Effect of Gamma Radiation on Furan Formation in Ready-to-Eat Products and their Ingredients

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ABSTRACT: Besides meat as the major component, ready-to-eat (RTE) meat and poultry products often contain ingredients such as Na-ascorbate, Na-erythorbate, glucose, honey, corn syrup, and Na-nitrite. Furan is a potential carcinogen and information is needed on its formation in irradiated RTE products. In the present study, we investigated the generation of irradiation-induced furan in aqueous solutions of those ingredients, and in 9 RTE food products (8 meat and poultry-based and 1 vegetable burger). Irradiation at doses up to 4.5 kGy induced formation of furan in aqueous solutions of Na-ascorbate, Na-erythorbate, glucose, honey, and corn syrup. Addition of Na-nitrite into these solutions prior to irradiation completely eliminated, or significantly reduced, furan formation. Most of the nonirradiated RTE products contained less than 1 ng/g of furan, except for beef and turkey frankfurters which contained 6 to 8 ng/g furan. Exposure of RTE food products to 4.5 kGy radiation in the nonfrozen state (5 °C) or to 10 kGy radiation in the frozen state (−18 °C) did not significantly increase furan levels in most of the samples. Furthermore, the irradiation treatments reduced furan levels in samples (that is, frankfurters) that contained more than 3 ng/g of furan. Our results suggested that irradiation induces furan formation in solutions of many RTE food ingredients, but not in RTE meat and poultry products themselves.

Keywords: frankfurters, furan, ionizing radiation, ready-to-eat, SPME

Introduction

The presence of furan in processed foods is a concern because furan is listed as a "reasonably anticipated to be human carcinogen" in the Department of Health and Human Services Report on Carcinogens (NTP 2004) and is considered "possibly carcinogenic to humans" by the International Agency for Research on Cancer (IARC 1995). The U.S. Food and Drug Administration (FDA) is seeking information related to the analysis of furan, occurrence of furan, mechanism of furan formation, and toxicology of furan (FDA 2004b).

Ionizing radiation is a nonthermal processing technology that effectively inactivates foodborne pathogens such as *Listeria monocytogenes* in ready-to-eat (RTE) foods (Sommers and Fan 2002; Sommers and others 2004). The use of irradiation has not been approved for use on RTE products. However, a petition filed by a coalition led by the National Food Processors Association (now Food Processor Association) requested that the FDA allow the use of ionizing radiation on RTE products (FDA 2000). The maximum doses petitioned for RTE products were 4.5 kGy for nonfrozen (refrigerated) foods and 10 kGy for frozen foods. During the review of the petition, the FDA identified the substance furan in many thermally processed foods including RTE meat products (FDA 2004a). Among the products surveyed, furan levels in thermally processed RTE meat products (such as sausages) ranged from nondetectable to 39 ng/g. Becalski and others (2005) detected 22 ng/g of furan in luncheon meat using a headspace method. Although these and other studies showed formation of furan in RTE products due to thermal treatment, there is no information on formation of furan from irradiation of those products.

RTE meat and poultry products have many ingredients (additives) besides meats. These additives include sugars, honey, corn syrup, starch, Na-erythorbate (or Na-ascorbate), phosphates, and Na-nitrite (Pearson and Gillett 1996). Typically, most of the additives are used in levels below 2% in RTE meat products. Maximum permitted levels are 500 ppm (0.05%) for Na-erythorbate and Na-ascorbate, and 200 ppm (0.02%) for Na-nitrite (Madhavi and others 1995). Studies have suggested that furan could be formed from ascorbic acid, erythorbic acid, fatty acids, sugars, and mixtures of sugars and amino acids upon thermal processing (Maga 1979; Locas and Yaylayan 2004; Becalski and Seaman 2005). Becalski and Seaman (2005) found that 10 times more furan was formed from isoascorbic acid (erythorbic acid) solution than from ascorbic acid upon thermal treatment. No data are available on the formation of furan from erythorbic acid in comparison with ascorbic acid due to irradiation. Our earlier studies suggested that irradiation induced accumulation of low levels of furan in apple and orange juices as a result of furan synthesis from simple carbohydrates and ascorbic acid (Fan 2005a; 2005b). Lower amounts of furan were formed from glucose compared with sucrose or fructose upon irradiation.

