

Effect of Ionizing Radiation Dose, Temperature, and Atmosphere on the Survival of *Salmonella typhimurium* in Sterile, Mechanically Deboned Chicken Meat

DONALD W. THAYER and GLENN BOYD

Food Safety Research Unit, Eastern Regional Research Center, USDA, Agricultural Research Service, 600 East Mermaid Lane, Philadelphia, Pennsylvania 19118

ABSTRACT The response to gamma radiation (0 to 3.60 kGy; 100 krad = 1 kGy) of *Salmonella typhimurium* was tested in otherwise sterile, mechanically deboned chicken meat (MDCM) in the absence of competing microflora. Response was determined at temperatures of -20 to +20 C and when the MDCM was packaged in vacuum or in the presence of air. A central composite response-surface design was used to test the response of the pathogen to the treatments in a single experiment. Predictive equations were developed from the analyses of variances of the resulting data. The accuracy of each predictive equation was tested by further studies of the effects of gamma radiation on *S. typhimurium* in the presence or absence of air at -20, 0, and +20 C. All data were then analyzed to refine the predictive equations further. Both the original and the refined equations adequately predicted the response of *S. typhimurium* in MDCM to gamma radiation doses up to 3.60 kGy in the presence of air or *in vacuo*. Gamma irradiation was significantly more lethal for *S. typhimurium* in the presence of air and at higher temperatures. The final equations predict a reduction in the number of surviving *Salmonella* in MDCM irradiated to 1.50 kGy at -20 C of 2.53 logs in air or 2.12 logs if irradiated in vacuum. If the contaminated MDCM were to receive a dose of 3.0 kGy at -20 C in air, the number of *Salmonella* would be decreased by 4.78 logs, and if irradiated in vacuum, by 4.29 logs. At an irradiation temperature of +20 C and a dose of 3.0 kGy, the number of viable *Salmonella* would be decreased by 6.38 logs if irradiated in air. (Key words: chicken, gamma radiation, temperature, atmosphere, *Salmonella*)

INTRODUCTION

The incidence of salmonellosis in human beings in the United States continues to increase. The Center for Infectious Diseases reported 38,886, 36,061, 56,750, and 42,028 isolates of *Salmonella* species associated with human disease in 1983, 1984, 1985, and 1986, respectively (Hargrett-Bean *et al.*, 1988). The 1985 data include 16,000 cases of salmonellosis due to a single outbreak from *Salmonella typhimurium* in the East North Central Region in 1985. The Food Safety and Inspection Service (FSIS) of the USDA petitioned the Food and Drug Administration (FDA) to approve the use of ionizing radiation treatments of retail packaged, frozen or fresh, uncooked poultry products to decrease the potential of foodborne illness from such foodborne pathogens as *Salmonella*, *Campylobacter*, and *Yersinia* species (FDA, 1987). This petition specified a dose range of 1.5 to 3.0 kGy (100 krad = 1 kGy) and was approved (*Federal Register*, 1990).

Many studies have demonstrated the potential for the reduction or elimination of salmo-

nellae from meat products by treatments with ionizing radiation. Mulder *et al.* (1977) reported that a dose of 2.5 kGy effectively destroyed salmonellae on frozen (-20 C) chicken carcasses and greatly reduced the number of salmonellae on chilled carcasses. These results contrast with reports by others (Matsuyama *et al.*, 1964; Previte *et al.*, 1970; Thayer *et al.*, 1990) in which radiation treatments at freezing temperatures were less effective. Matsuyama *et al.* (1964) conducted their studies with broth and buffer suspensions of cells and noted a ratio of 8.5:1 for the dose required to effect a reduction of 90% in the microbial population (D_{10} values) for *Pseudomonas* species irradiated at subfreezing temperatures versus room temperature. These authors also noted that the presence of oxygen decreased the resistance of *Pseudomonas* species to ionizing radiation. Mulder (1976) estimated that a dose of at least 7.0 kGy would be required to reduce to 1 in 10,000 the number of salmonellae-positive, deep-frozen chicken carcasses based on their work with *Salmonella panama*. Hanis *et al.* (1989) examined the effects of gamma radiation on

