

Effect of Low-Dose Irradiation and Post-Irradiation Cooking and Storage on the Thiamin Content of Fresh Pork

R.K. JENKINS, D.W. THAYER, and T.J. HANSEN

ABSTRACT

Low-dose gamma irradiation of vacuum-packaged, ground fresh pork resulted in a dose-dependent, first-order rate of thiamin destruction ($R^2=0.99$). Thiamin losses for raw pork irradiated at 0.57, 1.91, 3.76, 5.52 and 7.25 kGy were 7.7, 23.5, 38.1, 49.8 and 57.6%, respectively, of the nonirradiated sample. Post-irradiation cooking resulted in additional thiamin losses of 11.3, 11.5, 13.0, 13.6, 13.5 and 15.0% for respective treatment samples irradiated at doses of 0, 0.57, 1.91, 3.76, 5.52 and 7.25 kGy. Time of storage had little effect on the thiamin content of raw irradiated and nonirradiated pork.

INTRODUCTION

IN GRANTING APPROVAL for certain foods to be irradiated at doses not to exceed 1.0 kiloGray (kGy), the Food and Drug Administration (FDA) stated that, as based on the available literature, foods irradiated at such low doses would have the same nutritional value as comparable, nonirradiated foods (Anonymous, 1986a, b). The FDA, therefore, concluded that destruction of nutrients at such dose applications was "not an issue in this rulemaking" (Anonymous, 1986b). Limited evidence does, however, exist in the literature indicating that some radiation-induced destruction of thiamin occurs at doses as low as 1.0 kGy. Wilson (1959) found that a 1.0 kGy X-ray dose, as applied to a beef sample at room temperature in air, resulted in a thiamin loss of 19%. Diehl (1975) reported a 5% loss in thiamin of ground pork that had been electron-irradiated (1.0 kGy) at room temperature.

With government and industry officials showing an increasing interest in low-dose irradiation processing of fresh meats and poultry at doses exceeding 1.0 kGy (but less than that required for sterilization) to increase product shelf-life and safety (Anonymous, 1985b, 1986c; Roberts, 1985; LaBell, 1986), there is a need to understand the impact of such irradiation processing on the micronutrient content of such foods. Likewise, the need exists to evaluate the impact of various environmental conditions of processing and handling that may affect the lability of micronutrients in low-dose irradiated meat and poultry products. Environmental conditions such as product temperature (Wilson, 1959; Diehl, 1981; Thomas et al., 1981) and oxygen presence during irradiation treatment (Groninger et al., 1956), dose level (Groninger et al., 1956; Ziporin et al., 1957; Wilson, 1959; Thomas and Wierbicki, 1971; Tobback, 1977; Thomas et al., 1981), dose rate (Thomas et al., 1981) and post-irradiation storage duration (Diehl, 1969, 1975) and cooking (Diehl, 1969; Thomas and Calloway, 1957) have been reported to affect the nutrient content of irradiated foods.

Noting that "very little, if any, research has been reported on the effects of low-dose irradiation at refrigeration temperatures on the nutrient quality of pork—the very parameters recently approved by FDA for use in the control of trichinae in fresh pork," the USDA Food Safety and Inspection Service

(FSIS) recently requested the Agricultural Research Service (ARS), U.S. Department of Agriculture to initiate research on this subject (Anonymous, 1985b). The following study only focused upon the irradiation dose level and those post-irradiation treatment processes of cooking and storage that may affect the lability of one known radiolabile micronutrient, thiamin, as it occurs in low-dose irradiated fresh pork.

The sensitivity or lability of thiamin to radiation treatment has been well documented. An increase in the total radiation dose as applied to aqueous thiamin solutions (Ebert and Swallow, 1957; Groninger and Tappel, 1957) and meat and poultry products (Groninger et al., 1956; Ziporin et al., 1957; Wilson, 1959; Thomas and Wierbicki, 1971; Tobback, 1977; Thomas et al., 1981), is known to result in a decrease of thiamin content with such a decrease being particularly extensive at the higher (> 10 kGy) or sterilizing doses. With regard to those low (nonsterilizing) irradiation doses now of interest for fresh meat shelf-life extension and pathogen control, only Wilson (1959) has characterized and confirmed the ionizing radiation-dose/thiamin-content response. In his study, Wilson (1959) reported thiamin losses of 19, 21 and 25% from beef that had been X-ray irradiated in room temperature air at 1.0, 2.0 and 3.0 kGy.

