

Water Concentration/Activity and Loss of Vitamins B₁ and E in Pork Due to Gamma Radiation

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ABSTRACT

When irradiated, increasing the water content of pork by partial rehydration of freeze-dried L. dorsi muscle resulted in increasing rate of thiamin loss from zero in dry tissue to ca 6%/kGy of irradiation in tissue with 70% water. Conversely, the rate of loss of α -tocopherol decreased, from 44%/kGy at 0% to 32%/kGy at 70% water. Decreasing water activity in buffers or in ground or freeze-dried pork by salt or sucrose had no effect on rate of loss of either vitamin following irradiation. Salt decreased the loss of both vitamins in pork due to competition for the hydroxyl radical by chloride ions.

Key Words: thiamin, tocopherol, water activity, pork, gamma radiation

INTRODUCTION

THE MAJOR PROTECTIVE EFFECT in reducing thiamin loss in irradiated pork was due to the presence of reducing substances and/or hydroxyl radical scavengers (Fox et al., 1993). There was, however, a residual protective effect on the loss of thiamin that was due to some unidentified source, probably related to the structure of the meat tissues. The most likely reason is the activity of water, since a large degree of organization of the water molecules occurs in meats. The extent of the organization may be deduced from the heats of rehydration of freeze-dried meat, about 3500 calories/mole of water in the initial phases of the process (Thomson et al., 1962) as compared with 80 calories/mole for freezing. This organization of water molecules affects water activity (a_w), which in turn has a substantial effect on bacterial growth. Very few bacteria grow at $a_w < 0.92$. Our objective was to define the effects of a_w and/or concentration on vitamin loss in irradiated pork.

MATERIALS & METHODS

Ground pork

Pork loins were purchased from a local processor one day after slaughter. The longissimus dorsi muscle was cut from the bone, trimmed of fat and cut into 1.2 cm strips. The strips were then ground through a 0.476 cm plate under nitrogen. Various quantities of either salt or sucrose were added to the ground pork in oxygen-impermeable bags to achieve levels of 0, 2, 4, 6 or 8% added salt or sucrose. The additives were mixed into the samples by blending and mixing with a spatula.

Freeze-dried pork

Pork was obtained and trimmed as above, but the fat-free meat was cut into 1.2 cm cubes. The cubes were frozen in dry ice and pulverized in a bowl cutter while frozen (Pettinati et al., 1983). The resulting frozen powder was spread on large trays in a 0.6 cm thick layer and freeze-dried in a NYECO (New York Engineering Co., Yonkers, NY) steam-jet freeze drier. The resulting dry powder was not homogeneous with respect to particle size and it was passed through a 40 mesh stainless steel sieve under nitrogen. The powder was stored under nitrogen in a freezer until rehydrated.

Table 1—Target and final water in partially rehydrated freeze-dried pork and salt in salt solution-rehydrated freeze-dried pork

Target, % water	% Water		% Salt	
	First set	Second set	First set	Second set
10.0	9.3	13.1	1.00	1.06
25.0	22.3	24.7	5.00	5.10
40.0	37.4	39.8	8.30	8.95
55.0	53.5	54.6	13.70	13.53
70.0	70.5	71.1	17.70	17.60

Table 2—Water activities (a_w) and molality of added solutions of sucrose and sodium chloride

Water activity	Molality	
	Sucrose	Sodium chloride
0.850	5.98	4.03
0.900	4.11	2.83
0.920	3.48	2.31
0.940	2.72	1.77
0.960	1.92	1.20
0.980	1.03	0.607
0.995	0.272	0.150
1.000	0.000	0.000

Partial rehydration of freeze-dried pork

For the partial rehydration study, water contents and dry weights of powdered pork were determined before and after freeze-drying. The weights of water to be added to achieve the various desired water fractions in the meat were then calculated from the following formula:

$$W = f_d \times P[x/(1-x)] - f_d \times P \times w_d \quad (1)$$

where W is weight of water to be added to yield weight of sample P and x is the desired fraction of water in the rehydrated sample; f_d and w_d are the fractions of dry solids in the original meat and water remaining in the dry sample, respectively (Table 1).