A total of 2 sample preparation techniques have been used for furan analysis in conjunction with gas chromatography-mass spectrometry (GC-MS): headspace sampling and solid phase microextraction (SPME) (FDA 2004b; Becalski and Seaman 2005; Fan 2005a, 2005b; Goldmann and others 2005). Both approaches offer simple and repeatable measurement of furan. We have developed an SPME-GC-MS method that has been employed to analyze furan in fruit juice and aqueous solutions (Fan 2005a, 2005b). The objective of the present study was to investigate the irradiation-induced furan formation from RTE ingredients and the RTE products using the modified SPME-GC-MS method.

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Materials and Methods

Chemicals and materials

Furan (99%), d_4-furan (99%), glucose (dextrose), soluble starch, Na-ascorbate, Na-erythorbate, and Na-phosphate were purchased from Sigma-Aldrich (St. Louis, Mo. U.S.A.). RTE products, ground beef and pork, light corn syrup, and honey were purchased from a local supermarket.

Sample preparation

The formation of furan in aqueous solutions of various food ingredients was first studied. A series of concentrations of corn syrup or honey (0%, 0.5%, 1%, 1.5%, and 2%), and Na-ascorbate or Na-erythorbate (0%, 0.0125%, 0.025%, 0.05%, and 0.1%) were prepared separately in deionized cold (5 °C) water. A total of 2% solutions of glucose, starch, corn syrup, and honey, and 0.05% solutions of Na-ascorbate and Na-erythorbate were prepared with or without 0.02% sodium nitrite in deionized water. The solutions (5 mL) were then placed into 15-mL glass vials. The vials were sealed, stored at 5 °C overnight, and then irradiated at a dose of 4.5 kGy at 5 °C. After irradiation, all samples were spiked through a septum with d_4-furan to a level of 4 ng/mL. Furan was then measured.

To study the formation of furan from RTE ingredients added in ground turkey, glucose, corn syrup, and honey (4%), and Na-ascorbate and Na-erythorbate (0.10% in water) were mixed with an equal amount (weight) of fresh ground turkey in a Waring blender, Model 51BL31 (Waring Products, Torrington, Conn., U.S.A.) at a low speed for 30 s. Then 20 g of the homogenates were added into 40-mL vials and sealed using septa and caps. Half of the samples were placed at 5 °C overnight without cooking. The other half of the vials were cooked in a heating block (Supelco, Bellefonte, Pa., U.S.A.) with temperature set at 90 °C. After about 25 min of heating when the sample temperature reached 90 °C, the samples were quickly cooled down by placing the vials in ice water, and the vials were then stored at 5 °C overnight. All noncooked and cooked samples were irradiated at a dose of 4.5 kGy at 5 °C. After irradiation, all samples were spiked with d_4-furan (approximately 10 ng/mL). Furan and d_4-furan were measured.

The effect of irradiation on furan formation in RTE products was finally studied. Turkey frankfurter, turkey bologna, beef frankfurter, beef bologna, ham, fat-free bologna, light beef bologna, vegetable burgers, and turkey breast were purchased from a local supermarket. Table 2 lists food composition from the labels of these RTE products. The RTE meats were diced into 3 × 3 mm cubes on a stainless pan placed on ice. The diced samples (10 g) were placed into chilled 40-mL vials, and the vials were sealed using the septa and caps. The vials were then equilibrated at 5 °C or −18 °C overnight before irradiated at doses of 4.5 kGy at 5 °C or 10 kGy at −18 °C, respectively. After irradiation, 10 mL cold (5 °C) and room temperature (23 °C) water was injected into the nonfrozen and frozen samples, respectively, through septa using 10-mL syringe. The vials were vortexed for 30 s. Then d_4-furan was injected into the vials through the septum to reach final concentration of approximately 9 ng/g d_4-furan in the homogenates. The vials were vortexed briefly and equilibrated at 5 °C for 2 h before furan and d_4-furan were analyzed.