Diehl (1969, 1975) reported that storage-related losses of thiamin in low-dose irradiated dried whole egg (0.35 kGy), oat flakes (0.25 kGy) and wheat flour (0.35 kGy) greatly exceeded those losses obtained from the similarly stored, non-irradiated sample complement. Such interaction between irradiation treatment and post-irradiation storage was not evident, however, in irradiated (1.0 kGy) pork following 2 months of 0°C refrigerated storage (Diehl, 1975).

The combined effects of irradiation treatment and post-irradiation cooking of foods may result in thiamin losses greater than the additive effects of the individual treatments. The results of Thomas and Calloway (1957) indicate that the thiamin lost due to cooking was greatest, i.e., nonadditive, for those turkey samples that had first been gamma-irradiated in the frozen state (18.6, 27.9 and 55.8 kGy). In their study, thiamin losses due to cooking increased with subsequent increases in the dose treatment applications. Diehl (1969) reported that the thiamin of electron-irradiated (0.25 kGy) wheat flour and rolled oats was destroyed by an amount that was greater than the additive effects of the two processes (irradiation and heating). In contrast to such findings, Kennedy and Ley (1971) found no evidence of treatment synergism in evaluating the thiamin content of fish that had been irradiated (6.0 kGy) and then cooked.

Previous studies have not investigated the combined effects of low dose irradiation applications (when performed at refrigeration temperatures and within a dose range which might be used for trichina and microbial pathogen control and shelf-life extension) and the post-irradiation practices of storage and cooking on the thiamin content of fresh pork products. Whether such practices serve additively or interactively to effect changes in the thiamin of these products remains subject to further study. The objectives of this study were: (1) to compare the effect of various low irradiation doses on the thiamin of fresh pork; (2) to determine and compare the influence of those post-irradiation practices of cooking and storage on the thiamin of

nonirradiated and low-dose irradiated, fresh pork; (3) to determine whether thiamin retention differences (if any) between the irradiated and nonirradiated treatments were due to additive effects of, or interactive effects with cooking and storage.

MATERIALS & METHODS

Experimental design

The experimental design included 6 gamma radiation doses (0, 0.50, 1.75, 3.50, 5.25, 7.0 kGy), 6 storage times starting at 1 day post-irradiation (0, 1, 2, 3, 4, 5 weeks), and raw or cooked (30 min immersion at 100°C) for a total of 72 individual treatments. Each treatment in turn, was performed in triplicate thus requiring a total of 216 individually packaged and treated samples.

Sample preparation and packaging

Two matched pairs of pork loins were obtained 2 days post-mortem from a local abattoir. The longissimus dorsi muscles from each of the 4 loins were removed and then ground through a 9.5 mm metal plate using a Model 4612 Hobart food grinder (Hobart Corporation, Troy, OH). After chill tempering to a firm state, the ground lean from each of the loins was combined, mixed and cut to a homogeneous state using a Model HCM-450 Hobart Food Cutter (Hobart Corporation, Troy, OH) following those procedures outlined by Pettinati et al. (1983).

Fifteen gram samples of the lean pork mass were placed into separate plastic pouches of 12.7 cm × 17.8 cm. The pouch film (All-Vak #13; International Kenfield Dist. Co., Rosemont, IL), comprised of nylon (2 mil) and a food-contact layer of medium-density polyethylene (1 mil) and designed for use in vacuum packaging of cold meats, provided properties of low oxygen permeability (15.5 cc/m²/24 hr at 25°C) and resistance to heating for boil-in-bag processing. The enclosed sample was distributed within the bottom pouch boundaries to an area of 10.8 cm × 8.3 cm and to an approximate thickness of 0.16 cm. Such a distribution was made to maximize surface area and to standardize sample thickness for purposes of ensuring rapid and uniform heat transfer throughout the sample during the cooking treatment. Each sample was then vacuum-sealed to a dial reading of 690 mm Hg using a Swiss-Vac vacuum packaging machine (Transvac-Maschinen AG, Luzern, Switzerland). Following vacuum packaging, all pouches were coded according to sample treatment and kept chilled overnight (2 ± 2°C) prior to irradiation.