Rehydration of pork with salt solutions

Freeze-dried pork was prepared as above and rehydrated with salt solutions of 0, 25, 50, 75, and 100% saturation; the resulting average salt concentrations in the rehydrated pork were 1.0, 5.0, 8.6, 13.6, and 17.7%. For both the water and salt solution rehydrations, the liquid was added to the dry pork powder in a plastic bag and thoroughly mixed by hand massage.

Buffered samples

Thiamin. To study effects of a_w on loss of thiamin due to irradiation, solutions of sodium chloride and sucrose were prepared to provide predetermined water activities. The two different solutes were used to identify specific effects of either solute which were not related to reduction in water activity. The pH was held at 6.0 to approximate that usually found in meats by 0.05M phosphate. Solutions of varying molalities of both sodium chloride and sucrose were made up in phosphate buffer to produce given water activities (Scott, 1957) (Table 2).

Tocopherols. To measure effects of radiation on tocopherols in buffers, we prepared an emulsion, α -n and γ -tocopherol were dissolved separately in iso-octane. A 1/20 ratio (v/v) of iso-octane-tocopherol solution to buffer was sonicated in an ice bath to form an emulsion.

Irradiation

All samples were irradiated in a gamma ray source using ¹³⁷Cs (Lockheed Corp., Marietta, GA; dose rate 0.114 kGy/min). The dose rate was

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Table 3—Thiamin and α -tocopherol loss due to γ -irradiation of pork as affected by added salt or sucrose

Factor	Probability level, Pr > F ^a			
	Sodium chloride		Sucrose	
	Exp. #1	Exp. #2	Exp. #1	Exp. #2
% Thiamin				
Intercept	0.0001	0.0001	0.0001	0.0001
A ₁ ^b (d ^c)	0.0005	0.0001	0.0001	0.0012
A ₂ (s ^c)	0.41	0.89	0.11	0.18
A ₃ (d × s)	0.024	0.007	0.41	0.67
A ₄ (d ²)	0.93	0.29	0.001	0.61
A ₅ (s ²)	0.47	0.002	0.021	0.30
α-Tocopherol				
Intercept	0.0003			
A ₁ (d)	0.018			0.0001
A ₂ (s)	0.19			0.0006
A ₃ (d × s)	0.49			0.45
A ₄ (d ²)	0.077			0.83
A ₅ (s ²)	0.51			0.002
				0.56

^a Pr > F (SAS Institute, Inc., 1987) is a measure of the significance of the term. If 0.05 the term is significant.

^b A₁, A₂, A₃, A₄ and A₅ are the coefficients of the indicated factors.

^c d = dose, s = salt or sucrose in Eq. (2).

established using reference dosimeters from the National Physical Laboratory (Middlesex, U.K.). Dosimetry and dose distribution for this radiation source were described by Shieh et al. (1985). In the pork samples, dose were 0, 1.5, 3.0, 4.5, and 6.0 kGy. In the buffer systems with thiamin the doses were 0, 0.3, 0.7, 1.0 and 1.5 kGy; with α -tocopherol the doses were 0, 0.025, 0.050, 0.100, and 0.150 kGy. The temperature during irradiation was thermostatically controlled between 0 and 2°C by injection of cold, gaseous nitrogen.

Methods of determination

Water, salt concentrations and a_w. Water concentration was determined by microwave heating in a CEM AVC80 moisture analyzer. Salt concentration was determined by ashing in a CEM Microwave Ashing System 300 (CEM Corporation, Matthews, NC). The a_w of 5-g samples were determined in duplicate using a Rotronic "Hygroskop DT," with WA40TH temperature and humidity sensors with integral water jackets (Rotronic Instrument Corporation, Huntington, NY). Initial measurements were made with the instrument calibrated at 80% relative humidity, then recalibrated immediately before measurement using a reference salt solution of a concentration as near as possible to that of the sample.