chilled (10 C) and frozen (-15 C), artificially contaminated broiler carcasses. The carcasses were inoculated with 10^6 cfu/g of *Pseudomonas aeruginosa*, *S. typhimurium*, or *Serratia marcescens* prior to irradiation. They found that a dose of 5 kGy was insufficient at either temperature to eliminate *S. typhimurium*. The *P. aeruginosa* and *Serr. marcescens* were eliminated, respectively, by radiation doses of 1.0 and 2.5 kGy at 10 C. Survival of both the *Pseudomonas* and the *Serratia* increased at the lower irradiation temperature. The authors attributed some of these effects to competition with the residual natural flora.

Mechanically deboned chicken meat (MDCM) was chosen for the present study because it is a major item of commerce and little data exist on the effects of ionizing radiation on its microbial flora. A previous study (Thayer *et al.*, 1990) established the D_{10} values for six serotypes of *Salmonella* in radiation-sterilized, MDCM under both anaerobic and aerobic conditions and noted a marked decrease in the sensitivity of *S. typhimurium* and *Salmonella enteritidis* to gamma radiation at subfreezing temperatures. The chicken meat was sterilized by gamma radiation *in vacuo* to a dose of 42 kGy at -40 C to eliminate the possible effects of competition with any residual natural microflora on the results (Anellis *et al.*, 1977). Extensive data indicate that poultry products sterilized by this technique are not significantly altered chemically or toxicologically (Thayer *et al.*, 1987). The purpose of the current study was to determine the responses of *S. typhimurium* in MDCM to various doses of gamma radiation at normal processing temperatures in the presence or absence of air and to develop predictive equations from responses from a limited study. The predictive equations were then tested by additional experimentation and refined. The ultimate use of such predictive equations, it is hoped, will be by regulatory agencies and by the poultry industry to predict the response of salmonellae in chicken to irradiation treatment.

Organisms and Culture Maintenance

Salmonella typhimurium ATCC 14028 was used for these studies. Each strain was maintained and cloned on tryptic soy agar (TSA)¹ and incubated at 35 C. Cultural purity and identity were verified with Gram stains and API 20E diagnostic kits.² Each strain was cultured overnight (15 to 18 h at 35 C) in trypticase soy broth (TSB).³ A 1-mL sample was used to inoculate 100 mL of TSB in a 500-mL baffled DeLong flask. The inoculated TSB was incubated at 35 C and agitated at 150 rpm for 16 h. A 10-fold concentrated inoculum was prepared by centrifuging the cells from TSB and resuspending them in one-tenth volume of .1% sterile peptone water.¹

Mechanically Deboned Chicken Meat

The MDCM was obtained from a commercial manufacturer of poultry frankfurters. The meat was received in two commercial 18-kg lots and consisted of approximately 90% rib and 10% back meat. The average proximate analysis of this product was 65.3% moisture, 21.7% fat, and 25.0% protein. The chicken meat was mixed well and subdivided into $50.00 \pm .05$ -g lots, vacuum sealed in stomacher[®] Number 400 polyethylene (stomacher) bags⁴ and then vacuum sealed in International Kenfield Distributing Co. IKD All-Vak Number 13 bags.⁵ These bags have an oxygen permeability of 1.0 mL/645 cm² per 24 h and consist of a 2-mil nylon outer layer and an inner 1-mil medium-density, polyethylene, food-contacting film. Nonsterile chicken was stored at -20 C until used. Other replicate samples were cooled to -50 C and then irradiated at the same temperature to an absorbed dose of 42 kGy with gamma radiation. Sterility was confirmed by plate count. The radiation-sterilized product was stored at -20 C until used.