Irradiation

The samples were irradiated at a dose rate of 0.129 kGy/min using a self-contained Cesium-137 gamma source (Shieh et al., 1985). The temperature was maintained at 2 ± 2°C during irradiation. Absorbed dose measurements were made using ferrous-cupric sulfate dosimetry (Jarrett and Halliday, 1979). Variation between the maximum and

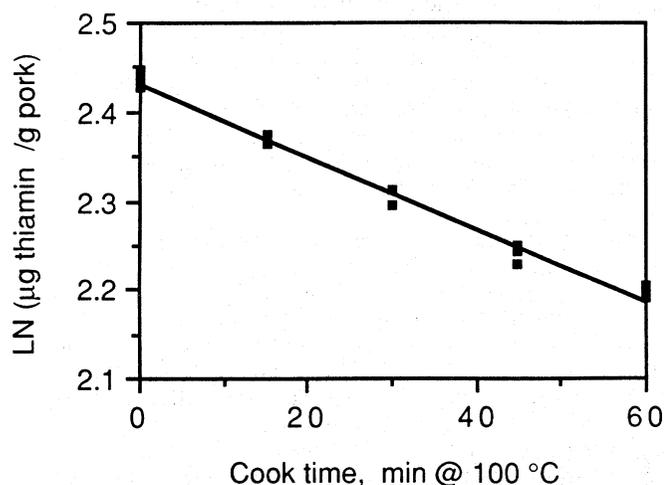


Fig. 1—Mean thiamin cooking losses of pork (3 replicates per cook time; Std. dev. = 0.01).

minimum calculated doses was approximately 4.6%. The calculated treatment doses were 0, 0.57, 1.91, 3.76, 5.52 and 7.25 kGy.

Storage treatment

Immediately following irradiation processing, the samples were segregated according to storage withdrawal period and then stored in the dark at 2 ± 2°C for the treatment storage durations of 0, 1, 2, 3, 4 and 5 weeks. Shelf-life for the purposes of this study was defined according to a subjective evaluation of the sample odor and appearance at the time of sample withdrawal. Using 3 panelists, weekly, informal evaluations were conducted to compare the odor of stored irradiated and nonirradiated samples to that of a thawed (frozen) control sample. No odors indicative of a non-fresh state or microbial-induced decomposition were detected in the non-irradiated samples throughout the course of the 5 week study.

Cooking treatment

To simulate the effect of cooking on the thiamin of the irradiated and nonirradiated samples, a 30 min immersion of the vacuum-sealed sample pouches in boiling (100°C) water was performed. Such a heat treatment was selected since it would otherwise be extremely difficult to simulate kitchen-type cooking processes without a prior removal of the sample from the vacuum-sealed sample pouch. An enclosed, within-pouch cooking procedure guaranteed against loss of the water-soluble nutrients as well as the proximate composition of the ground pork during the cooking process. To maintain the use of the vacuum-packaged model system while demonstrating the known heat lability of thiamin, it was necessary, prior to the implementation of this experiment, to evaluate the effect of different heating times at 100°C on the thiamin of the packaged samples. An evaluation was, therefore, performed by applying various 100°C treatments to nonirradiated vacuum-packaged (pouched) comminuted pork (longissimus dorsi) by water immersion for fixed increments of 15, 30, 45 and 60 min. Because thermal destruction of thiamin is first-order in nature (Felicetti and Esselen, 1957; Mulley et al., 1975a) above 77°C (Ricc and Beuk, 1945), i.e., the log of thiamin concentration decreases with increasing heating time, such an evaluation was expected to provide a range of thiamin yields in a linear decreasing order. As can be seen in Fig. 1, such a linear response was obtained from this preliminary cooking experiment thus confirming the findings of these previous studies. A resulting rate or slope coefficient of -0.0041 min^{-1} was similar to that (-0.0049 min^{-1}) reported by Rice and Beuk (1945) for pork that had been heated at 98°C in sealed test tubes. Mean ($n=3$) cooking losses in this preliminary work were 6.7, 12.9, 17.9 and 21.4% for respective 100°C treatment durations of 15, 30, 45 and 60 min. Since an arbitrary thiamin cooking loss of at least 10% was desired, the 30 min cooking treatment (loss = 12.9%) was selected as the experimental cooking time. It should be noted that the lean pork used in the preliminary experiment was derived from only one hog and not from that source used in the main experiment. The method used to cook the samples was, however, identical to that used in the preliminary experiment. Upon completion of each storage period, samples were cooked by complete immersion in the boiling water for 30 min and then rapidly cooled by immersion in a crushed ice-water mixture.