Thiamin. Thiamin was determined as described previously (Fox et al., 1992a): precipitation of proteins in trichloroacetic acid, heating and centrifugation of solutions. Thiamin concentration in supernatants was determined by conversion to thiochrome and measuring fluorescence, $\lambda_{excitation} = 365$ nm, $\lambda_{emission} = 460$ nm. Thiamin purchased from Sigma Chemical Company (St. Louis, MO; CAS #59-43-8, various lots) was used to prepare standards. Improvement was made in the preparation of samples for vitamin determination by dispersing pork samples into trichloroacetic acid solution using a Tissumizer (Tekmar Co., Cincinnati, OH).

Tocopherols. Both α - and γ -tocopherol were determined as described previously (Lakritz and Thayer, 1992). Samples in cyclohexane were homogenized and dried. The solvent was evaporated and the residue reconstituted in isooctane. Samples were chromatographed in normal phase HPLC on Chromosorb SI and the fluorescence measured, $\lambda_{excitation} = 292$ nm, $\lambda_{emission} = 324$ nm. α -Tocopherol (purchased from Kodak) and γ -tocopherol (purchased from Sigma) were used to prepare standards.

Data reduction and analysis. All treatments included two independent variables: radiation dose plus one of the following: water content, a_w, salt or sugar concentration. The coefficients A₁ and B₁ of the following linear expressions were calculated by the GLM curve fitting procedure of SAS Institute, Inc. (1987):

$$\% V_{d,w} = \% V_{0,0} + A_1 \times d + A_2 \times w + A_3 \times d \times w + A_4 \times d^2 + A_5 \times w^2 \quad (2)$$

Where the reaction was clearly first order, usually in buffer systems, the following equation was used:

$$\ln(\% V_{d,w}) = \ln[\% V_{0,0}] + B_1 \times d + B_2 \times w + B_3 \times d \times w + B_4 \times d^2 + B_5 \times w^2 \quad (3)$$

In these equations, d is the dose in kGy, w is the particular form in

which the water or salt content is expressed. The subscripts are: d for the given dose, w for the given water or salt content, 0 for the conditions at zero dose and/or water/salt. When the independent variable was water, the term "w" is used; when it was salt or sugar, the term "s" is used. % V is the fraction of the concentration of vitamin remaining in the sample after a given dose, d, divided by the initial concentration, times 100. The vitamin remaining was expressed as percent to more easily compare results for the two vitamins. The cross term, d × w is a measure of the dose/water interaction. The squared terms, d² and w², are a measure of the curvature in dependency of vitamin concentration on dose or water/salt, respectively. When the coefficients of the last three terms are zero, the regression is a straight line.

RESULTS

Ground pork

For both thiamin and α -tocopherol dose was a highly significant (Table 3), for both NaCl and sucrose treatments. No significant salt or sucrose concentration effects occurred. The major difference between NaCl and sucrose was in the dose/salt interaction in the thiamin treatment. That was significant for salt but not for sucrose, that is, the rate of thiamin loss decreased as salt concentration increased, but sucrose had no effect. Neither salt nor sucrose had any effect on loss of α -tocopherol. The squared terms, d² and s², were variably significant for both thiamin and α -tocopherol but, regardless of significance, were very small and did not introduce appreciable changes to the dose or salt response graphs.

Partially rehydrated freeze-dried pork

Thiamin. The only significant term for thiamin loss was the dose × water term (A₃) which was negative, indicating an increase in slope with water concentration, seen on the response surface (Fig. 1a). At the lowest water content, thiamin concentration increased slightly with dose and decreased with dose at 70% water, that is, the slope changed from positive to negative. For this reason the dose term was not significant, but the significant dose/water term indicated that the decrease in the slope was a true effect.

α - and γ -Tocopherol. The dose (A₁), dose/water (A₃) and dose² (A₄) terms were highly significant for α -tocopherol loss (Table 4). Gamma radiation caused a loss of α -tocopherol at all doses (Fig. 1b), but the loss decreased with increasing water concentration (dose/water term was positive), the reverse of results with thiamin. The dose term (A₂) was significant for γ -tocopherol and was of the same order of magnitude as it was for α -tocopherol (−31.8 and −43.6, respectively, Table 4). The d × w (A₃) term was marginally significant, but indicated a decrease in rate of loss with increased water concentration, similar to the α -tocopherol reaction.

