Impact of Ionizing Radiation and Thermal Treatments on Furan Levels in Fruit Juice

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ABSTRACT: The formation of furan in freshly prepared apple and orange juices as affected by ionizing radiation and thermal treatments was studied using a newly developed solid-phase microextraction method coupled with gas chromatography-mass spectrometry (GC-MS). Results show that furan levels increased linearly as radiation dose increased from 0 to 5 kGy. Irradiation induced more furan in apple juice than in orange juice. During post-irradiation storage at 4 °C, furan levels increased in both apple and orange juices, particularly in the first 3 days. On the other hand, irradiation degraded furan (d₄-furan) spiked in water and fruit juices. The rate of degradation as a function of radiation dose was the highest in water and the lowest in orange juice. Submerging the juice samples in boiling water for 5 min induced higher amounts of furan in orange juice than in apple juice, but autoclaving (121 °C, 25 min) resulted in more furan formation in apple juice than in orange juice. Results reported here suggest that both ionizing radiation and thermal treatments induce furan formation in fruit juices.

Keywords: furan, ionizing radiation, juice, apple, orange, solid-phase microextraction, thermal treatments

Introduction

Ionizing radiation is a nonthermal processing technology that effectively inactivates foodborne pathogens in fruit juices (Buchanan and others 1998; Niemira and others 2001; Foley and others 2002) and other foods. A petition filed by a coalition led by the Natl. Food Processors Assn. (NFPA) requested that U.S. Food and Drug Administration (USFDA) (2000) allow the use of ionizing radiation on ready-to-eat products, including fruit juice. During the review of the petition, the USFDA identified the substance furan in a number of foods that undergo heat treatment (USFDA 2004a). Furan is listed in the Dept. of Health and Human Services report as “reasonably anticipated to be human carcinogen” (NTP 2004) and as “possibly carcinogenic to humans” by the Intl. Agency for Research on Cancer (IARC 1995). Due to the concerns on the carcinogenicity of furan, the USFDA requested more information related to the occurrence of furan, mechanism of furan formation, and toxicology of furan (USFDA 2004b).

Furan belongs to a class of compounds that contribute to the flavors of many foods. Most of the compounds are unstable and occur in low concentrations in foods and have low sensory thresholds (Maga 1979). The primary source of furan and its derivatives in foods is believed to be from the thermal degradation of carbohydrates such as glucose, lactose, and fructose. Furan, the simplest form of furans, has been found in some thermally degraded carbohydrate products such as sucrose (Walter and Fagerson 1968) and ascorbic acid (Tatum 1969). In a recent study, LOCAS and Yaylayan (2004) found that furan could be formed from carbohydrates, amino acids, and mixtures of the 2. Ascorbic acid, among the model systems studied, had the highest potential for producing furan, followed by glycoaldehyde/alanine, erythrose, ribose/serine, sucrose/serine, fructose/serine, and glucose/cysteine. A pathway from the oxidation of polysaturated fatty acids was also proposed by LOCAS and Yaylayan (2004). Fruit juices are rich in carbohydrates and ascorbic acid, and one may expect furan to be produced in fruit juice upon thermal treatment. Indeed, the USFDA has identified furan in thermally processed fruit juices at concentrations up to 8 ng/mL. There is a lack of published data in the literature regarding formation of furan in fruit juices as a function of exposure to ionizing radiation. Furan and its derivatives are usually present in very small amounts in foods, and isolation and quantification of these compounds are tedious. Therefore, the objectives of this study were to develop an analytical method for furan in juices and to investigate the effects of ionizing radiation and thermal processing on the formation of furan in fresh apple and orange juices.

Materials and Methods

Chemicals

Furan (99%) and d₄-furan (99%) were purchased from Aldrich (Milwaukee, Wis., U.S.A.).