Experimental Design

A central composite response-surface design was used to develop a model for the effects of irradiation dose, temperature, and atmosphere on *S. typhimurium* ATCC 14028 in sterile MDCM. A sample of 200 g of sterile MDCM was inoculated with about $10^{9.5}$ cells/g. The chicken meat and the inoculum were mixed in a

¹Difco, Detroit, MI 48232-7058. Mention of any company or product name does not constitute endorsement.

²API Analytab Products, Plainview, NY 11803.

³BBL, Cockeysville, MD 21030.

⁴Tekmar Co., Cincinnati, OH 45222-1856.

⁵International Kenfield Distributing Co., Rosemont, IL 60018.

sterile stomacher bag for 90 s using a stomacher. Samples ($5.0 \pm .05$ g) of the inoculated MDCM were aseptically transferred to sterile stomacher bags. The MDCM was spread uniformly over an area of approximately 10×10 cm within the bag and heat-sealed either *in vacuo* or with air in the bag. Each stomacher bag containing a sample was vacuum packaged within an IKD Number 13 pouch to prevent the absorption of oxygen and to provide additional microbiological security. The following temperatures and radiation doses were used for the study: -20 C, 1.80 kGy; -10 C, .90 and 2.70 kGy; 0 C, 0, 1.80, and 3.60 kGy; $+10$ C, .90 and 2.70 kGy; and $+20$ C, 1.80 kGy. Immediately following irradiation, all samples were frozen at -20 C. A nonirradiated control sample was used to determine the effect of freezing on the total colony-forming units of the *S. typhimurium* ATCC 14028 in MDCM. The nonfrozen samples averaged 1.1×10^{10} and the frozen samples 8.3×10^9 cfu/g of MDCM. The entire study was replicated twice.

A series of three independent studies was conducted with the sterile MDCM to test and improve the first model response-surface equation. At irradiation temperatures of -20 C, 0 C, and $+20$ C, MDCM samples inoculated with *S. typhimurium* ATCC 14028 and packaged as described were irradiated to doses of 0, .30, .60, .90, 1.20, 1.80, 2.70, and 3.60 kGy. The number of colony-forming units was determined as described. Each study was replicated three times.

Microbiological Assay of Mechanically Deboned Chicken Meat

Samples of MDCM were assayed for colony-forming units by standard pour-plate procedures with serial dilutions in sterile .1% Difco Bacto peptone.¹ The pour plates were prepared using TSA and incubated for 24 h at 35 C. The colony-forming units on three Petri plates at a dilution giving 30 to 300 colonies were counted using a New Brunswick Scientific Biotran II[®] automated colony counter.⁶

Irradiation

Samples were irradiated in a self-contained cesium-137 gamma radiation source (135,708 Ci) at a dose rate of .12 kGy/min. The dosimetry

and dose distribution for this radiation source were described by Shieh *et al.* (1985). Routine dosimetry was conducted with ferrous sulfate and cupric sulfate dosimeters (Jarrett and Halliday, 1979). The samples were brought to the desired temperature before irradiation, and this temperature was maintained ± 2 C during irradiation by injecting liquid nitrogen. Because of the low heat capacity of gaseous nitrogen, the actual variation in sample temperature did not exceed .5 C. The samples were placed in a uniform portion of the radiation field and arranged to minimize any differences in the radiation dose. The mean deviation of the absorbed dose from the target dose was .038 kGy, with a standard error of .018 kGy.

Statistical Analysis

Responses were expressed as the logarithm of the number of viable bacterial cells per gram. For each experiment, the average (N) of the colony-forming units values for the three plate counts obtained for each replicate sample was determined and divided by the average of the three zero-dose colony-forming units values (N_0) to give a value for survivors (N/N_0). The log survivor values (\log_{10} of N/N_0) were then used for subsequent calculations. The D values were the reciprocal of the slope of the regression of the log survivor values determined by least-squares analysis. Regression techniques were used to fit second-order response-surface models (Draper and Smith, 1981). Statistical calculations were performed with the general linear models procedure of the SAS statistical package (Freund *et al.*, 1986; SAS Institute, 1987).