Salt solution-rehydrated freeze-dried pork

Effect of salt on thiamin. All of the factors in Eq. (2) were significant except for the dose² coefficient (A₄, Table 5), though it was relatively large compared with coefficients of other interaction terms [dose × salt (A₃) and salt² (A₅)]. The lack of significance indicated the linear model did not fit. The thiamin loss curves for the three higher salt concentrations showed a lag phase before the logarithmic phase which Eq. (2) could not resolve. The first order rate constants were calculated from the log phase of by Eq. (3) (Table 6). The rate of thiamin loss decreased with increasing salt and was constant at 8.3% salt and higher.

Effect of water activity on thiamin. Data for thiamin retention as related to a_w (Table 5) showed the dose (A₁) term was not significant, which rendered the calculation questionable. Thiamin concentration decreased with dose at all a_w values. The fit was not as good as it was for the % NaCl plots (R² = 0.84 for a_w versus R² = 0.90 for % NaCl).

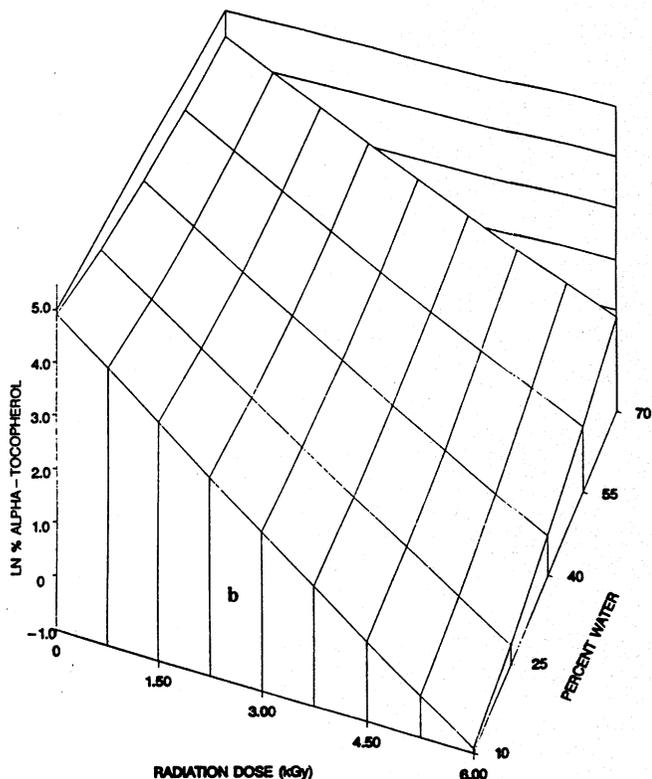
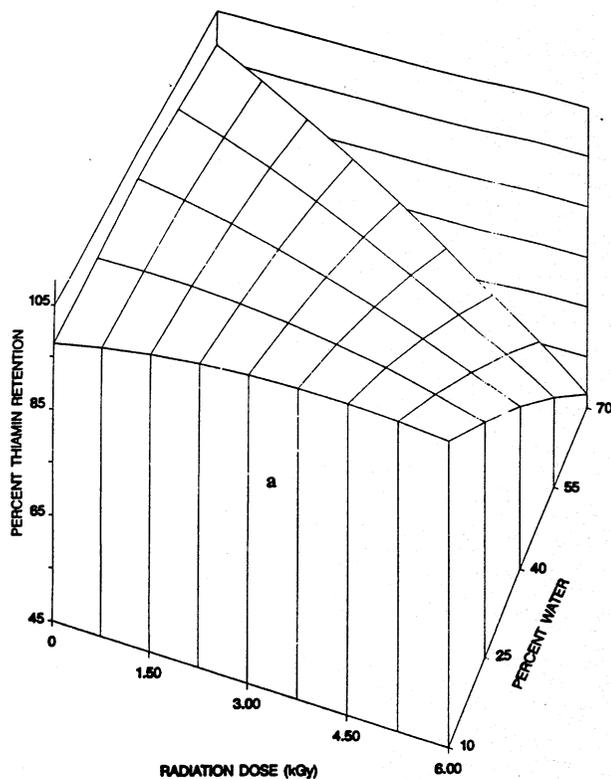


Fig. 1—Response surface for relationships of thiamin (a) and Ln per cent α -tocopherol (b) in partially rehydrated pork to gamma irradiation dosage.