Table 1—Analysis of variance (ANOVA)

Dependent variable: Thiamin content (μg/g pork)					
Source:	Degrees of freedom	Sum of squares	Mean Square	F-Value	Pr > F
Model	71	731.3191	10.3003	1189.79	0.0001
Error	144	1.2466	0.0087		
Corrected total	215	732.5657			
Model source:					
Time	5	2.4829	0.4966	57.36	0.0001
Dose	5	690.2492	138.0498	15946.16	0.0001
Cook	1	33.9293	33.9293	3919.18	0.0001
Time × dose	25	1.3331	0.0533	6.16	0.0001
Time × cook	5	0.9802	0.1969	22.65	0.0001
Dose × cook	5	1.4659	0.2932	33.87	0.0001
Time × dose × cook	25	0.8784	0.0351	4.06	0.0001

R² = 0.998; Root Mean Square Error = 0.093.

Thiamin analysis

Following completion of the cooking procedure, both the raw and cooked samples were prepared for thiamin analysis. The exudate or drip resulting from the cooking process and as contained within the sample pouch, was mixed back into the cooked meat mass prior to sample withdrawal. One 3-gram sample was removed from each of the raw and cooked replicate pouches for thiamin extraction. Thiamin content for each treatment sample and standard was determined according to a semi-automated fluorometric method using a Technicon Autoanalyzer (Technicon Instrument Corp., Tarrytown, NY) as described in the *Technicon Instrument Methods Manual* (Anonymous, 1977).

Statistical analysis

The data were statistically analyzed using the Analysis of Variance (ANOVA), General Linear Model, Means and Regression programs as contained within the PC-version of SAS (1985). A heterogeneity of slope analysis (Freund et al., 1986) was used to test for significant differences between regression slope coefficients. Significant differences between mean thiamin contents were determined using either Duncan's Multiple Range Test (SAS, 1985) or Dunnett's (1955, 1964) procedure for comparing treatment effects to a control.

RESULTS & DISCUSSION

Overall treatment effects

The thiamin content for the untreated pork sample of 8.83 µg/g pork was comparable to the 10.01 µg thiamin/g pork value for "pork fresh, loin, whole, separable lean only, raw" as cited in the USDA Agricultural Handbook No. 8-10 (Anderson, 1983). The three independent treatment variables (Dose, Time and Cook) as well as combinations of each variable (interactions), each contributed significantly ($P < 0.0001$) to variation in the overall analysis of variance (ANOVA) model (Table 1).

Dose effect

Of the three main treatment variables studied, Dose provided the largest contribution to variation in the overall ANOVA model (Table 1). Figure 2 provides a comparison of raw and cooked pork thiamin contents.

Parameter estimates for simple linear regression of both the raw and cooked pork thiamin data were highly significant ($P < 0.0001$). An observed logarithmic decrease in thiamin with increasing dose suggested that the reaction of thiamin in fresh pork irradiated with increasing low doses was of a first-order nature. Such findings agree with those of Thomas et al. (1981), who reported a first-order dependence of thiamin loss on dose level in cooked (76°C) pork lean irradiated at much higher doses (10 to 75 kGy) and lower temperatures (-15°C to -45°C).

Thiamin losses attributed to irradiation treatment at doses ranging from 1.91-7.25 kGy differed significantly ($P < 0.01$) from one another and from the raw pork thiamin content. Respective thiamin losses for raw pork irradiated to 1.91, 3.76,

5.52 and 7.25 kGy were 23.5%, 38.1%, 49.8% and 57.6%. Irradiation in this dose range has been proposed for purposes of controlling or eliminating spoilage microorganisms in fresh pork (ICRPF, 1978; Kampelmacher, 1981).

Irradiation treatment of raw pork at 0.57 kGy, a dose within the range (0.3 to 1.0 kGy) presently approved for trichina control in pork (Anonymous, 1986c), resulted in a significant ($P < 0.01$) thiamin loss of 7.7%. A predicted loss of 11.2% after 1.0 kGy was calculated from a regression equation involving the raw pork thiamin content data (pooled-for-storage) versus dose [$\text{LN} (\mu\text{g thiamin/g pork}) = 2.1653 - 0.1189 (\text{kGy}^{-1})$; $R^2 = 0.989$]. The predicted thiamin value from the present study exceeded the observed value of 5% reported by Diehl (1975) for raw ground pork also irradiated at 1.0 kGy. One possible explanation for this disparity in thiamin loss values may be due to differences in the irradiation dose rate. Diehl (1975) used a 10 Mev electron irradiator having a dose rate of 0.752 kGy/min while a gamma (Cs-137) source having a dose rate of 0.129 kGy/min was used in the present study. According to Thomas et al. (1981), the dose rate of irradiation affects the degradation rate of thiamin. These workers reported that the higher dose rate provided by an electron irradiator resulted in a lower rate of thiamin degradation while the lower dose rate of a gamma irradiator provided a greater rate of thiamin degradation in pork.