RESULTS

The means for the estimates of the colony-forming units found in each of the experiments are presented with their standard deviations in Table 1. The response-surface equations developed by analyses of data presented in Table 1 are presented with their respective R^2 values in Table 2. Analysis of the data in Experiment 1 by analysis of variance indicated that radiation dose, temperature, and atmosphere were significant ($P > .0001$) for samples irradiated in either air or vacuum.

Response-Surface Model

Because very high inocula numbers were used, neither freezing to a temperature of -20 C

⁶New Brunswick Scientific Co., Inc., Edison, NJ 08818.

THAYER AND BOYD

TABLE 1. *Surviving, colony-forming units (± SD) of Salmonella typhimurium per gram of mechanically deboned chicken meat following gamma irradiation at five discrete temperatures in the presence or absence of air and in the absence of competing microflora*

Experiment	Dose (kGy) ¹	Irradiation temperature (C)	n	log cfu/g	
				Air	Vacuum
1	0	0	2	9.87 ± .06	9.95 ± .02
1	.90	-10	2	7.99 ± .04	8.51 ± .02
1	.90	+10	2	7.10 ± .18	7.90 ± .03
1	1.80	-20	2	7.28 ± .24	7.22 ± .59
1	1.80	0	2	4.84 ± .44	6.42 ± .87
1	1.80	+20	2	4.94 ± .01	5.47 ± .07
1	2.70	-10	2	4.20 ± .04	5.54 ± .30
1	2.70	+10	2	3.16 ± .02	3.68 ± .14
1	3.60	0	2	2.41 ± .13	3.20 ± .90
2	0	-20	3	9.09 ± .02	9.14 ± .10
2	.30	-20	3	8.64 ± .24	8.73 ± .11
2	.90	-20	3	7.79 ± .32	7.93 ± .19
2	1.20	-20	3	6.57 ± .70	6.77 ± .20
2	1.80	-20	3	6.66 ± .38	7.13 ± .32
2	2.70	-20	3	5.14 ± .16	5.56 ± .44
2	3.60	-20	3	3.93 ± .34	4.28 ± .68
3	0	0	3	9.44 ± .08	9.26 ± .09
3	.30	0	3	8.74 ± .18	8.91 ± .13
3	.60	0	3	8.22 ± .04	8.22 ± .28
3	.90	0	3	8.00 ± .11	8.26 ± .09
3	1.20	0	3	7.17 ± .59	7.26 ± .04
3	1.80	0	3	5.60 ± .05	5.88 ± .12
3	2.70	0	3	2.32 ± .18	2.48 ± .55
4	0	+20	3	9.22 ± .11	9.10 ± .11
4	.30	+20	3	8.12 ± .14	8.93 ± .04
4	.60	+20	3	7.66 ± .12	8.69 ± .08
4	.90	+20	3	7.09 ± .16	7.97 ± .09
4	1.20	+20	3	6.40 ± .09	7.38 ± .04
4	1.80	+20	3	5.14 ± .11	6.11 ± .03
4	2.70	+20	3	3.63 ± .13	4.57 ± .03
4	3.60	+20	3	2.75 ± .04	3.06 ± .16

¹100 krad = 1 kGy.

nor warming of the MDCM to a temperature of +20 C would be expected to alter significantly the number of colony-forming units. The analysis of variance of the experimental data obtained in Experiment 1 generated equations producing values for the response surface at zero dose at both -20 and +20 C, which did not match those expectations. Therefore, the values obtained at 0 kGy and 0 C were duplicated at -20 and +20 C to eliminate the poor fit at 0 kGy. The effects of freezing and warming the inoculated MDCM were tested and found to agree with this hypothesis. The response-surface equations generated from these data are presented in Table 2.

