JARQ 32, 293–299 (1998)

Decontamination of Dry Food Ingredients with "Soft-Electrons" (Low-Energy Electrons)

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Abstract

Electrons with energies of 300 keV or lower were defined as "soft-electrons". Soft-electrons eradicated microorganisms residing on the surface of grains, pulses, spices and dehydrated vegetables, and reduced their microbial loads to levels lower than 10 CFU/g. Soft-electrons penetrated only into the surface of grains and did not significantly degrade starch molecules inside grains. The use of electrons with a higher energy and with a higher penetration capacity resulted in a higher thiobarbituric acid value (TBA, parameter for lipid oxidation) of brown rice. Milling of rice at a yield of 90% or 88% after exposure to electrons resulted in a TBA value of rice treated with electrons at 65 keV almost the same as that of untreated rice, indication that the milling process removed the portion of brown rice exposed to soft-electrons. It is concluded that soft-electrons can decontaminate dry food ingredients with few adverse effects on the quality.

Discipline: Food
Additional key words: grains, pulses, spices, dehydrated vegetables

Introduction

Grains, pulses, spices and dehydrated vegetables are frequently contaminated with microorganisms, especially heat-resistant bacterial spores, although they are widely used for food processing. Bacterial spores contaminating these dry food ingredients can not be inactivated completely by heating processes such as steaming and boiling at food processing plants. Thus dry ingredients for food processing should be decontaminated to prevent food spoilage and food-borne diseases. Decontamination techniques including fumigation with ethylene oxide gas (EOG), irradiation with ionizing radiation and treatment with super-heated steam are applied to some of the dry food ingredients. However, these techniques are associated with some drawbacks. EOG fumigation is prohibited in Japan, because of the carcinogenic effect of the residues. Irradiation with gamma-rays or electron beams can effectively inactivate bacterial spores contaminating spices and dehydrated vegetables with minimal quality alteration, and irradiation of spices is practiced on a commercial basis in more than 20 countries[12)]. However, irradiation of food products other than potato is not approved in Japan. Irradiation at high doses for decontamination is not applicable to grains such as rice and wheat. Ionizing radiation causes oxidation and degradation of components such as lipid and starch molecules[1,11,12)], which results in quality deterioration of grain products such as noodles and rice cake in terms of flavor and texture. Treatment with super-heated steam is the only method widely used for decontaminating dry ingredients in Japan. However, super-heated steam sometimes brings about changes of flavor and color of dehydrated vegetables and herbs. No method has been developed for decontaminating all the dry food ingredients.

It is generally recognized that since most of the microorganisms contaminating dry food ingredients reside on their surfaces, the inner parts do not have to be exposed to heat, gas or radiation for decontamination. The penetration capacity of an electron beam is controlled by the energy; electrons with lower energies display lower penetration capacities[2)]. We have defined low-energy electrons at 300 keV or lower as "soft-electrons". Soft-electrons reach only the

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surface of food, and the quality changes of food caused by such electrons are expected to be much more limited than those caused by gamma-rays or high-energy electron beams with much higher penetration capacities. We carried out studies on the efficacy of soft-electron treatment to decontaminate dry food ingredients.

Equipment for soft-electron treatment

Dry ingredient samples were treated with soft-electrons under rotation to expose all the sample surfaces to electrons with low penetration capacity. A grain rotator was developed which enabled samples to rotate by shaking and vibrating them simultaneously at variable speeds (Fig. 1). The rotator was placed under the window of a Van de Graaff electron accelerator (Nissin High Voltage Engineering Co., Ltd., Kyoto, Japan), which generated electrons at acceleration voltages of 170–300 kV. The distance between the window of the electron accelerator and the plastic tray of the grain rotator was 17 cm.