Optimization of extraction conditions for furan analysis in RTE samples

Effect of the type of SPME fibers for RTE samples. RTE turkey breasts were diced into 3 × 3 mm cubes on a stainless steel pan that was placed on ice. A total of 10 g of the diced samples were placed into 40-mL chilled vials, and sealed immediately with septa and caps. A total of 10 mL deionized cold (4 °C) water was injected into vials through the septum using a 10-mL syringe. The vials were vortexed for 30 s at high speed. Then d_4-furan (approximately 1 μg/mL) was injected into the vials through the septa to reach a final concentration of approximately 10 ng/g d_4-furan in the homogenates. The vials were vortexed again for 10 s and equilibrated at 5 °C for 2 h before analysis. The samples were then incubated at 35 °C for 25 min in a heating block before SPME fibers were inserted into the headspace of the sample bottle for 20 min to adsorb d_4-furan. A total of 7 types of SPME fibers were tested for their efficiency in extraction of d_4-furan. Only 3 fibers of each type were used. The film thickness/stationary phase of these fibers were 85 μm polyacrylate (white), 65 μm carboxen (CAR)/divinylbenzene (DVB) (orange), 100 μm polydimethylsiloxane (PDMS) (red), 65 μm PDMS/DVB (blue), 75 μm partially cross-linked CAR/PDMS (black), 85 μm highly cross-linked CAR/PDMS (light blue), and 50/30 μm highly cross-linked DVB/CAR/PDMS (gray). The fibers were conditioned in the manufacturer's recommended temperatures and durations prior to use. d_4-Furan was then measured as described previously (Fan 2005a, 2005b).

Effect of SPME fiber adsorption time for RTE samples. Approximately 10 ng/g d_4-furan was prepared as described earlier in 20 g cooked turkey breast homogenates in 40-mL vials. The vials were equilibrated at 5 °C for 2 h before incubation at 35 °C for 25 min in a heating block before 85 μm highly cross-linked CAR/PDMS SPME fiber was inserted into the headspace of the sample vial to adsorb d_4-furan. The adsorption time varied from 0 to 30 min. After the incubation, the SPME fiber with adsorbed furan was inserted into the GC injection port and d_4-furan was analyzed.

Irradiation and dosimetry

Irradiation was conducted using a self-contained, Lockheed Corporation (Marietta, Ga. U.S.A.) ^{137}Cs gamma radiation source. The dose rate was about 0.090 kGy/min. The differences between actual doses and targeted doses were less than 5%. Temperature was maintained by injecting the gas phase from a liquid nitrogen tank into the radiation chamber. Routine dosimetry was performed using 5-mm-dia alanine dosimeters (Bruker Instruments, Rjeomstettem, Germany), and the free-radical signals were measured using a Bruker EMS 104 EPR Analyzer. The dosimeters were placed into 1.2-mL cryogenic vials (Nalgene, Rochester, N.Y., U.S.A.), and the cryogenic vials were taped onto the tubes containing samples prior to irradiation.

Standard analysis conditions for furan and d_4-furan

The analysis of furan and d_4-furan has been described earlier (Fan 2005a, 2005b). Briefly, samples in vials were incubated at 35 °C for 25 min before a 85-μm highly cross-linked CAR/PDMS SPME fiber was inserted into the headspace of a vial. After 20 min of extraction time, the SPME fiber was inserted into the GC injection port at 240 °C and held for 5 min to desorb volatile compounds. Volatile compounds were separated by a Hewlett-Packard 5890/5971 GC-MSD (Agilent Technologies, Palo Alto, Calif., U.S.A.) equipped with a 3.5-M GasPro capillary column (0.32 mm id) connected to a DB-5 column (30 m H, 0.32 mm i.d., 0.1-μm film thickness; J & W Scientific, Folsom, Calif., U.S.A.). The temperature program of the GC oven was set to 50 °C for 2 min, increased to 130 °C at 10 °C/min, then to 250 °C at 15 °C/min, and held for 2 min at the final temperature. Helium was the carrier gas at a flow rate of 39 cm/s. The transfer line was held at 250 °C during the entire run. Furan and d_4-furan were identified by comparison of the spectra and retention times of the sample compounds with those of the standards. Because food matrix had an impact on the extraction efficacy of furan using SPME, furan was quantified using a standard curve established in the individual

RTE meat homogenates or solutions of each food ingredient, and corrected using the internal standard (d_4-furan) to compensate for possible leakage of furan during sample handling.