Experiments 2, 3, and 4 were performed specifically to test the accuracy of the predictions made by the response-surface equations for Experiment 1. There were two tests of fit. The first asked: Do the majority of individual data

points fall within the 95% confidence interval predicted by the response-surface equation for each relevant temperature and dose? The second asked: Does an analysis of covariance at each study temperature (-20.0, 0, and +20.0 C) reveal a difference between the regressions generated from the data from Experiment 1 relative to those generated from Experiments 2, 3, and 4? The only result from Experiment 1 at -20 C was for a dose of 1.8 kGy, and the 95% confidence intervals for the means for the log₁₀ of survivors were -2.57 to -3.43 for samples irradiated in air and -2.10 to -3.04 for samples irradiated in a vacuum. The comparable values obtained for a dose of 1.8 kGy in Experiment 2 had means ± SD of -2.46 ± .38 and -1.99 ± .34 for samples irradiated in air or vacuum, respectively. Both means fall outside the 95% confidence limits for the values predicted for Experiment 1. However,

TABLE 2. Response-surface equations for the effects of gamma radiation dose (kGy),¹ temperature (Temp) and atmosphere on the survival of *Salmonella typhimurium* in mechanically deboned chicken meat in the absence of competing microflora

Equation	Experiment	Atmosphere	Equation
[1]	1	Air	$\text{Log}_{10} \text{ survivors} = -.377 - .005 \times \text{Temp} - 2.684 \times \text{kGy} - .026 \times \text{Temp} \times \text{kGy} + .001 \times (\text{Temp})^2 + .187 \times \text{kGy}^2$; $R^2 = .987$.
[2]	1	Vacuum	$\text{Log}_{10} \text{ survivors} = .097 + .001 \times \text{Temp} - 2.108 \times \text{kGy} - .029 \times \text{Temp} \times \text{kGy} + .053 \times \text{kGy}^2$; $R^2 = .981$.
[3]	1, 2, 3, 4	Air	$\text{Log}_{10} \text{ survivors} = -.166 - .010 \times \text{Temp} - 2.552 \times \text{kGy} - .010 \times \text{Temp} \times \text{kGy} + .002 \times (\text{Temp})^2 + .068 \times \text{kGy}^2$; $R^2 = .931$.
[4]	1, 2, 3, 4	Vacuum	$\text{Log}_{10} \text{ survivors} = -.170 + .006 \times \text{Temp} - 2.013 \times \text{kGy} - .013 \times \text{Temp} \times \text{kGy} + .002 \times (\text{Temp})^2 + .068 \times \text{kGy}^2$; $R^2 = .921$.

¹100 krad = 1 kGy.

for both air and vacuum-packaged samples, two of the three replicate values did fall within the 95% confidence limits. An analysis of covariance of the predicted regressions at -20 C from Experiment 1 and the regressions obtained in either air or vacuum in Experiment 2 did not indicate significant differences between regressions. Thus, the predictions of the response-surface equations for the effects of gamma radiation at -20 C on the populations of *Salmonella* in MDCM were reliable.

At 0 C, it was possible to compare predicted log₁₀ survivor values from Experiment 1 with values from Experiment 3 for 1.80 kGy. The results from the 3.60-kGy samples were not included because circumstances caused the pour plates to be counted after a longer period of incubation than was used for the remainder of the study. The predicted 95% confidence limits for the log₁₀ survivor values at 0 C and 1.80 kGy in air were -4.30 to -4.91, and the equivalent value from Experiment 3 was -3.75 ± .11. The predicted 95% confidence limits for the log₁₀ survivor values at 0 C and 1.80 kGy *in vacuo* were -3.20 to -3.85, and the equivalent value from Experiment 3 was -3.47 ± .09. The mean and the individual values for the samples irradiated in air lie outside the 95% confidence interval for the predicted value for Experiment 1. The mean and all three individual values for samples irradiated in vacuum to 1.80 kGy at 0 C fall within the predicted values. Analysis of covariance for the respective regression under air or vacuum at 0 C did not indicate a significant difference between the predicted regressions from Experiment 1 and those from Experiment 3 at 0 C. Thus, the predictions from the analysis of

Experiment 1 for the log₁₀ survivor values at 0 C were reliable.