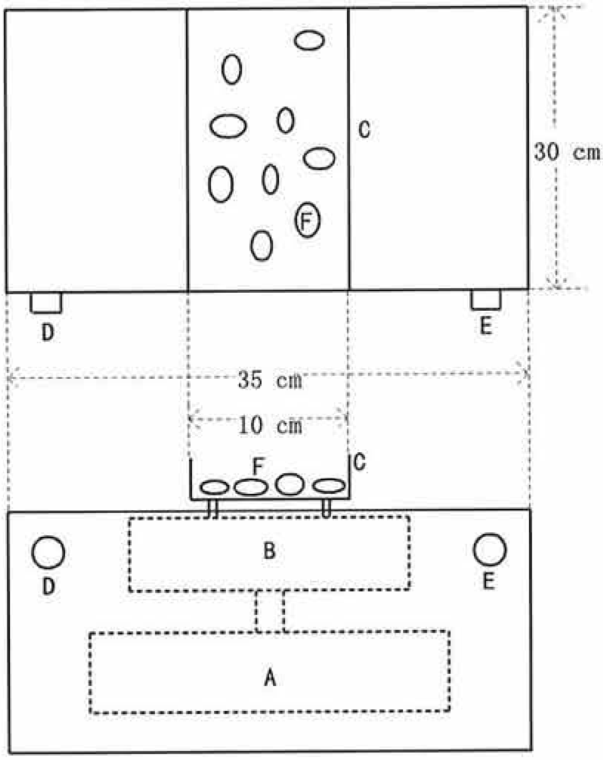

Fig. 1. Grain rotator for treating grains with low-energy electrons
A; Shaker, B; Vibrator, C; Plastic tray, D; Speed controller for shaker, E; Speed controller for vibrator, F; Grain.

Penetration capacity of soft-electrons

Penetration capacities of soft-electrons at different energies were determined based on depth-dose curves. Several pieces of radiochromic film dosimeter (RCF) (5.94 mg/cm^2, FWT-60-00, Far West Technology Inc., Goleta, California, USA) were stacked together in layers at the bottom of the plastic tray of the grain rotator (C of Fig. 1) which was placed under the window of the electron accelerator at a distance of 17 cm, and irradiated with electrons for 60 min under various conditions (170 kV, 4 μA; 180 kV, 8 μA; 190 kV, 10 μA; 200 kV, 14 μA). Absorbances at 510 nm of all RCF films before and 30 min after irradiation were measured and the dose absorbed by each RCF film was determined according to the method of McLaughlin et al.[8].

Energies of electrons at a distance of 17 cm (air) from the window (50 μm thick titanium) of the electron accelerator were lower than those of the electrons at the window (acceleration voltage). The energies of electrons irradiating samples at 17 cm from the window were estimated to be 60, 75, 90, 100, 130, 160 and 210 keV for acceleration voltages of 170, 180, 190, 200, 225, 250 and 300 kV, respectively, based on the mass stopping power of air and titanium[7,10].

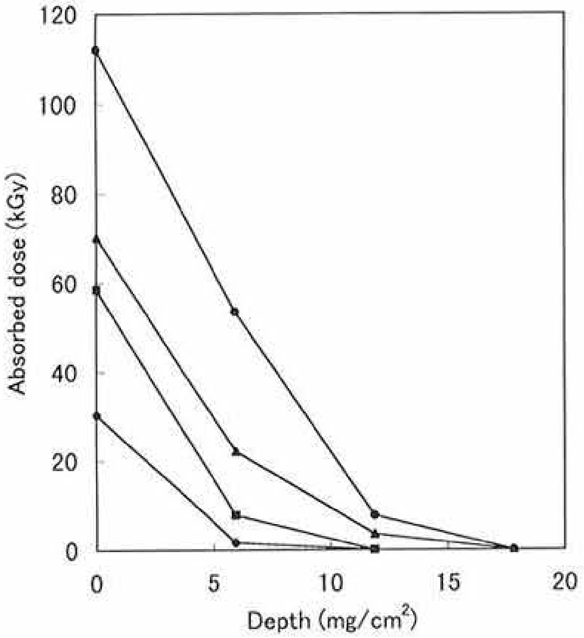

Fig. 2. Depth-dose curves of electrons determined with radiochromic film dosimeter (RCF)
◆; 60 keV, 4 μA, ■; 75 keV, 8 μA, ▲; 90 keV, 10 μA, ●; 100 keV, 14 μA.