α - and γ -Tocopherol. The dose \times salt (A_3) term was significant and showed a protective effect of salt (Table 5). The d^2 (A_4) term indicated a first order reaction, so the data were plotted as \ln % α -tocopherol (Eq. (3), Fig. 2). Some curvature remained but it was not significant. The rate of loss decreased with increasing salt concentration. When α -tocopherol data were plot-

Table 4—Retention of thiamin, α - and γ -tocopherol in partially rehydrated freeze-dried pork after gamma irradiation

Coefficient	Estimate	Pr > F ^a	Std. error
% Thiamin _{0,0}	96.1	0.0001	6.37
A ₁ ^b (d ^c)	4.19	0.11	2.49
A ₂ (w ^c)	0.17	0.60	0.31
A ₃ (d \times w)	-0.15	0.0001	0.026
A ₄ (d ²)	-0.35	0.34	0.36
A ₅ (w ²)	-0.002	0.64	0.004
% α -Tocopherol _{0,0}	111.6	0.0001	8.31
A ₁ (d)	-43.6	0.0001	3.25
A ₂ (w)	-0.57	0.17	0.408
A ₃ (d \times w)	0.10	0.006	0.0351
A ₄ (d ²)	4.34	0.0001	0.468
A ₅ (w ²)	0.004	0.34	0.00471
% γ -Tocopherol _{0,0}	107.0	0.0001	21.3
A ₁ (d)	-31.8	0.001	8.58
A ₂ (w)	-0.41	0.78	1.05
A ₃ (d \times w)	0.19	0.06	0.093
A ₄ (d ²)	2.10	0.11	1.24
A ₅ (w ²)	0.006	0.65	0.01

^a Pr > F (SAS Institute, Inc., 1987) is a measure of the significance of the term. If < 0.05 the term is significant.

^b A₁, A₂, A₃, A₄, and A₅ are the coefficients of the indicated factors.

^c d = dose in kGy; w = % water in Eq. (2).

Table 5—Retention of thiamin, α - and γ -tocopherol in salt-solution rehydrated pork after gamma irradiation

Factor	Estimate	Pr > F ^a	Std. error
% Thiamin	90.2	0.0001	3.321
A ₁ ^b (d ^c)	-8.83	0.0001	1.554
A ₂ (s ^c)	2.66	0.0004	0.620
A ₃ (d \times s)	0.21	0.006	0.068
A ₄ (d ²)	0.14	0.54	0.228
A ₅ (s ²)	-0.12	0.001	0.030
% α -Tocopherol	78.3	0.0001	12.2
A ₁ (d)	-27.4	0.0001	5.64
A ₂ (s)	0.74	0.048	2.24
A ₃ (d \times s)	0.69	0.001	0.25
A ₄ (d ²)	2.91	0.002	0.82
A ₅ (s ²)	-0.22	0.058	0.11
% γ -Tocopherol	82.77	0.0001	7.22
A ₁ (d)	-4.40	0.20	3.35
A ₂ (s)	-4.39	0.0037	1.33
A ₃ (d \times s)	0.39	0.016	0.147
A ₄ (d ²)	0.08	0.87	0.489
A ₅ (s ²)	-0.18	0.012	0.0648

Water activity

	Estimate	Pr > F ^a	Std. error
% Thiamin _{0,0}	-656.5	0.0067	215.95
A ₁ (d)	9.8	0.24	8.13
A ₂ (a _w ^c)	17.5	0.0024	5.02
A ₃ (d \times a _w)	0.22	0.021	0.087
A ₄ (d ²)	0.47	0.27	0.41
A ₅ (a _w ²)	0.10	0.0026	0.029

^a Pr > F (SAS Institute, Inc., 1987) is a measure of the significance of the term. If < 0.05 the term is significant.

^b A₁, A₂, A₃, A₄ and A₅ are the coefficients of the indicated factors.

^c d = dose in kGy; s = salt; a_w = water activity in Eq. 2.