Sample preparation

Fresh apple and orange juices were prepared from Washington-produced ‘Fuji’ apples and California-produced ‘Valencia’ oranges purchased from a local supermarket, using a Champion MAR-48C juicer (Plastaket Manufacturing Co., Lodi, Calif., U.S.A.). The juices were prepared at 7 °C and placed into 15-mL (21 x 70 mm) screw-top glass vials (Supelco, Bellefonte, Pa., U.S.A.) for subsequent treatments.

Preparation of stock and working solutions

Stock solutions of furan and d₄-furan were prepared similarly as described by the USFDA (2004c). To 10 mL methanol in a sealed and weighed 15-mL glass vial, approximately 10 μL furan was injected through the septum using a 10-μL microsyringe (Hamilton Co., Reno, Nev., U.S.A.). The exact amount of furan added in the methanol was calculated using the difference in weights before and after the addition of furan or d₄-furan. The stock solutions were stored at 5 °C after the pierced septum was replaced. Stock solutions...
were stored for a maximum of 14 d. A working solution was prepared freshly by taking 10 μL stock solution through the septum using a 10-μL microsyringe and adding it into 10 mL water (4 °C) in a 15-mL glass vial through a septum. The working solutions were then shaken vigorously by hand. The pierced septum for the stock solution was replaced promptly before the solution was returned to 5 °C.

**Standard analysis conditions for furan and d₄-furan**

Samples in 15-mL vials were incubated at 35 °C for 25 min in a 15-mL vial holder sitting on a Corning heat/stir plate (Supelco) before a solid-phase microextraction (SPME) fiber (75 μm Carboxen-PDMS) was inserted into the headspace of a vial. After 20 min of extraction time, the SPME fiber was inserted into the gas chromatography (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-MS (Agilent Technologies, Palo Alto, Calif., U.S.A.) equipped with a 3.5 M GasPro capillary column (0.32-mm inner dia) connected to a DB-5 column (30 m × 0.32 mm inner dia, 0.1-μm film thickness; J & W Scientific, Folsom, Calif., U.S.A.) using a Universal PreStitch Connector (Restek Chromatography Products, Bellefonte, Pa., U.S.A.). The GS-GasPro column, which is ideal for separating compounds that are gases at ambient temperature, was connected to a DB-5 column to establish an appropriate flow rate as required by the mass spectrometer. 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 d₄-furan were identified by comparison of the spectra of the sample compounds with those of standards and by comparing retention times of sample compounds with those of the standards. The m/z (mass/charge) 39 and 68 and the ratio of 39/68 were used for the confirmation of furan, and m/z 68 was used as the quantifier. The m/z 41 and 72 and the ratio of 41/72 were used for the confirmation of d₄-furan, and m/z 72 was used as the quantifier. Furan was quantified using a standard curve established with the individual matrix (orange juice, apple juice, or water) and corrected using the internal standard (d₄-furan).

**Effect of SPME fiber adsorption time**

Deionized water, apple juice, and orange juice (5 mL each at 4 °C in 15-mL vials) were opened briefly and spiked with the furan working solution using microsyringes to reach the final concentration of about 9 ng/mL. The vials were sealed immediately and equilibrated at 4 °C for 2 h. The samples were then incubated at 35 °C for 25 min in a heating block before the 75 μm Carboxen-PDMS SPME fiber was inserted into the headspace of the sample bottle to adsorb furan. The absorption time varied from 0 to 25 min. After the incubation, the SPME fiber with adsorbed volatile compounds was inserted into the GC injection port.

**Establishment of standard curve in water, apple juice, and orange juice**

Various amounts of furan working solutions were added to 5 mL cold (4 °C) water or fresh juice in 15-mL vials using glass microsyringes. Furan in the samples was then measured using the standard procedures of the gas chromatography-mass spectrometry (GC-MS) method described previously.