Cook effect

As expected, the Cook treatment also contributed significantly ($P < 0.0001$) to variation in the overall ANOVA model (Table 1). The relative effect of cooking on the thiamin content of the irradiated and nonirradiated treatment samples can be seen in a plot of the thiamin content data versus dose (Fig. 2). Thiamin losses due to cooking and a by-dose comparison of raw and cooked pork thiamin losses are provided in Table 2.

Although it may be difficult to see from a visual comparison of plotted regression curves for the raw and cooked thiamin content data (Fig. 2), a slight increase in thiamin loss on cooking with increasing dose was evident (Table 2). The conclusion that there was an increased thiamin loss on cooking with increasing dose was supported by the significance ($p < 0.0001$) of the Dose \times Cook interaction in the ANOVA model (Table 1) and the significant ($P < 0.01$) difference between thiamin degradation rates, i.e., regression slope coefficients (log thiamin vs. dose), for the pooled-for-storage raw (-0.1189 kGy^{-1}) and cooked pork (-0.1243 kGy^{-1}) data. Cooking losses for

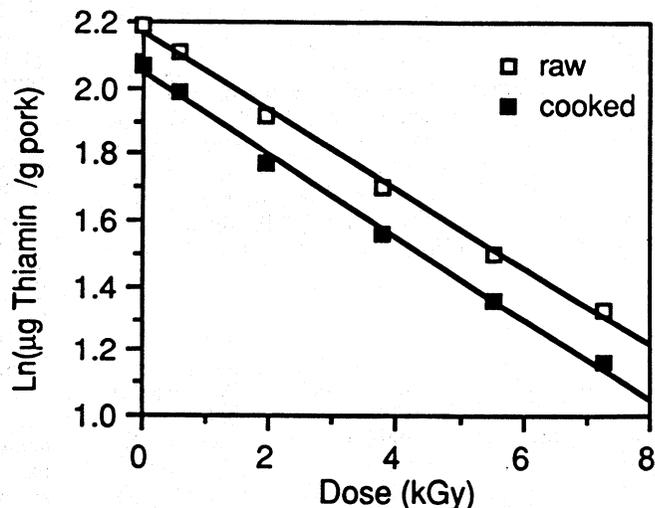


Fig. 2—Mean thiamin in irradiated raw and post-irradiated cooked pork. Each plotted value represents a pooled for (post-irradiation) storage mean ($n = 18$).

Table 2—Effect of post-irradiation cooking on thiamin content

Irradiation dose (kGy)	Thiamin ^a (µg/g pork)		Thiamin loss ^b on cooking (%)
	Raw	Cooked	
0	8.89	7.88	11.29
0.57	8.20	7.26	11.48
1.91	6.80	5.91	13.03
3.76	5.50	4.75	13.59
5.52	4.46	3.86	13.54
7.25	3.77	3.20	14.99

^a MEAN from data pooled ($n = 18$) with respect to storage treatments.

^b Percentage expressed as the average of 18 values of the form: $\frac{((R/C)100) - 100}{18}$, where R = Raw mean from (and C = cooked replicate within) the respective "Dose \times Storage" treatment.

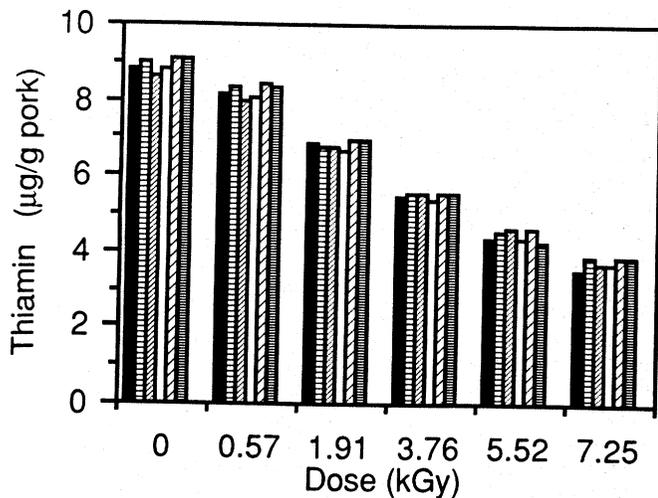


Fig. 3—Mean thiamin content of raw pork following post-irradiation storage. Expressed by irradiation dose with 3 replicates per post-irradiation storage (2°C) period. ■ 0 wk; ▨ 1 wk; ▩ 2 wk; ▪ 3 wk; ▫ 4 wk; ■ 5 wk.

each irradiated treatment exceeded that of the nonirradiated treatment, although only the cooking loss at the 7.25 kGy ($P < 0.01$) dose treatments was significantly greater than the non-irradiated treatment (Table 2).