Table 1. Sterility of grains exposed to low-energy electrons or gamma-rays (CFU/g)

	Brown rice	Rough rice	Wheat	Buckwheat
Control[a)]	$4.1 \times 10^6 \pm 4.6 \times 10^5$	$4.7 \times 10^7 \pm 1.5 \times 10^7$	$2.7 \times 10^4 \pm 1.2 \times 10^4$	$1.4 \times 10^6 \pm 6.8 \times 10^5$
75 keV, 8 μA, 10 min	$5.1 \times 10^2 \pm 2.1 \times 10^2$	-------- [b)]	$1.2 \times 10^3 \pm 8.3 \times 10^2$	--------
75 keV, 8 μA, 20 min	< 100	--------	$2.3 \times 10^2 \pm 1.6 \times 10^2$	--------
75 keV, 8 μA, 30 min	< 10	--------	< 100	--------
75 keV, 8 μA, 40 min	< 10	--------	< 10	--------
100 keV, 14 μA, 5 min	$1.2 \times 10^3 \pm 5.6 \times 10^2$	$5.8 \times 10^5 \pm 7.0 \times 10^4$	$3.1 \times 10^2 \pm 2.1 \times 10^2$	$1.4 \times 10^3 \pm 9.2 \times 10^2$
100 keV, 14 μA, 10 min	$7.5 \times 10^2 \pm 1.3 \times 10^2$	$1.8 \times 10^5 \pm 1.0 \times 10^5$	$1.1 \times 10^2 \pm 9.1 \times 10^1$	$3.7 \times 10^2 \pm 1.7 \times 10^2$
100 keV, 14 μA, 15 min	< 10	$9.6 \times 10^3 \pm 3.1 \times 10^3$	< 10	$4.4 \times 10^2 \pm 3.8 \times 10^2$
100 keV, 14 μA, 20 min	< 10	$6.3 \times 10^3 \pm 1.3 \times 10^3$	< 10	$3.3 \times 10^2 \pm 3.6 \times 10^2$
130 keV, 22 μA, 1 min	$2.5 \times 10^3 \pm 1.6 \times 10^3$	$1.6 \times 10^5 \pm 3.8 \times 10^4$	$2.9 \times 10^3 \pm 1.8 \times 10^3$	$1.8 \times 10^3 \pm 9.0 \times 10^2$
130 keV, 22 μA, 2 min	$1.5 \times 10^2 \pm 1.3 \times 10^2$	$5.3 \times 10^4 \pm 2.1 \times 10^4$	$5.9 \times 10^2 \pm 2.8 \times 10^2$	< 100
130 keV, 22 μA, 4 min	< 10	$1.0 \times 10^4 \pm 6.6 \times 10^3$	< 10	< 10
130 keV, 22 μA, 6 min	< 10	< 100	< 10	< 10
160 keV, 40 μA, 0.5 min	$7.4 \times 10^2 \pm 1.8 \times 10^2$	$1.3 \times 10^5 \pm 4.5 \times 10^4$	$2.0 \times 10^3 \pm 8.9 \times 10^2$	$9.7 \times 10^2 \pm 8.0 \times 10^2$
160 keV, 40 μA, 1 min	$1.3 \times 10^2 \pm 1.1 \times 10^2$	$5.7 \times 10^3 \pm 2.8 \times 10^3$	$4.3 \times 10^2 \pm 1.1 \times 10^2$	$1.3 \times 10^2 \pm 1.6 \times 10^2$
160 keV, 40 μA, 2 min	< 10	$2.2 \times 10^2 \pm 2.0 \times 10^2$	< 10	< 10
160 keV, 40 μA, 3 min	< 10	< 10	< 10	< 10
210 keV, 40 μA, 0.5 min	$1.4 \times 10^3 \pm 7.1 \times 10^2$	$1.3 \times 10^5 \pm 3.5 \times 10^4$	$1.7 \times 10^3 \pm 1.3 \times 10^2$	$6.7 \times 10^2 \pm 2.6 \times 10^2$
210 keV, 40 μA, 1 min	< 100	$8.0 \times 10^2 \pm 4.4 \times 10^2$	$4.5 \times 10^2 \pm 2.8 \times 10^2$	< 100
210 keV, 40 μA, 2 min	< 10	< 10	< 10	< 10
210 keV, 40 μA, 3 min	< 10	< 10	< 10	< 10
γ-ray, 2.5 kGy	$2.2 \times 10^4 \pm 3.6 \times 10^3$	$3.2 \times 10^5 \pm 4.2 \times 10^4$	$2.5 \times 10^4 \pm 4.7 \times 10^3$	$2.0 \times 10^3 \pm 2.1 \times 10^3$
γ-ray, 5.0 kGy	$3.3 \times 10^3 \pm 1.6 \times 10^3$	$8.4 \times 10^4 \pm 3.8 \times 10^4$	$4.6 \times 10^3 \pm 1.4 \times 10^3$	< 100
γ-ray, 7.5 kGy	$5.8 \times 10^2 \pm 1.9 \times 10^2$	$7.4 \times 10^3 \times 3.2 \times 10^3$	$7.5 \times 10^2 \pm 6.3 \times 10^1$	< 10
γ-ray, 10.0 kGy	< 10	$6.3 \times 10^2 \pm 3.2 \times 10^2$	< 10	< 10
γ-ray, 12.5 kGy	< 10	< 100	< 10	< 10

a): Untreated sample. b): Data not obtained. Source: Hayashi et al. (1997)[5)].