**Effect of radiation dose on furan formation and destruction of ascorbic acid**

Two types of thermal treatments were used. For treatment 1, juice (5 mL) in 15-mL vials was submerged into boiling water for 5 min. Juice temperature reached 100 °C after 3 min. For treatment 2, samples in the 15-mL vials were heated to 121 °C using a liquid cycle for 25 min in an autoclave (Amresco G120 Eagle/Century series, Steris Corp., Mentor, Ohio, U.S.A.). During treatment, the vials were set upside down to minimize leakage of furan from the gas phase. For treatment 1, the juice in a vial was stirred during heating using an enclosed stir bar and a stir plate. After thermal treatments, the vials were then cooled rapidly by submerging the vials into ice water for 10 min. Samples without any thermal treatment served as controls. Furan in the samples was then analyzed after equilibrium at 5 °C for about 1 h. Similarly, juices made from different batches of fruit were treated with the 2 types of thermal treatments. Ascorbic acid in the juices was measured.

**Stability of furan in apple juice and orange juice during storage**

Apples and orange juices (5 mL) were placed in 15-mL glass vials and sealed with septa and caps. After incubating at 5 °C for 2 h, the samples in the vials were exposed to 10 kGy gamma radiation at 5 °C. After irradiation, the samples were kept on ice and briefly opened when spiking with about 9 ng/mL d₄-furan as internal standard. The nonirradiated juices were spiked with about 9 ng/mL furan and d₄-furan. All samples were sealed with septa and caps and stored at 4 °C for 14 d in the dark. Furan and d₄-furan in the samples were analyzed on days 0, 3, 7, and 14 of storage. Furan was calculated from standard curves established and adjusted from the internal standard assuming no leakage from the vials.

**Degradation of d₄-furan by irradiation**

Water, apple juice, and orange juice (5 mL) in 15-mL glass vials were spiked with d₄-furan so that the final concentration of d₄-furan was about 10 ng/mL. The samples were exposed to 0, 1, 2, 3, 4, and 5 kGy radiation at 5 °C. On the day of irradiation, d₄-furan was analyzed using the standard procedure and quantified using standard curves.

**Effects of thermal treatment on furan formation and destruction of ascorbic acid**

Titratable acidity, pH, and soluble solids content of the juices were measured as described elsewhere (Fan and others 2005). Ascorbic acid in juice was analyzed using the HPLC method (Fan and others 2002), and antioxidant capacity was measured using a ferric reducing antioxidant power assay (Benzie and Strain 1996).

**Irradiation and dosimetry**

Irradiation was conducted using a self-contained, Lockheed Corp. (Marietta, Ga.) 137Cs gamma radiation source with a dose rate of approximately 0.091 kGy/min. The dose rate was established using alanine transfer dosimeters from the Natl. Inst. of Standards and Technology (Gaithersburg, Md., U.S.A.). The temperature was maintained at 5 ± 2 °C by injecting the gas phase from a liquid nitrogen tank into the radiation chamber. Routine dosimetry verification was performed using alanine dosimeters (Bruker Instru-
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ments Inc., Billerica, Mass., U.S.A.). The dosimeters were placed into 2-mL cryogenic vials (Nalgene, Rochester, N.Y., U.S.A.), and the vials were attached to the tubes containing the juice samples before irradiation. The free radical signal induced in response to radiation was quantified by inserting the alanine dosimeters into a 104 Electron Paramagnetic Resonance instrument (Bruker Instruments Inc.).

**Experimental design and statistical analysis**

All experiments were repeated independently at least 4 times. Results and Discussion

Typical gas chromatograms of volatile compounds in apple juice either thermally treated or gamma-irradiated (Figure 1) show the retention time for furan was approximately 8 min. Nonirradiated and nonheated juice did not produce detectable furan.