Table 6—Rate constants for thiamin loss in pork rehydrated with solutions of varying salt concentration

% NaCl	k _{1st} in kGy ⁻¹
1.0	0.070 ^a
5.3	0.040 ^b
8.3	0.026 ^c
13.7	0.024 ^c
17.7	0.024 ^c

^{a,b,c} Numbers with different superscripts are significantly different from each other.

ted as a function of a_w, the dose term (A₂) was not significant. The results of γ -tocopherol determinations were similar to those for α -tocopherol. Using the data (Table 5) to calculate the change in γ -tocopherol concentration with dose, a decrease at 1% salt and an increase at 17% with dose occurred (similar to α -tocopherol data) where increased salt protected the vitamin.

Buffer systems, thiamin, and α -tocopherol

Thiamin concentrations as a function of dose (Fig. 3) for sodium chloride (a) and sucrose (b) indicated similar results for

NaCl concentration but not with increasing sucrose concentration. The greatest changes in vitamin loss came over a range where a_w was minimal. In the buffer samples major decreases in rate of thiamin loss were between 0.00 and 0.150 and between 0.150 and 0.607 molal NaCl, for which a_w was 1.000, 0.995, and 0.98, respectively. Thus a_w had little or no effect on thiamin or tocopherol loss and the observed decrease in loss with increasing NaCl was specific for the salt.

Sodium chloride

The NaCl results were probably due to reaction of chloride with the hydroxyl radical (Anbar and Thomas, 1964), the competition reducing the concentration of hydroxyl radical available to oxidize the vitamin. Such inhibition is essentially the same mechanism as determined for radical scavengers (Fox et al., 1992b). The concentration at which NaCl reduced the rate of thiamin loss by half was 63 mM (0.37%) as compared with a range of 0.08 to 0.20 mM for reductant radical scavengers (Fox et al., 1992b). The concentration of chloride in skeletal muscle tissue has been reported as 0.065% (Lawrie, 1981), but it is principally extracellular whereas thiamin is intracellular (Merkel, 1987). If all of the chloride were intracellular, 0.065% NaCl would result in only 15% reduction of the free solution rate of thiamin loss of ca. 15 kGy⁻¹. Since the observed rate constant in skeletal muscle was about 0.08 kGy⁻¹, we concluded that chloride had little effect on thiamin loss in fresh meats. In cured meats, chloride concentrations range around 1% (2-3% salt, Merkel, 1987) so that it could have appreciable effect.

a_w and radical reactions

The lack of any effect of a_w on rate of thiamin loss is due to the nature of both initial ionizing radiation reaction, the character of the radical so produced, and radical reactions in general. The rate at which thiamin is destroyed is a function of three phases of the irradiation process: (1) the initial reaction of the ionizing radiation quantum with the nucleus of a water molecule; (2) the translation of the hydroxyl radical through the solution until contact is made with a thiamin molecule; and (3) the oxidation of thiamin by the hydroxyl radical. The initial event produces a "spur," or locale of high energy activity. The hydroxyl radical is ejected from the water molecule at high velocity (as is an electron). The collision between ionizing radiation quanta and the nucleus is not dependent upon the energy level of the water molecule. Though the motion of the molecule is restricted by being in crystalline or semi-crystalline state, the nuclear event would still occur.

The translational energy of the hydroxyl radical would be dispersed more quickly in the crystalline state, which explains in part the large decrease in nutrient destruction in irradiated frozen meats. However, the major effect in frozen meats is the physical separation of nutrients into an increasingly concentrated solute phase, with the water separated in the ice (crystalline) phase. Hydroxyl radicals in the ice crystalline lattice have a short free path. In unfrozen tissue the water is highly organized

with restricted molecular motion, hence lowered water activity. Nevertheless, the water is not in the crystalline state, the solutes are not separated from the solvent and restriction of translational energy of the hydroxyl is reduced only very slightly.