Experimental design and statistical analysis

There were 4 replicates in each treatment. Replicated treatments were conducted independently using different packages of meat samples from the same brands often purchased at different times. For cooked turkey breast, 2 brands were used. Only 1 brand of sample which had no detectable furan was used for studying effects of SPME fiber type and incubation time while another brand had measurable furan and was used for studying irradiation effects on furan levels. Data were analyzed using SAS version 8.2 (SAS Institute, Cary, N.C., U.S.A.). General linear model and the Duncan's Multiple Range test were performed to test the significant effect among the treatments.

Results and Discussion

Formation of furan from honey, light corn syrup, starch, Na-ascorbate, and Na-erythorbate

As the concentration of honey and corn syrup increased from 0% to 1.0%, furan formation due to irradiation (4.5 kGy) increased (Figure 1). However, further increase in the concentration of honey or syrup from 1.0% (syrup) or 1.5% (honey) to 2.0% did not increase furan formation. There was more furan formed in honey than in corn syrup. The difference in furan formation between honey and light corn syrup may reflect the differences in the nature of the sugars and the concentrations of simple sugars in the 2 sweeteners. Honey contains about 41% fructose, 36% glucose, and 1% sucrose while the concentration of total simple sugars in light corn syrup is only about 27% (USDA 2005). The major carbohydrates in corn syrup are maltodextrins, a partially hydrolyzed starch. Earlier results have showed that more furan was formed from sucrose and fructose than glucose (Fan 2005b). The sugar composition of sweeteners has an important role in the formation of furan. There was no measurable furan formation from irradiation of starch solution (data not shown).

As the concentration of Na-ascorbate and Na-erythorbate increased from 0% to 0.05% in aqueous solutions, the irradiation-induced formation of furan increased dramatically. Further increase in concentrations of the 2 compounds did not significantly increase furan formation (Figure 2). Amounts of furan formation from the 2 compounds were similar in response to irradiation. Results on thermally induced furan formation demonstrated that more furan was formed from erythorbic acid than ascorbic acid (Becalski and Seaman 2005). However, the rates of irradiation-induced furan formation were similar for the 2 isomers, suggesting that different mechanisms may exist for furan formation between ionizing radiation and thermal processing. Our earlier results (Fan 2005b) showed that the furan formation was higher from ascorbic acid (pH approximately 3) than from sugars (pH approximately 6.4) when pH of the solutions was not adjusted. However, at neutral pH, formation of furan was actually higher in sucrose solution than in ascorbic acid solution, suggesting the importance of pH for irradiation-induced furan formation. The pH of all solutions in the present study was around 6.4.

Effect of Na-nitrite on formation of furan from glucose, honey, corn syrup, Na-ascorbate, and Na-erythorbate

Na-nitrite is commonly used in RTE meat products for color enhancement and for the prevention of toxin production by *Clostridium botulinum* (Anonymous 1987). In our experiments, addition of nitrite (0.02%) to corn syrup, honey, Na-ascorbate, Na-erythorbate, and glucose significantly reduced or eliminated irradiation-induced furan formation (Figure 3). For glucose, Na-ascorbate, and Na-erythorbate solutions, addition of Na-nitrite before irradiation completely prevented furan formation. For honey and corn syrup solutions, Na-nitrite did not totally eliminate furan formation, but

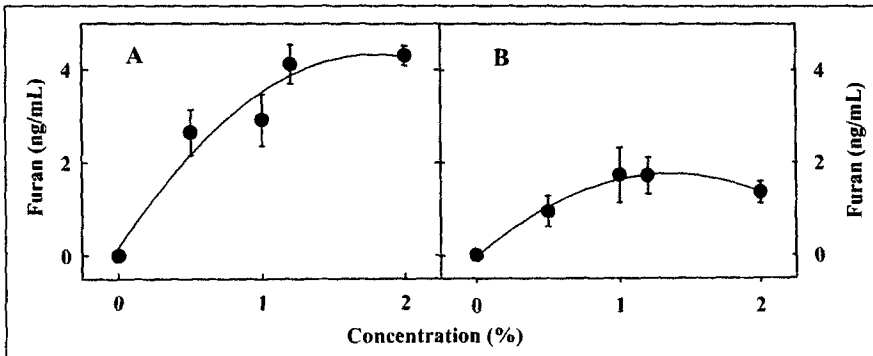

Figure 1 — Effects of substrate concentration on irradiation-induced accumulation of furan from honey (A) and corn syrup (B). A series of concentrations of honey and corn syrup solutions were irradiated with 4.5 kGy gamma rays at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

