiated meat *(10)*.

Based on sensory (odor) analysis, TMA-N and TVB-N values of ca. 2.5 to 2.6 and 28 to 29 mg N/100 g of muscle are proposed as the upper limits for initiation of spoilage in fresh chicken meat stored aerobically. The APC that indicated spoilage for aerobically stored chicken meat was ca. 10^7 CFU/g.

The effect of low-dose radiation and aerobic packaging of poultry and products has not been studied extensively. Apart from being beneficial for extending the shelf life of such products *(25)*, these treatments eliminate several non–spore-forming pathogens, many of which (e.g., *Listeria*, *Vibrio*, and *Salmonella*) have low D_{10}-values (dose required for 90% inactivation) *(40, 41)*.

Based primarily on sensory evaluation, low-dose radiation (0.5 and 1.0 kGy) in combination with aerobic packaging extended the shelf life of fresh chicken fillets by ca. 4 to 5 days, whereas a radiation dose of 2.0 kGy extended the shelf life by more than 15 days, compared with that of nonirradiated chicken.

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