Evidence of a Dose \times Cook interaction occurring at the low irradiation doses used in this study coincides with the findings reported for higher dose applications by Thomas and Calloway (1957). These workers in studying the effects of post-irradiation cooking on turkey irradiated at 18.6, 27.9 and 55.8 kGy, found thiamin losses in the irradiated-then-cooked turkey to be greater than the additive effects (losses) of each of the individual treatments. In their study, no attempt was made by Thomas and Calloway (1957) to explain such an interaction. There is evidence, however, that different forms of thiamin (free, protein-bound, phosphate-bound) have varying rates of thermal degradation (Farrer, 1955; Feliciotti and Esselen, 1957; Mulley et al., 1975b). The question as to whether radiation treatment of a meat product alters the ratio of each thiamin form is at present unknown and remains subject to further study.

Should radiation treatment of meat alter the ratios of the various thiamin forms, such an effect may explain this slight change in thiamin cooking loss on changing dose treatment levels. Regardless of the explanation for such an observance, the slight increased cooking loss obtained with increasing irradiation dose level was not considered to be of a practical significance with regards to affecting the value of pork as a source of dietary thiamin. Thiamin losses for those samples cooked following irradiation and expressed as percentages of the non-irradiated cooked sample mean were found to be similar to those obtained for the raw irradiated sample complement: 7.9%, 25.0%, 39.7%, 51.1% and 59.4% thiamin loss for the respective treatment doses of 0.57, 1.91, 3.76, 5.52 and 7.25 kGy.

Storage duration effect

Storage duration (Time) treatment provided a significant ($P < 0.0001$) contribution to the ANOVA model and likewise served as a component of the significant ($P < 0.0001$) ANOVA model terms for interaction: Time \times Dose, Time \times Cook and Time \times Dose \times Cook (Table 1). Thiamin changes in raw pork, attributable to increasing storage duration (Fig. 3), showed no pronounced trend (within dose) by regression analysis.

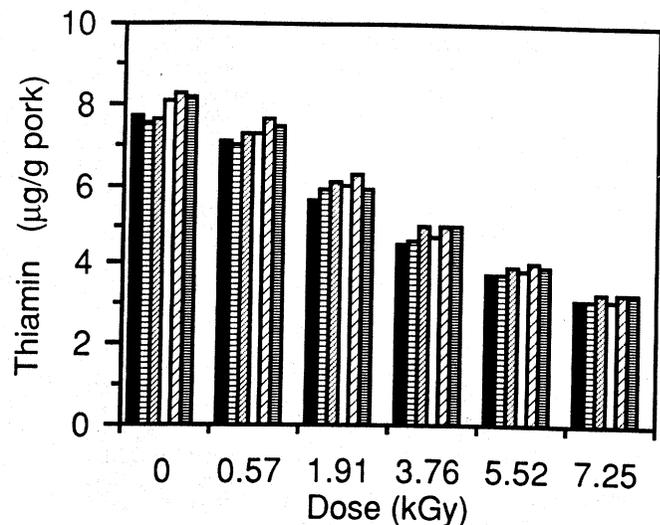


Fig. 4—Mean thiamin content of pork following post-irradiation storage and subsequent, post-irradiation cooking. Expressed by irradiation dose with 3 replicates per post-irradiation storage (2°C) period. ■ 0 wk; ▨ 1 wk; ▩ 2 wk; ▪ 3 wk; ▫ 4 wk; ■ 5 wk.

For both the irradiated and nonirradiated cooked pork samples, thiamin content tended, however, to increase as storage duration increased from 0 to 5 weeks. Such an increase, apparent in the graphed data (Fig. 4), was found to be significant ($P < 0.05$) via linear regression analysis. The magnitude or rate of such thiamin changes tended to decrease with increasing dose level. Significant differences in the rate of thiamin change with Time were found between the nonirradiated and irradiated cooked pork data for treatment doses: 1.91 ($P < 0.05$), 3.76 ($P < 0.05$), 5.52 ($P < 0.01$) and 7.25 ($P < 0.01$) kGy.