At 20 C and 1.80 kGy in air the predicted 95% confidence limits for the log₁₀ survivor value were -4.13 to -5.06; the equivalent value from Experiment 4 was -4.03 ± .05. At 20 C in vacuum the predicted 95% confidence limits for the log₁₀ survivor values were -4.64 to -5.50; the equivalent value from Experiment 4 was -3.06 ± .09. In this case the means and all three individual values for both air and vacuum-packaged chicken irradiated to 1.80 kGy at 20 C were not included by the 95% confidence intervals predicted by Experiment 1. Analyses of covariance indicated a different regression for samples irradiated in air but not for samples irradiated in vacuum.

Refinement of Model

The results from all four experiments were analyzed to develop new response-surface equations excluding the extrapolated values at -20 C and +20 C for Experiment 1. The resulting Equations 3 and 4 are presented in Table 2. The analysis of variance indicated highly significant effects for the interactions of irradiation temperature, radiation dose, temperature × dose, and temperature squared under both air and vacuum. The R² values, although not quite as high as obtained for the analysis of Experiment 1, exceeded .92. The response surface generated by the equation for the effect of irradiation of *S. typhimurium* in vacuum is presented graphically in Figure 1. Comparison of the predictive Equations [1] and [3] for irradiation in air by

THAYER AND BOYD

TABLE 3. Effect of temperature and atmosphere on the D value for the survival of *Salmonella typhimurium* in mechanically deboned chicken meat in the absence of competing microflora.

Experiment	Temperature (C)	n	Observed values		Predicted values ²	
			Air	Vacuum	Air	Vacuum
			[D(kGy)]			
2	-20	12	.45 ± .01	.48 ± .06	.48	.60
2	-20	18	.70 ¹ ± .07	.79 ¹ ± .08	.56 ¹	.64 ¹
3	0	12	.61 ± .11	.61 ± .09	.44	.52
4	+20	12	.53 ± .03	.56 ± .03	.40	.46
4	+20	18	.52 ¹ ± .01	.53 ¹ ± .01	.46 ¹	.48 ¹

¹Values (± SE) were determined for the dose range .30 to 2.70 kGy (100 krad = 1 kGy); all others were determined for the dose range .30 to 1.20 kGy.

²Values computed using predictions of Equations 3 and 4 derived from data obtained during Experiments 1, 2, 3, and 4. The D values were the reciprocal of the slope of the least-squares analysis of the regression of the log₁₀ of the survivor values (Thayer *et al.*, 1990).

analysis of covariance indicated that they differed significantly. However, the predictive equations for irradiation in a vacuum (Equations [2] and [4]) did not differ significantly.

Effect of Air

The analysis of covariance of Equations [1] and [2] (Table 2) for Experiment 1 and of Equations [3] and [4] (Table 2) for all data indicated significant effects of air during the irradiation of the chicken meat on the survival of *Salmonella*. Analysis of covariance failed to indicate a significant difference between the effects of irradiation at -20 C and at 0 C on the survival of *S. typhimurium* when irradiated in air or in vacuum in Experiments 2 and 3, respectively. However, the analysis of covariance did indicate a significant difference between the effects of irradiation at +20 C on the survival of *S. typhimurium* when irradiated in air or in vacuum in Experiment 4. The D values computed for the destruction of *S. typhimurium* based on the results of Experiments 2, 3, and 4 are contrasted with those generated by Equations [3] and [4] in Table 3.