**Effect of SPME adsorption time**

As adsorption time increased from 0 to 10 min, the amount of extracted furan in the SPME fiber increased for water, orange juice, and apple juice (Figure 2). Continuous increase in furan was observed for water in the range of 10 to 25 min. For apple juice and orange juice, the increase reached plateaus at 15 min. The results indicate that adsorption time of 15 min was long enough for analysis of furan in apple juice and orange juice, but for analyzing furan in water, a longer time may be required. Adsorption time of 20 min was chosen to correspond to the GC run time (20 min). Apple juice and orange juice contain sugars, organic acids, and other solutes that may help furan to reach equilibrium; and, at the same extraction times, area count for furan was the highest in water and lowest in orange juice. The presence of the other volatiles in the juices may shift the partitioning constant in the fiber coating to lower the efficiency of furan extraction efficacy. The Carboxen-PDMS fiber is designed for low-boiling-point volatiles. Our preliminary results suggested that the fiber had higher extraction efficacy for furan than several other fibers tested. The equilibrium temperatures ranging from 20 °C to 40 °C did not affect extraction efficacy of the SPME fiber using the 25-min incubation time, probably due to the high volatility of the compound. We used the 75-μm Carboxen-PDMS fiber, an adsorption time of 20 min, and an incubation temperature of 35 °C for the study.

**Establishment of standard curves**

Standard curves were established in water, apple juice, and orange juice (Figure 3). The curves were linear in the range of 0 to 20 ng/mL in all 3 matrixes, with \( R^2 \) values of 0.999, 0.998, and 0.999 in water, apple juice, and orange juice, respectively. Sensitivity was highest in water and lowest in orange juice. The results suggest that matrix may influence the measurement of furan, and standard curves had to be matrix-matched.

**Effect of radiation dose**

Irradiation induced formation of furan in apple and orange juices (Figure 4a and 4b). As the radiation dose was increased, the amount of furan increased. Although an exponential expression fitted the curve better than a linear line in apple juice, the increase could be expressed as a linear response (\( R^2 = 0.97 \)). The increase in orange juice appeared to be linear in the dose range of 0 to 5 kGy. If the dose-furan relationship was expressed as a linear response, the rate of furan formation as a function of dose was much higher in apple juice than in orange juice. The increases in furan as a function of dose were 0.87 and 0.40 ng/mL per kGy for apple and orange juice, respectively. It is unclear why the formation of furan was lower in orange juice than in apple juice. The difference in the composition of juices may be a factor. The composition of apple juice and orange juice were therefore measured. Although there were significant differences (\( P < 0.05 \)) among all attributes between the

![Figure 1](https://example.com/figure1.png)

**Figure 1**—Gas chromatogram of furan and volatile compounds from apple juice either nonirradiated (0 kGy) or irradiated at 4 kGy. The arrow indicates the furan peak.

![Figure 2](https://example.com/figure2.png)

**Figure 2**—Effect of adsorption time on the solid-phase microextraction (SPME) extraction efficiency of furan spiked in water (a), apple juice (b), and orange juice (c). Vertical bars represent standard deviations of means (\( n = 4 \)).

URLs and E-mail addresses are active links at www.ift.org
2 juices, the differences in titratable acidity, ascorbic acid, and antioxidant capacity were much larger than soluble solids content and pH. Titratable acidity, ascorbic acid, and antioxidant capacity in orange juice were 4.1, 103, and 7.7 times higher, respectively, than those in apple juice (Table 1). The differences in soluble solids content (sugars) and pH were similar between the 2 juices. It appears that antioxidants, ascorbic acid, and organic acids are probably responsible for the reduced rate of furan formation in orange juice although the extent of the contribution from each group is unclear. Our earlier results showed that the addition of antioxidants, such as ascorbic acid, inhibited the formation of radiolytic compounds from sugars (Fan 2003). Each μmol/L ascorbic acid equals 2 μmol/L ferric reducing antioxidant power (Benzie and Strain 1996). The contribution of ascorbic acid to the total antioxidant activity could therefore be calculated. In apple juice, ascorbic acid contributed very little (2%) to the total antioxidant capacity, whereas about 25% of total antioxidant activity was due to ascorbic acid in orange juice. It is also possible that the high amount of organic acids and antioxidants other than ascorbic acid in orange juice reduce the formation of furan.