Because the pork was stored prior to cooking, the increased thiamin content observed on increased storage time may be due to a time related change in the relative proportion of the raw pork thiamin forms. According to Janitz and Rdesinska (1977) and Janitz and Grodzka-Zapytowska (1981), autolytic changes occurring in raw pork during storage result in a higher proportion of free thiamin to the bound form. Free thiamin has been reported to have a lower thermal degradation rate than bound thiamin (Farrer, 1955; Feliciotti and Esselen, 1957; Mulley et al., 1975b). Mulley et al. (1975b) in reporting that phosphate-bound thiamin (cocarboxylase) was more heat-labile than thiamin hydrochloride, theorized that the heat lability of cocarboxylase was due to the presence of the pyrophosphate group which appeared to strain the cocarboxylase molecule during heating.

Since dose affected the rate of thiamin destruction associated with increasing storage time, the conjecture made earlier that radiation treatment might alter the ratio of thiamin forms, combined with evidence that storage had some effect on the heat lability of thiamin, might provide the basis for explaining such results. Further research would, however, be necessary to answer the question as to what effect irradiation treatment and the post-irradiation treatments of storage and cooking have on the various forms of thiamin.

Although there was evidence of storage-related change in thiamin, the effect of such change was not considered to be of a practical significance with regards to affecting the dietary value of pork as a thiamin source. The primary factor influencing the thiamin of the fresh pork used in this study was that of the irradiation treatment. Such treatment, particularly at doses greater than 0.57 kGy, resulted in considerable destruction of thiamin. In considering the pork product as it would be consumed, i.e., stored then cooked, the post-irradiation storage and cooking treatments had little practical effect on the

irradiated pork product's thiamin content when compared to the thiamin of similarly-treated, nonirradiated pork.