Table 2. Viscosity of 7.5% aqueous suspensions of grains exposed to low-energy electrons or gamma-rays (mPa.s)

	Brown rice	Rough rice	Wheat	Buckwheat
Control[d)]	211.1 ± 12.5[c)]	149.5 ± 7.7[c)]	287.4 ± 18.2[b,c)]	211.3 ± 21.6[c)]
75 keV, 8 μA, 40 min	206.0 ± 3.5[c)]	----- [e)]	293.6 ± 12.5[b,c)]	-----
100 keV, 14 μA, 20 min	185.9 ± 8.6[a,c)]	147.3 ± 8.9[c)]	246.6 ± 10.8[a,c)]	199.9 ± 25.4[c)]
130 keV, 22 μA, 6 min	146.7 ± 11.9[a,b)]	137.3 ± 7.3[c)]	206.4 ± 3.5[a,b)]	192.5 ± 6.4[c)]
160 keV, 40 μA, 3 min	136.2 ± 4.6[a,b,c)]	133.4 ± 4.8[a,c)]	192.8 ± 8.0[a,b,c)]	165.6 ± 7.5[a,b,c)]
210 keV, 40 μA, 3 min	88.5 ± 3.0[a,b,c)]	105.5 ± 6.8[a,b)]	133.6 ± 3.6[a,b,c)]	108.7 ± 10.9[a,b,c)]
γ-ray, 0.1 kGy	198.4 ± 4.1[c)]	138.3 ± 5.6[c)]	246.5 ± 3.4[a,c)]	189.6 ± 12.2[c)]
γ-ray, 0.5 kGy	160.8 ± 8.3[a,b)]	117.9 ± 5.5[a,b)]	211.3 ± 4.7[a,b)]	143.2 ± 8.3[a,b)]
γ-ray, 10.0 kGy	21.1 ± 1.0[a,b,c)]	31.9 ± 4.9[a,b,c)]	34.6 ± 1.7[a,b,c)]	26.8 ± 4.6[a,b,c)]

a): Significantly different from control ($P < 0.05$).
b): Significantly different from samples irradiated at 0.1 kGy with gamma-rays ($P < 0.05$).
c): Significantly different from samples irradiated at 0.5 kGy with gamma-rays ($P < 0.05$).
d): Untreated sample. e): Data not obtained.
Source: Hayashi et al. (1997)[5)].

Depth-dose curves of electrons at various energies were developed by plotting all the absorbed doses determined with RCF films (Fig. 2)[6)]. The penetration capacity of electrons at 60 keV was about 6 mg/cm^2 and that at 75 keV was about 10 mg/cm^2, while those at 90 and 100 keV were lower than 17.82 mg/cm^2 (5.94 mg/cm^2 × 3 pieces). Doses absorbed by the first RCF film for 1 h were about 30, 58, 70 and 110 kGy at 60, 75, 90 and 100 keV, respectively (Fig. 2)[6)].

Sterility and viscosity of grains exposed to soft-electrons

Energies of electrons necessary to reduce microorganism levels to less than 10 CFU/g were 75 keV for brown rice, 130 keV for rough rice, 75 keV for wheat and 160 keV for buckwheat (Table 1)[5]. The results suggested that most of the contaminating microorganisms resided in the region that the electrons with such low energies could reach. Gamma-rays at 7.5 – 12.5 kGy were necessary to achieve the same levels of sterility.

Viscosity of heat-gelatinized grain suspensions decreased with the energy of electrons (Table 2)[5]. Viscosity of brown rice and wheat treated with electrons at 75 keV was almost the same as that of untreated samples. Viscosity of rough rice and buckwheat exposed to electrons at 130 keV was slightly lower than that of untreated samples, but much higher than that of the samples irradiated with gamma-rays at 10 kGy. The viscosity values of a grain suspension which was heat-gelatinized under an alkaline condition is a parameter for starch degradation[3,4]. The results suggested that electrons with minimum energy for decontamination did not degrade starch molecules inside the grains.