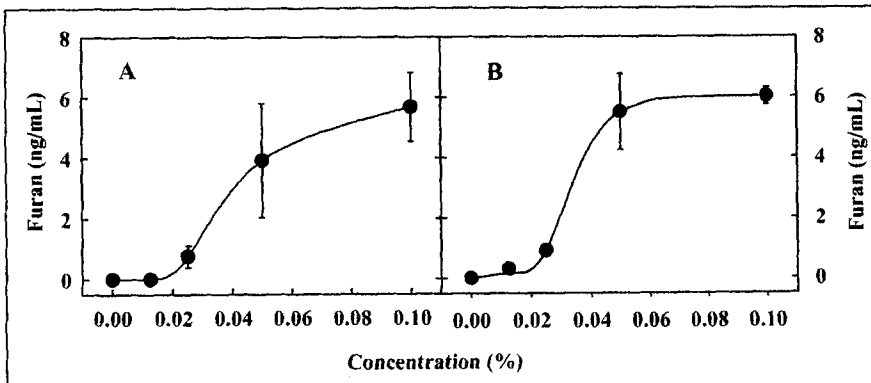

Figure 2 — Effects of substrate concentration on irradiation-induced accumulation of furan from Na-ascorbate (A) and Na-erythorbate (B). A series of concentrations of Na-ascorbate and Na-erythorbate solutions were irradiated with 4.5 kGy gamma rays at 5 °C. Vertical bars represent standard deviation of means ($n = 4$).

dramatically reduced furan formation. It is unclear why nitrite inhibited formation of furan from Na-ascorbate, Na-erythorbate, glucose, and the sweeteners. Irradiation exerts its effects mostly through free radicals (hydroxyl radicals and hydrated electrons) generated from radiolysis of water in aqueous solutions and in foods that contain mostly water. It is known that anionic species such as nitrite ions can easily react with hydroxyl radicals (Simic 1983). Thus, the inhibitory effects of nitrite on the formation of furan suggest that furan may be formed mainly through the reaction of hydroxyl radicals with the RTE food ingredients. Other antioxidants that scavenge hydroxyl radicals may be added to foods to reduce formation of furan.

Effect of the type of SPME fibers for RTE samples

We have developed an analysis procedure for furan in liquid samples such as juice and solutions (Fan 2005a, 2005b). To establish protocols for analyzing furan in solid food, we homogenized diced RTE meats with water and optimized SPME conditions such as fiber type and incubation time. In the RTE meat homogenates, the 2 CAR/PDMS fibers had the highest sensitivity to furan, followed by CAR/DVB/PDMS. PDMS/DVB had little sensitivity to furan (Table 1). Other fibers could not adsorb furan. It is obvious that SPME fibers with CAR and PDMS had the highest sensitivity. CAR probably contributed most to the adsorption of furan to the fiber. It is known that when mixed with PDMS, CAR creates a bipolar phase with unique characteristics, including pore size, distribution, volume, shape, and particle size, that are ideal for small analytes (Shirey 1999). Although the 2 CAR/PDMS fibers had no significant difference in sensitivity, there were more variations among the 3 fibers of the same type in the highly cross-linked SPME fiber than the partially cross-linked one. Because the highly cross-linked CAR/PDMS has a more stable coating with a less breakable fiber and is more durable, the fiber was chosen for the present study. The order in sensitivity of the fibers in meat homogenates was similar to that in water and fruit juice (Fan 2005a, 2005b). Goldmann and others (2005) tested 5 SPME fibers in water and found the sensitivity of the fibers to furan in the similar order: CAR/PDMS > DVB/CAR/PDMS > PDMS/DVB > polyacrylate, CW/DVB.