Ascorbic acid levels in both apple juice and orange juice decreased with increasing radiation dose (Figure 4c and 4d). The decrease in ascorbic acid in apple juice appeared to be linear ($R^2 = 0.97$). When the changes in ascorbic acid in orange juice were expressed as a linear curve, $R^2$ was only 0.87. Despite the lower ascorbic acid in apple juice, the rate of destruction by irradiation was much lower than in orange juice. At 4 kGy, only about 0.55 μg/mL (12% of nonirradiated) ascorbic acid was destroyed in apple juice, whereas 157 μg/mL (50%) was degraded in orange juice. It appears that the amount of degradation in ascorbic acid due to irradiation is not necessarily correlated with the formation of furan. Degradation of ascorbic acid by irradiation does not always contribute to furan formation.

Changes in furan levels during the post-irradiation period

The levels of furan that had been spiked into nonirradiated apple and orange juices did not change during the 14-d storage period (Figure 5). Exposure of apple and orange juices to 10 kGy gamma rays raised the furan levels to 4.5 and 10.0 ng/mL, respectively, compared with samples exposed to 5 kGy radiation (Figure 4). The levels continued to increase during storage, particularly during the 1st 3 d of storage. A 43% increase was observed in both apple juice and orange juice. After 3 d, the furan levels continued to increase but at reduced rates. The increases in furan during the earlier storage period may be due to the residue effect of irradiation. Irradiation exerts its effect through generation of primary radicals from radiolysis of water (Simic 1983). The primary radicals include hydrated electrons, hydrogen atoms, and hydroxyl radicals. Hydrogen peroxide can also be a radiolytic product of water. The primary radicals then react with food components to form secondary radicals. Most of the free radicals are very short-lived (sub-seconds). However, some radicals and reactive compounds may be present for a much longer time (days). These stable radicals and reactive

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**Table 1—Difference in soluble solids content (SSC), pH, titratable acidity (TA), ascorbic acid (AA) content, and antioxidant capacity of apple and orange juices used in the study**

<table>
<thead>
<tr>
<th>Juice</th>
<th>SSC (%)</th>
<th>pH</th>
<th>TA (mg/100 mL)</th>
<th>AA (μg/mL)</th>
<th>FRAP (μmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>15.0 ± 0.2a</td>
<td>4.2 ± 0.1a</td>
<td>0.23 ± 0.02b</td>
<td>3.6 ± 0.2b</td>
<td>1067 ± 162b</td>
</tr>
<tr>
<td>Orange</td>
<td>14.6 ± 0.2b</td>
<td>4.0 ± 0.1b</td>
<td>0.95 ± 0.28a</td>
<td>372.6 ± 31.1a</td>
<td>8174 ± 464a</td>
</tr>
</tbody>
</table>

*Means with same letters are not significantly different (least significant difference [LSD], $P < 0.05$).

*Antioxidant capacity expressed as ferric reducing antioxidant power (FRAP).

*Values are means ± standard deviations, $n = 4$. **

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**Figure 3**—Standard curves for furan in water (a), apple juice (b), and orange juice (c). Vertical bars represent standard deviations of means ($n = 4$).

**Figure 4**—Effect of radiation dose on formation of furan (a, b) and destruction of ascorbic acid (c, d) in apple (a, c) and orange juice (b, d). Vertical bars represent standard deviations of means ($n = 4$). a = furan in apple juice, b = furan in orange juice, c = ascorbic acid in apple juice, d = ascorbic acid in orange juice.
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Compounds may continue to induce the formation of furan. It should be noted that the furan levels presented in Figure 5 have been corrected for leakages or losses from the vials. In reality, furan in the glass vials decreased slowly during storage.