Once the radical contacts a target molecule (thiamin in this case) the reaction is little affected by the energy of the target. Radical reactions typically have very low heat of activation energies, of the order of 1000 to 2000 calories/mole. In an earlier study we measured the rate of thiamin destruction as a function of temperature (Fox et al., 1989b). Using data from that study in the Arrhenius expression, we calculated the heat of activation for the thiamin/hydroxyl radical reaction to be 2048 calories/mole. Any reduction in energy levels in the thiamin molecule induced by the organized state of water molecules would have little effect on rate of radical oxidation of the vitamin.

REFERENCES

- Anbar, M. and Thomas, J.K. 1964. Pulse radiolysis studies of aqueous sodium chloride solutions. *J. Phys. Chem.* 68: 3829-3835.
- De Groot, A.P., van der Mijl Dekker, L.P., Slump, P., Vos, H.J., and Willems, J.J.L. 1972. Composition and nutritive value of radiation-pasteurized chicken. Report No. R3787. Central Institute for Nutrition and Food Research, The Netherlands.
- Fox, J.B. Jr., Ackerman, S.A., and Thayer, D.W. 1992a. Fluorometric determination of thiamin vitamers in chicken. *J. Assoc. Off. Anal. Chem.* 75: 346-354.
- Fox, J.B. Jr., Ackerman, S.A., and Thayer, D.W. 1992b. The effect of radiation scavengers on the destruction of thiamin and riboflavin in buffers and pork due to gamma irradiation. *Prehrambeno-tehnol. Biotechnol. Rev.* 30: 171-175.
- Fox, J.B. Jr., Lakritz, L., and Thayer, D.W. 1993. The effect of reductant level in skeletal muscle and liver on the rate of loss of thiamin due to gamma radiation. *Int. J. Radiat. Biol.* 64: 305-309.
- Fox, J.B. Jr., Thayer, D.W., Jenkins, R.K., Phillips, J.G., Ackerman, S.A., Beecher, G.R., Holden, J.M., Morrow, F.D., and Quirbach, D.M. 1989a. Effect of gamma irradiation on the B vitamins of pork chops and chicken breasts. *Int. J. Radiat. Biol.* 55: 689-703.
- Fox, J.B. Jr., Thayer, D.W., and Phillips, J.G. 1989b. An exponential model equation for thiamin loss in irradiated ground pork as a function of dose and temperature of irradiation. *Radiat. Phys. Chem.* 34: 957-961.
- Lakritz, L. and Thayer, D.W. 1992. Effect of ionizing radiation on unesterified tocopherols in fresh chicken breast muscle. *Meat Sci.* 32: 257-265.
- Lawrie, R.A. 1981. Nutrient variability due to species and production practices. In *Meat in Nutrition and Health, An International Symposium*, National Live Stock and Meat Board, Chicago.
- Merkel, R.A. 1987. Chemistry of animal tissues. Part 4. Inorganic constituents. Chap. 3. In *The Science of Meat and Meat Products*, 3rd ed., J.F. Price and B.S. Schweigert (Ed.). Food & Nutrition Press, Inc, Westport, CT.
- Pettinati, J.D., Ackerman, S.A., Jenkins, R.K., Happich, M.L., and Phillips, J.G. 1983. Comparative analysis of meat samples prepared with food chopper and bowl cutter. *J. Assoc. Off. Anal. Chem.* 66: 759-765.
- SAS Institute, Inc. 1987. *SAS[®]/STAT Guide for Personal Computers, Version 6 Edition*. SAS Institute Inc., Cary, NC.
- Scott, W.J. 1957. Water relations of food spoilage microorganisms. *Adv. Food Res.* 7: 83-127.
- Shieh, J.J., Jenkins, R.K., and Wierbicki, E. 1985. Dosimetry and dose distribution in cesium-137 irradiation unit used at the Eastern Regional Research Center. *Radiat. Phys. Chem.* 125: 779-792.
- Thomson, J.S., Fox, J.B. Jr., and Landmann, W.A. 1962. The effect of water and temperature on the deterioration of freeze-dried beef during storage. *Food Technol.* 16: 131-136.
- Woods, R.J. and Pikaev, A.K. 1994. Selected topics in radiation chemistry. Ch. 6. In *Applied Radiation Chemistry: Radiation Processing*. John Wiley & Sons, Inc., New York.

Ms received 10/7/93; revised 6/25/94; accepted 7/11/94.