The applicability of soft-electrons to wheat depended upon the variety of wheat. Soft-electrons could decontaminate wheat grains of Australian Standard White (ASW), Shirogane and Western White (WW) varieties, but could not decontaminate those of Dark Northern Spring (DNS), Norin No. 61 and No. 1 Canadian White (1CW) varieties (Table 3). No relationship was observed between the application of soft-electrons and the sensitivity of the contaminating microorganisms to gamma-rays. The difference in the application of soft-electrons was ascribed to the structure of the wheat grain. In varieties such as DNS, Norin No. 61 and 1CW, microorganisms would reside in areas which soft-electrons did not reach.

Quality of milled rice prepared from brown rice treated with soft-electrons

Both Koshihikari and Nihonbare could be decontaminated with soft-electrons even at 60 keV[6]. No significant difference in the viscosity was observed at any milling yield between the control and the rice grains exposed to electrons at 60 – 90 keV. Milling reduced the effect of electrons on the viscosity;

Table 3. Sterility of various wheat samples exposed to low-energy electrons or gamma-rays (CFU/g)

	ASW	Shirogane	DNS	Norin No. 61	WW	1CW
Control[a)]	$2.7\times10^4\pm1.2\times10^4$	$3.5\times10^4\pm1.5\times10^4$	$3.3\times10^5\pm3.7\times10^5$	$9.0\times10^4\pm5.1\times10^4$	$6.0\times10^4\pm2.1\times10^4$	$2.8\times10^5\pm1.1\times10^5$
75 keV, 4 μA, 45 min	<10	<10	$2.2\times10^4\pm8.9\times10^3$	$3.0\times10^3\pm1.8\times10^3$	<10	$1.8\times10^4\pm7.3\times10^3$
75 keV, 4 μA, 90 min	<10	<10	$3.6\times10^4\pm1.7\times10^4$	$2.1\times10^3\pm1.1\times10^3$	<10	$2.1\times10^4\pm8.9\times10^3$
100 keV, 14 μA, 15 min	<10	<10	$1.8\times10^4\pm1.7\times10^4$	$3.6\times10^3\pm1.2\times10^2$	<10	$2.2\times10^4\pm5.4\times10^3$
100 keV, 14 μA, 30 min	<10	<10	$2.7\times10^4\pm1.4\times10^4$	$9.1\times10^2\pm7.7\times10^2$	<10	$1.7\times10^4\pm7.9\times10^3$
210 keV, 40 μA, 2 min	<10	<10	$1.4\times10^4\pm1.1\times10^4$	$6.5\times10^3\pm8.0\times10^2$	<10	$2.3\times10^4\pm1.3\times10^4$
210 keV, 40 μA, 4 min	<10	<10	$1.4\times10^4\pm1.1\times10^4$	$3.8\times10^3\pm1.7\times10^3$	<10	$1.9\times10^4\pm9.5\times10^3$
400 keV, 40 μA, 2 min	<10	<10	<10	<10	<10	<10
γ-ray, 2.5 kGy	$2.5\times10^4\pm4.7\times10^3$	$3.2\times10^3\pm7.0\times10^2$	$2.8\times10^4\pm7.7\times10^3$	$7.3\times10^2\pm2.3\times10^2$	$3.9\times10^3\pm5.4\times10^2$	$5.2\times10^2\pm9.2\times10^1$
γ-ray, 5.0 kGy	$4.6\times10^3\pm1.4\times10^3$	$1.3\times10^2\pm5.7\times10^1$	$1.2\times10^4\pm3.3\times10^3$	<100	$1.3\times10^2\pm4.5\times10^1$	<100
γ-ray, 7.5 kGy	$7.5\times10^2\pm6.3\times10^1$	<100	$6.5\times10^2\pm3.2\times10^2$	<10	<100	<10
γ-ray, 10.0 kGy	<10	<10	<10	<10	<10	<10

a): Untreated sample.

milling of rice grains at a yield of 88% did not result in a significant difference in the viscosity between untreated samples and 100 keV-electron treated samples[6]. However, milling did not affect the viscosity of rice irradiated with gamma-rays. The results suggested that soft-electrons degraded starch molecules near the surface of rice grains, which could be removed easily by milling. On the contrary, gamma-rays degraded all the starch molecules in rice grains most of which could not be removed by milling[6].