REFERENCES

- Anderson, B. A. 1983. "Composition of Foods: Pork Products—Raw, Processed, Prepared," p. 45. Agricultural Handbook No. 8-10 (rev.) U.S. Department of Agriculture.
- Anonymous. 1977. Thiamin-Industrial Method No. 479-77A. In "Industrial Methods Manual." Technicon Instrument Corp. Tarrytown, NY.
- Anonymous. 1985a. FSIS to expand *Listeria*, *Salmonella*, control efforts. Food Chem. News 27(42): 20.
- Anonymous. 1985b. FSIS considering ban on cosmetic uses of vitamin C because of vitamin B-12 inhibition. Food Chem. News 27(39): 38.
- Anonymous. 1986a. Irradiation of fresh pork to prevent Trichinosis. "FSIS Background." Food Safety and Inspection Service, U.S. Department of Agriculture. March, 1986.
- Anonymous. 1986b. Irradiation in the production, processing, and handling of food; Final rule. 21 CFR Part 179, Fed. Reg. 51(75): 13376.
- Anonymous. 1986c. 250 Krad sufficient to eliminate poultry *Salmonella*, Canadian study shows. Food Chem. News 28(3): 30.
- Diehl, J. F. 1969. Combined effects of irradiation, storage and cooking on the vitamin E and B-1 levels of foods. Food Irrad. 10(1-2): 2.
- Diehl, J. F. 1975. Thiamine in bestrahlen lebensmitteln. II. Kombiniertes einfluß von bestrahlung, lagerung und erhitzen auf den thiamingehalt. Z. Lebensm. Unters. Forsch. 158: 83.
- Diehl, J. F. 1981. Effects of combination processes on the nutritive value of food. In "Combination Processes in Food Irradiation," Proceedings Series. International Atomic Energy Agency, p. 349, Vienna, Austria.
- Dunnnett, C. W. 1955. A multiple comparison procedure for comparing several treatments with a control. J. Am. Stat. Assoc. 50(272): 1096.
- Dunnnett, C. W. 1964. New tables for multiple comparisons with a control. Biometrics 20: 482.
- Ebert, M. and Swallow, A. J. 1957. The action of X-rays on cocarboxylase. Rad. Res. 7: 229.
- Farrer, K. T. H. 1955. The thermal destruction of vitamin B₁ in foods. Adv. Food Res. 6: 257.
- Fellicioti, E. and Esselen, W. B. 1957. Thermal destruction rates of thiamin in pureed meats and vegetables. Food. Technol. 11(2): 77.
- Freund, R. J., Littell, R. C., and Spector, P. C. 1986. "SASTM System for Linear Models," 1986 ed., p. 154. SAS Institute Inc., Cary, NC.
- Groninger, H. S. and Tappel, A. L. 1957. The destruction of thiamin in meats and in aqueous solution by gamma radiation. Food Res. 22: 519.
- Groninger, H. S., Tappel, A. L., and Knapp, F. W. 1956. Some chemical and organoleptic changes in gamma-irradiated meats. Food Res. 21: 555.
- ICRPF. 1978. Final report of the Panel on Irradiation of Meat and Meat Products. In "Food Irradiation in the United States," Interdepartmental Committee on Radiation Preservation of Food, G. C. Smith, Chairman. Appendix VI, p. 1.
- Janitz, W. and Grodzka-Zapytowska, S. 1981. The effect of selected technological factors on the changes of free and bound thiamin content in sterilized pork meat. As translated by M. Szczawinska. Medycyna Wet. 37(2): 97.
- Janitz, W. and Rdesinska, L. 1977. Impact of technological factors upon thiamin content in sterilized pork meat. As translated by M. Szczawinska. Medycyna Wet. 33(8): 499.
- Jarrett, R. D. and Halliday, J. W. 1979. Dosimetry in support of wholesomeness studies. J. Food Proc. Preserv. 3: 145.
- Kampelmacher, E. H. 1981. Prospects of eliminating pathogens by the process of food irradiation. In "Combination Processes in Food Irradiation," Proceedings Series, p. 265. International Atomic Energy Agency, Vienna, Austria.
- Kennedy, T. S. and Ley, F. J. 1971. Studies on the combined effect of gamma radiation and cooking on the nutritional value of fish. J. Sci. Food Agric. 22: 146.
- LaBell, F. 1986. Irradiation facilities geared to process pork. Food Process. 47(7): 64.
- Mulley, E. A., Stumbo, C. R., and Hunting, W. M. 1975a. Kinetics of thiamin degradation by heat. A new method for studying reaction rates in model systems and food products at high temperatures. J. Food Sci. 40: 985.
- Mulley, E. A., Stumbo, C. R., and Hunting, W. M. 1975b. Kinetics of thiamin degradation by heat. Effect of pH and form of vitamin on its rate of destruction. J. Food Sci. 40: 989.
- Pettinati, J. D., Ackerman, S. A., Jenkins, R. K., Happich, M. L., and Phillips, J. G. 1983. Meat and meat products: Comparative analysis of meat samples prepared with food chopper and bowl cutter. J. Assoc. Off. Anal. Chem. 66: 759.
- Rice, E. E. and Beuk, J. F. 1945. Reaction rates for decomposition of thiamin in pork at various cooking temperatures. Food Res. 10(2): 99.
- Roberts, T. 1985. Microbial pathogens in raw pork, chicken, and beef: benefit estimates for control using irradiation. Am. J. Agric. Econ. 67: 957.
- SAS. 1985. "SAS/STATTM Guide for Personal Computers," Version 6 ed. SAS Institute Inc., Cary, NC.
- 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. Rad. Phys. Chem. 25: 779.
- Thomas, M. H., Atwood, B. M., Wierbicki, E., and Taub, I. A. 1981. Effect of radiation and conventional processing on the thiamin content of pork. J. Food Sci. 46: 824.
- Thomas, M. H. and Calloway, D. H. 1957. Nutritive value of irradiated turkey. II. Vitamin losses after irradiation and cooking. J. Am. Diet. Assoc. 33: 1030.
- Thomas, M. H. and Wierbicki, E. 1971. Effect of irradiation dose and temperature on the thiamin content of ham. Technical Report 71-44 -FL. U.S. Army Natick Food Laboratory, Natick, MA.
- Tobback, P. P. 1977. Radiation chemistry of vitamins. In "Radiation Chemistry of Major Food Components," P. S. Elias and A. J. Cohen (Ed.), p. 187. Elsevier Scientific Publishing Co., New York.
- Wilson, G. M. 1959. The treatment of meats with ionising radiations. II. Observations on the destruction of thiamin. J. Sci. Food Agric. 10: 295.
- Ziporin, Z. Z., Kraybill, H. F., and Thach, H. J. 1957. Vitamin content of foods exposed to ionizing radiations. J. Nutr. 63: 201.

Ms received 11/2/88; revised 4/26/89; accepted 5/20/89.