DISCUSSION

The analysis of data from Experiment 1 resulted in Equations [1] and [2], which predict the response of *S. typhimurium* on MDCM to gamma radiation either in the presence or absence of air and between -20 to +20 C. The intent of the study was to develop and test such predictive equations over the range of temperatures used in normal processing. It is

conceivable that processing temperatures as low as -20 C might be used, but the upper range used in these studies is clearly beyond that permitted by US law; however, moderate abuse temperatures were covered with the predictive equations. Processors of fresh poultry would endeavor to irradiate the poultry

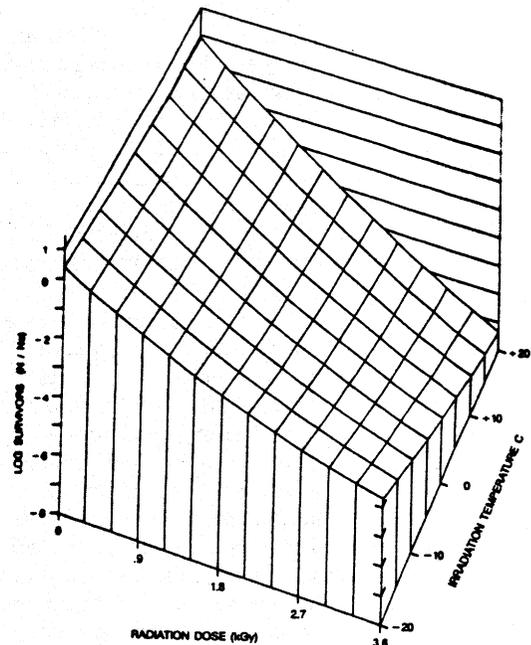


FIGURE 1. Prediction of Equation [4], from text, for the logarithm base 10 of the surviving *Salmonella typhimurium* contaminating vacuum-packed mechanically deboned chicken following gamma irradiation administered within the temperature range of -20 to +20 C.

meat at as close to the 40 F (4.4 C) temperature mandated by US law as possible, but few commercial radiation sources have refrigeration capabilities. Thus, some products might arrive at the irradiation plant slightly below freezing and could potentially reach temperatures outside the normally permitted maximum of 55 F (12.8 C). The temperature range of -20 to +20 C was then selected to allow the effects of such temperatures to be predicted.

The purpose of the present research was to determine if response-surface methodology could be used to develop equations that would predict, with reasonable accuracy, the response of salmonellae to gamma radiation doses under various temperatures and atmospheres. The analyses of data from Experiments 1 through 4 indicate that a single study, such as in Experiment 1, can indicate the patterns of the response, although not the actual response. The data also indicate that it is the patterns that are significant and not the individual responses, because of the high variability among such biological responses.

The variability of responses to irradiation can be illustrated by comparison of D_{10} values computed from the data obtained from Experiments 2, 3, and 4 and from computer-generated data points from Equations [3] and [4] shown in Table 3. The values generated from Experiments 2, 3, and 4 in general are larger than those predicted by the response surface. Based on the increased lethality at elevated temperatures, the authors predict a related decrease in the D_{10} values as the processing temperature increases from -20 to +20 C. Such a decrease did occur when the values were computed from the data points generated by Equation [3] or [4]. The results of calculations of D_{10} values from isolated experimental studies at -20, 0, and +20 C did not decrease in a uniform manner as the irradiation temperature increased, presumably due to biological variability, in spite of attempts to control such variability.

The final equations predict a reduction in the number of surviving *Salmonella* in MDCM irradiated to 1.50 kGy at -20 C of 2.53 logs in air or 2.12 logs if irradiated in vacuum. If the contaminated MDCM were to receive a dose of 3.0 kGy at -20 C in air, the number of *Salmonella* would be decreased by 4.78 logs, and if irradiated in vacuum by 4.29 logs. At an irradiation temperature of +20 C and a dose of 3.0 kGy, the number of viable *Salmonella*

would be decreased by 6.38 logs if irradiated in air. Based on both the actual experimental data and the predictions of the response-surface equations, the dose range requested by the FSIS of 1.5 to 3.0 kGy should result minimally in a 99% inactivation of any salmonellae present in or on chicken meat.