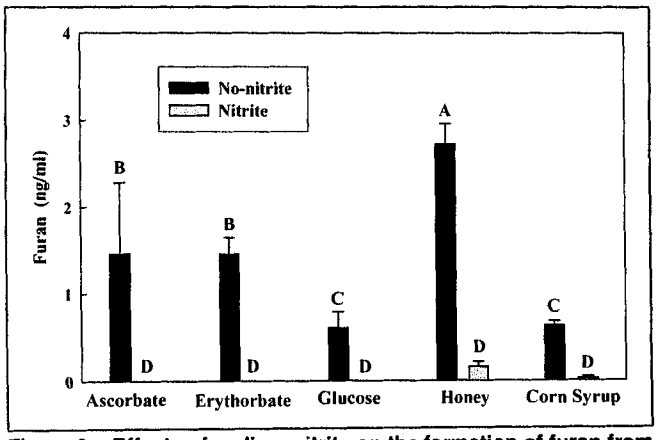

Figure 3 — Effects of sodium nitrite on the formation of furan from Na-ascorbate, Na-erythorbate, glucose, honey, and corn syrup solutions. All solutions were irradiated with 4.5 kGy gamma rays at 5 °C. Vertical bars represent standard deviation of means ($n = 4$). Means with the same letter are not significantly ($P > 0.05$) different.

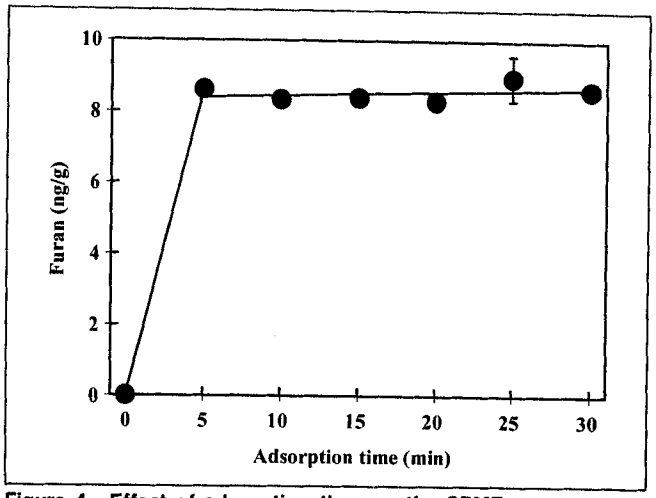

Figure 4 — Effect of adsorption time on the SPME extraction efficiency of furan spiked in cooked turkey breast homogenates. Vertical bars represent standard deviations of means ($n = 4$). The vertical bars are absent when standard deviations are smaller then the size of symbols.

Effect of SPME fiber adsorption time for RTE samples

As the adsorption time increased from 0 to 5 min, the amount of extracted furan in the SPME fiber increased (Figure 4). However, as the incubation time further increased, there was no significant increase in the extraction efficiency. It appears that furan in the RTE meat sample reached equilibrium very fast. The type of samples affects the time required to reach equilibrium. Earlier results (Fan 2005a) showed that furan reached equilibrium in apple and orange juice in about 15 min while 25 min was required in water. The present study showed that a much shorter adsorption time was sufficient for RTE meats. Food components in RTE products may help furan escape from solution (salting out). NaCl has been used to assist extraction of furan using SPME fibers from some lipid foods (Goldmann and others 2005). Even though 5 min of adsorption time was long enough for RTE meat samples, we chose an adsorption time of 20 min to correspond with the GC run time (20 min).

Formation of furan from RTE ingredients added to ground turkey meat

Although furan was formed from glucose, Na-ascorbate, Na-erythorbate, honey, and corn syrup in aqueous solutions upon

Table 1 — Relative extraction effectiveness (peak area ± standard deviation) of 7 SPME fibers for furan in cooked turkey breast homogenates containing ~10 ng/g furan

Fiber type	Description	Film thickness (μm)	Color code	Peak area
CAR/PDMS	Highly cross-linked	85	Light blue	435931 ± 165612a
CAR/PDMS	Partially cross-linked	75	Black	388097 ± 67012a
CAR/DVB/PDMS	Highly cross-linked	50/30	Gray	76516 ± 48868b
PDMS/DVB	Partially cross-linked	65	Blue	602 ± 602c
Polyacrylate	Partially cross-linked	85	White	0 ± 0c
PDMS	Nonbonded	100	Red	0 ± 0c
Carbowax	Partially cross-linked	65	Orange	0 ± 0c

Means with same letter are not significantly different ($P > 0.05$).
PDMS = polydimethylsiloxane; CAR: carboxen; DVB, divinylbenzene.

irradiation, there was no detectable furan (detection limit 0.5 ng/g) formation when the substrates were added to ground turkey meat prior to cooking (data not shown). Irradiation at 4.5 kGy did not induce detectable furan formation in either raw or cooked ground turkey or beef either (data not shown). Cooking of either ground turkey or ground beef patties with or without the additives to internal temperature of 90 °C did not induce furan formation (data not shown).