**Reduction of d₄-furan by ionizing radiation**

From the results discussed previously, it is clear that irradiation induced furan in both apple juice and orange juice. However, it is also known that irradiation degrades chemical compounds through either direct or indirect mechanisms (Simic 1983). Therefore, it is quite possible that furan induced by irradiation can be destroyed simultaneously by irradiation. The possible destruction of furan by irradiation could not be determined by simply measuring furan levels because the furan levels after irradiation are the result of an equilibrium between formation and degradation. To study the destruction of furan by irradiation, d₄-furan was spiked into juices before irradiation. Although both furan and d₄-furan had the same retention times, because of the difference in spectra, furan and d₄-furan could be simultaneously quantified in the same solutions using m/z 68 and 72, respectively, as quantifiers. Figure 6 shows d₄-furan levels as a function of radiation dose. As radiation dose increased, the levels of d₄-furan in all matrixes decreased. The decrease in d₄-furan was very rapid in water. At 0.5 kGy, there was no detectable d₄-furan. The decreases for all matrixes appeared to be exponential. The d₄-furan in apple juice decreased more rapidly than in orange juice. Most (87%) of the d₄-furan was destroyed in apple juice by 5 kGy radiation, whereas only about 12% was degraded by the same radiation dose in orange juice. The slower rate of degradation in orange juice was probably due to the higher amounts of organic acids and antioxidants. It is possible that irradiation be used to decrease thermally induced furan levels in certain foods when irradiation is applied after thermal treatments.

**Effect of thermal treatment on formation of furan in juices**

As expected, there was no measurable furan in juice without thermal treatments (Figure 7a and 7b). Submerging the juice into boiling water for 5 min induced approximately 1.4 ng/mL furan in orange juice. However, very little furan was induced in apple juice. Autoclaving (121 °C, 25 min) of both juices produced much more furan than submerging the samples in boiling water for 5 min. The amount of furan formed in apple juice had almost twice the amount of furan as in orange juice. In the samples heated in boiling water, more furan was formed in orange juice than in apple juice. But in autoclaved samples, more furan was formed from apple juice. It is unclear why the trend reversed as the method of thermal treatments changed.

Submerging samples into boiling water for 5 min had no signif-

**Figure 5**—Changes in furan levels in nonirradiated (a, c) and irradiated (10 kGy) (b, d) apple (a, b) and orange (c, d) juices during storage at 4 °C. Nonirradiated juices were spiked with about 9 ng/mL furan. Both spiked and irradiated juices in sealed vials were stored at 5 °C for 14 d. Vertical bars represent standard deviations of means (n = 8). a = nonirradiated apple juice, b = irradiated apple juice, c = nonirradiated orange juice, d = irradiated orange juice.

**Figure 6**—Degradation of d₄-furan by irradiation. Water (a), apple juice (b), and orange juice (c) spiked with 9 to 10 ng/mL d₄-furan were exposed to a series of radiation dose at 4 °C. Furan was measured on the day of irradiation. Vertical bars represent standard deviations of means (n = 4).

**Figure 7**—Effect of thermal treatments on the formation of furan (a, b) and destruction of ascorbic acid (c, d) in apple (a, c) and orange (b, d) juices. Fresh juices were either nontreated (CK), boiled at 100 °C for 5 min, or autoclaved at 120 °C for 25 min. Vertical bars represent standard deviations of means (n = 7). a = furan in apple juice, b = furan in orange juice, c = ascorbic acid in apple juice, d = ascorbic acid in orange juice.
significant effect on ascorbic acid in apple juice, but significantly reduced the levels in orange juice (Figure 7c and 7d). Autoclaving the samples destroyed all ascorbic acids in apple juice and most ascorbic acids in orange juice. It appears that the thermally induced furan was correlated with destruction of ascorbic acid. Treating apple juice samples in boiling water for 5 min resulted in no significant loss in ascorbic acid and little furan formation, whereas the same treatment destroyed some of the ascorbic acid and induced furan formation in orange juice. Similarly, while all or most of the ascorbic acid was destroyed by autoclave, much more furan was formed in both apple juice and orange juice.