ACKNOWLEDGMENTS

A portion of this manuscript was presented as the Halpin Lecture, Poultry Science Department, University of Wisconsin, Madison. The authors acknowledge the technical assistance of S. Baer, W. Hayne, and R. Jenkins, and thank J. Phillips for his advice on the statistical analyses of these data. The authors are grateful for the review of the manuscript by J. S. Bailey, R. Buchanan, and S. C. Thayer.

REFERENCES

- Anellis, A., E. Shattuck, M. Morin, B. Srisara, S. Qvale, D. B. Rowley, and E. W. Ross, 1977. Cryogenic gamma irradiation of prototype pork and chicken and antagonistic effect between *Clostridium botulinum* types A and B. *Appl. Environ. Microbiol.* 34: 823-831.
- Draper, N. R., and H. Smith, 1981. *Applied Regression Analysis*. 2nd ed. John Wiley and Sons, Inc., New York, NY.
- Federal Register, 1990. Irradiation in the production and handling of food. *Fed. Reg.* 55:18538-18544.
- Food and Drug Administration, 1987. [Docket No. 86F-0509] U.S. Department of Agriculture, Food Safety Inspection Service; Filing of Food Additive Petition. *Fed. Reg.* 52(34):5343.
- Freund, R. J., R. C. Littell, and P. C. Spector, 1986. SAS® System for Linear Models. SAS Institute, Inc., Cary, NC.
- Hanis, T., P. Jelen, P. Klir, J. Mmukova, B. Perez, and M. Pesek, 1989. Poultry meat irradiation-Effect of temperature on chemical changes and inactivation of microorganisms. *J. Food Prot.* 52(1):26-29.
- Hargrett-Bean, N. T., A. T. Pavia, and R. V. Tauxe, 1988. *Salmonella* isolates from humans in the United States, 1984-1986. *Morbidity and Mortality Weekly Report*. U.S. Department of Health and Human Services. 37(SS-2):25-31.
- Jarrett, R. D., Sr., and J. W. Halliday, 1979. Dosimetry in support of wholesomeness studies. *J. Food Process. Preserv.* 3:145-175.
- Matsuyama, A. T., M. J. Thornley, and M. Ingram, 1964. The effect of freezing on the radiation sensitivity of vegetative bacteria. *J. Appl. Bacteriol.* 27:110-124.
- Mulder, R.W.A., 1976. Radiation inactivation of *Salmonella panama* and *Escherichia coli* K 12 present on deep-frozen broiler carcasses. *Eur. J. Appl. Microbiol.* 3:63-69.
- Mulder, R.W.A.W., S. Notermans, and E. H. Kampelmacher, 1977. Inactivation of salmonellae on chilled

THAYER AND BOYD

- and deep frozen broiler carcasses by irradiation. *J. Appl. Bacteriol.* 42:179-185.
- Previte, J. J., Y. Chang, and H. M. El-Bisi, 1970. Effects of radiation pasteurization on *Salmonella*. I. Parameters affecting survival and recovery from chicken. *Can. J. Microbiol.* 16:465-471.
- SAS Institute, 1987. SAS/STAT[®] Guide for Personal Computers, Version 6 Edition. SAS Institute, Inc., Cary, NC.
- Shieh, J. J., R. K. Jenkins, and E. Wierbicki, 1985. Dosimetry and dose distribution in cesium-137 irradiation unit used at the Eastern Regional Research Center. *Radiat. Phys. Chem.* 25:779-792.
- Thayer, D. W., G. Boyd, W. S. Muller, C. A. Lipson, W. C. Hayne, and S. Baer, 1990. Radiation resistance of *Salmonella*. *J. Ind. Microbiol.* 5:373-380.
- Thayer, D. W., J. P. Christopher, L. A. Campbell, D. C. Ronning, R. R. Dahlgren, G. M. Thomson, and E. Wierbicki, 1987. Toxicology studies of irradiation-sterilized chicken. *J. Food Prot.* 50:278-288.