Effect of irradiation on furan formation from RTE food products

A total of 9 RTE products were analyzed to study possible irradiation-induced furan formation (Table 2). Only 8 of them were meat and poultry products; 1 was vegetable burger. Based on the labels from the packages, it appears that there was a lot of variation in the composition of the foods. Fat levels ranged from 0% to 29%. Earlier study has suggested that furan can be induced from fatty acid by thermal treatment (Locas and Yaylayan 2004). The sugar content of the samples also varied from 0% to 4%. Most of the RTE meat samples contained glucose, Na-erythorbate, and Na-nitrite besides meats as major components. Among the 9 products, turkey and beef frankfurters contained the highest levels of furan followed by cooked turkey breast (Table 3). Interestingly, another brand of cooked turkey breast containing Na-erythorbate and Na-nitrite did not show a detectable furan level (Figure 4). All other samples contained about 1 ng/g or less of furan, a level that was below the estimated limit of quantification (approximately 2 ng/g). For turkey and beef frankfurters, while the furan levels in nonirradiated samples were higher, irradiation at doses of 4.5 kGy at 5 °C, or 10 kGy at −18 °C, significantly decreased furan levels. Similarly, in turkey breast, furan levels were significantly reduced by irradiation at 4.5 kGy, while a nonsignificant effect was observed at dose of 10 kGy at −18 °C. The cooked turkey breast samples used for the 2 irradiation conditions were purchased on different dates, resulting in different amounts of furan, probably reflecting the volatile nature of furan. Furan levels in foods may decrease during storage, shipping, and display if packaging materials are permeable to furan. Irradiation had little effect on furan levels in any other samples. The results suggest that irradiation actually reduces the thermally induced furan in some products. Gamma irradiation at doses up to 5 kGy did not induce furan formation from fatty acid (data not shown).

Our results showed that some (that is, frankfurters) commercial RTE food products that were pasteurized thermally had furan levels above 3 ng/g, levels that were comparable to those in the FDA's survey (FDA 2004a). The elevated furan levels in the commercial RTE meat products are presumably due to thermal processing. Our results showed thermal treatments of raw meats at temperatures below 90 °C did not induce any furan formation. Therefore, the high furan levels in the frankfurters may be due to elevated processing temperature, prolonged heating time, packaging in nonpermeable materials after thermal treatments, and/or in-packaging thermal processing. Packaging may play an important role for actual furan levels in RTE meat products in local supermarkets. If the packages permit escape of furan, low levels of furan will likely be found in the products. It is unclear whether there was any difference in packaging materials for the RTE meat products used in the present study. Nevertheless, the primary focus of the present study was to investigate whether irradiation induced furan in the RTE food products.

There are some similarities and differences between heat- and irradiation-induced furan induction. For example, both processing technologies induced furan formation from sugars, ascorbate, and erythorbate solutions. On the other hand, thermal processing induced furan formation from fatty acid, meat products, and dehydroascorbic acid (FDA 2004a; Becalski and Seaman 2005) while irradiation did not induce or induced little furan formation from fatty acid and meat products.

Our results showed that irradiation induced furan formation in the aqueous solutions of many RTE food ingredients, but reduced or had no effect on furan levels in RTE foods. Upon irradiation of aqueous solutions or foods in which water is the major component,

Table 2 – Composition of RTE meat products used in the study

Meat type	Fat (%)	Sugar (%)	Major ingredients
Turkey frankfurter	18	2	Turkey, corn syrup, starch, dextrose, sodium erythorbate, sodium nitrite
Turkey bologna	4	<2	White turkey, starch, sugar, sodium phosphate, sodium erythorbate, sodium nitrite
Beef frankfurter	29	<2	Beef, corn syrup, dextrose, sodium phosphate, sodium erythorbate, sodium nitrite
Beef bologna	29	4	Beef, starch, corn syrup, dextrose, sodium phosphate, sodium erythorbate, sodium nitrite
Ham	3	3	Ham, honey, sugar, sodium phosphate, sodium erythorbate, sodium nitrite
Fat-free bologna	0	< 2	Turkey, beef, starch, dextrose, corn syrup, sodium phosphate, sodium erythorbate, sodium nitrite
Light beef bologna	14	<2	Beef, starch, corn syrup, sodium phosphate, sodium erythorbate, sodium nitrite
Vegetable burgers	9	0	Vegetables, wheat, oat and soy flours, proteins, starch
Turkey breast (cooked)	0	<2	Turkey breast, dextrose, sodium phosphate

Table 3 – Effect of irradiation on furan formation (ng/g) in RTE products. RTE products were exposed to 4.5 kGy radiation in nonfrozen state (5 °C) or 10 kGy in frozen state (−18 °C).