It has been shown that thermal treatment of ascorbic acid resulted in the formation of furan (Maga 1979; Locas and Ylayan 2004). At 100 °C, furan was generated only from ascorbic acid, and little was from simple carbohydrates (Fan 2005). At 121 °C, more furans were generated from carbohydrates in apple juice even though more ascorbic acids were destroyed in orange juice. The concentrations of ascorbic acid were much higher in orange juice than in apple juice, and treating juice at 100 °C destroyed much more ascorbic acids in orange juice than in apple juice. Therefore, the higher amount of furan in orange juice than in apple juice at 100 °C is probably due to the destruction of ascorbic acid. The high amount of antioxidants in orange juice may prevent excessive production of furan in orange juice, which may be the case when juice was autoclaved.

Treating both orange and apple juices by submerging samples at 70 °C water for 5 min produced no detectable furan (data not shown). The USFDA (USFDA 2004a) survey found that apple juice as baby food contained furan levels ranging from 2.5 to 8.4 ng/mL, whereas other shelf-stable apple juices had furan levels from less than 2.0 ng/mL to 3.4 ng/mL. The high furan levels found in some of the thermally processed juices in the USFDA survey are likely due to temperature abuse and/or prolonged thermal treatment.

Both thermal treatment and irradiation induced the formation of furan. The predicted amount of furan induced by 3.5 kGy gamma radiation in orange juice is similar to the level found in the samples that were submerged in boiling water for 5 min. A dose of 3.5 kGy radiation was sufficient to inactivate 99.999% of all common foodborne pathogens in fruit juices (Niemira and others 2001; Fan and others 2004). The highest furan levels found in irradiated juices were 10 ng/mL or less, even at the high radiation dose (10 kGy), levels lower than those found in autoclaved juice. The comprehensive study performed by the USFDA (2004a) suggested that some thermally processed juices found in supermarkets had furan levels up to 8 ng/mL. Therefore, the levels of furan induced by irradiation used for the purpose of pathogen inactivation were lower or comparable to those found in some of thermally processed juices. Our results show that furan is induced by irradiation in both orange and apple juices; the source(s) of furan is, however, unknown. It is known that thermally induced furan can be formed from carbohydrates and ascorbic acid (Maga 1979), which are the major components of fruit juices. It will be interesting to see whether irradiation-induced furan formation follows the same mechanisms. The mechanisms for furan formation may be different in thermally treated and irradiated samples, and techniques may be applied for mitigating furan in irradiated samples.

In the present study, we developed an SPME-based method, using a simpler extraction technique compared with the USFDA’s static headspace method (USFDA 2004c). The estimated limit of detection was 0.5 ng/mL using the present method, a level lower than the 2.0 ng/mL in the USEFDA method for fruit juices.

Our results demonstrated that irradiation can induce formation of furan in juice. On the other hand, irradiation also degrades furan. Therefore, the levels of furan in irradiated samples will be determined by the 2 simultaneous mechanisms. Both degradation and formation of furan were lower in orange juice than in apple juice. The low amounts of furan in orange juice may be due to the inhibitory effect of antioxidants or other compounds. Identification of these compounds may aid in the development of techniques or additives to reduce the formation of furan in foods.

Conclusions

Using an SPME-based method for analysis of furan in liquid foods, we found that ionizing radiation induced formation of furan in apple juice and orange juice. Also, the irradiation-induced furan levels were higher in apple juice than in orange juice. The furan levels in irradiated juice continued to increase during postirradiation storage at 4 °C. Interestingly, Δ4-furan spiked into apple juice and orange juice was degraded by irradiation. As expected, furan was induced by thermal processing. The levels of furan in orange juice that were submerged in boiling water for 5 min were similar to those irradiated at 3.5 kGy.

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