	Nonfrozen state		Frozen state	
Meat type	0 kGy	4.5 kGy	0 kGy	10 kGy
Turkey frankfurter	8.81 ± 1.15 xa	5.89 ± 0.50 za	9.13 ± 2.24 xa	6.79 ± 1.51 yza
Turkey bologna	0.28 ± 0.05 xd	0.40 ±0.09 xe	0.26 ± 0.05 xb	0.31 ± 0.16 xb
Beef frankfurter	6.24 ± 1.34 yb	4.17 ± 0.43 zb	8.96 ± 1.26 xa	6.01 ± 0.52 ya
Beef bologna	1.07 ± 0.30 xd	1.23 ± 0.21 xc	0.76 ± 0.44 xb	0.93 ± 0.50 xb
Ham	0.28 ± 0.07 xd	0.29 ± 0.24 xe	0.32 ± 0.15 xb	0.33 ± 0.06 xb
Fat-free bologna	0.59 ± 0.06 xd	0.44 ± 0.17 xde	0.81 ± 0.37 xb	0.47 ± 0.04 xb
Light bologna (beef)	0.77 ± 0.16 xd	0.84 ± 0.22 xcd	0.69 ± 0.18 xb	1.04 ± 0.29 xb
Vegetable burgers	0.37 ± 0.13 yd	0.61 ± 0.23 xyde	0.66 ± 0.50 xyb	1.20 ± 0.51 xb
Turkey breast (cooked)	3.24 ± 1.42 xc	1.16 ± 0.24 yc	1.06 ± 0.16 yb	0.96 ± 0.10 yb

Means with same letter in the same row (x–z) or same column (a–e) are not significantly different ($P > 0.05$).

the following primary free-radical species are generated: hydrated electrons (e_{aq}), hydroxyl radicals (OH), and hydrogen atoms (H); the relative amounts of e_{aq} and OH are more than 5 times higher than that of hydrogen atoms (Simic 1983). These free radicals then attack other chemicals or food components, such as ascorbic acid, sugars, and furan (if present), which results in the formation and degradation of furan. The exact scheme for the formation of furan from these compounds is unclear. Earlier steps may involve reaction of the primary radicals from water with the chemicals, resulting in the formation of secondary radicals. The later steps may be similar to the pathway as in thermal-induced furan formation (Locas and Yaylayan 2004). Similarly, the furan degradation pathway is not well known either although many radical products of furan have been identified (Schuler and others 1973). Whether furan will accumulate in a food system upon irradiation will depend on the balance between the rate of formation and the rate of degradation. In some aqueous solutions of food ingredients, irradiation will result in the formation of furan if the ingredients are sensitive to irradiation and the availability of furan precursors is not a limiting factor. However, in a real food, whether irradiation results in a decrease or an increase in furan levels will depend on many factors that may affect the formation and degradation of furan. Antioxidants and other competing food components may reduce formation and degradation of furan. The reactivity of food components and proximity to the primary free radicals may also influence furan accumulation. It appears that furan was relatively sensitive to irradiation, and the rate of furan formation was relatively lower in RTE food products.

In summary, our results showed that irradiation induced furan formation in aqueous solutions of many RTE ingredients, such as Na-ascorbate, Na-erythorbate, and sweeteners. But when these ingredients were added to meats, no irradiation-induced furan was found. Also Na-nitrite, a common RTE meat additive, significantly reduced or even eliminated furan formation in solutions of the food ingredients. Importantly, irradiation of commercial RTE products did not induce furan formation. To the contrary, irradiation reduced furan formation in those RTE meats that contained relatively high levels of furan due to thermal processing. Our results suggested that irradiation of RTE products did not induce the accumulation of this potential toxic compound.

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