Thiobarbituric acid (TBA) value is a parameter of lipid oxidation. TBA value of brown rice increased with the energy of electrons. TBA values of brown rice samples exposed to electrons at 60–100 keV were significantly higher than that of untreated control (Table 4)[6]. The use of gamma-rays at 7.5 kGy resulted in a higher TBA value than that of electrons with energies of 60–100 keV. Milling decreased the TBA values of all the samples, especially those of electron-treated samples. Accordingly, the differences in the TBA values between the control and the electron-treated rice grains decreased markedly after milling. The difference in the TBA values between the control and the rice samples exposed to electrons at 60 keV was not significant at a milling yield of 90% or lower, and the difference between the values of the control and the rice samples exposed to electrons at 75 keV was not significant at a milling yield of 88%. The results suggested that most of the lipids oxidized by electrons at 60 and 75 keV were removed by milling at yields of 90 and 88%, respectively.

Hardness and stickiness under low and high compressions of cooked rice grains (90% milling yield) exposed to electrons at 60–75 keV were almost the same as those of the control (Table 5)[6]. Hardness and stickiness under low and high compressions of gamma-irradiated samples were lower than those of the control. Hardness and stickiness under low compression are parameters for rheological properties of the surface of cooked rice grains, and those under high compression are parameters for the properties of overall cooked rice grains[9]. The results showed that rice grains which were exposed to electrons at 60–75 keV and milled at a yield of 90% displayed the same rheological properties as the control. The results shown in Tables 4 and 5 indicate that milling at yields of 88–90% removed the portion of rice

Table 4. TBA values of rice exposed to low-energy electrons or gamma-rays followed by milling (nmol/g of rice)

	Milling yield			
	100%[b]	92%[b]	90%[b]	88%[b]
Control[a]	17.69 ± 1.55	4.95 ± 0.38	4.75 ± 0.69	4.23 ± 0.81
60 keV, 4 μA, 45 min	29.68 ± 2.66[c]	7.98 ± 0.20[c]	5.18 ± 0.70	4.75 ± 0.57
75 keV, 8 μA, 30 min	34.21 ± 0.49[c]	9.05 ± 0.83[c]	8.37 ± 0.80[c]	5.43 ± 0.77
90 keV, 10 μA, 25 min	41.45 ± 0.90[c]	15.55 ± 3.96[c]	9.47 ± 0.71[c]	9.43 ± 0.93[c]
100 keV, 14 μA, 15 min	57.66 ± 2.47[c]	19.74 ± 0.67[c]	14.33 ± 0.28[c]	13.70 ± 0.74[c]
γ-ray, 7.5 kGy	60.59 ± 5.64[c]	46.59 ± 3.96[c]	43.83 ± 3.08[c]	43.23 ± 4.70[c]

a): Untreated sample. b): n = 3; mean ± standard deviation. c): Significantly different from control ($P<0.05$).
Source: Hayashi et al. (1998)[6].

Table 5. Physical properties of cooked rice grain[a]

	Low compression		High compression	
	Hardness[c] (10^4 dyne)	Stickiness[c] (10^4 dyne)	Hardness[c] (10^6 dyne)	Stickiness[c] (10^5 dyne)
Control[b]	7.02 ± 0.57	2.13 ± 0.28	2.03 ± 0.25	4.88 ± 0.49
60 keV, 4 μA, 45 min	6.94 ± 0.48	1.94 ± 0.23	1.99 ± 0.33	5.03 ± 0.41
75 keV, 8 μA, 30 min	7.08 ± 0.56	2.09 ± 0.28	1.99 ± 0.21	4.83 ± 0.38
90 keV, 10 μA, 25 min	6.74 ± 0.44	1.64 ± 0.29[d]	1.71 ± 0.18	4.76 ± 0.72
100 keV, 14 μA, 15 min	6.57 ± 0.51	1.59 ± 0.19[d]	1.52 ± 0.13[d]	4.81 ± 0.48
γ-ray, 7.5 kGy	4.89 ± 0.89[d]	0.77 ± 0.17[d]	1.06 ± 0.14[d]	4.46 ± 0.45

a): Rice samples were exposed to electrons or gamma-rays followed by milling at 90% yield, and then cooked.
b): Untreated sample. c): n = 3; mean ± standard deviation. d): Significantly different from control ($P<0.05$).
Source: Hayashi et al. (1998)[6].

Table 6. Sterility of dehydrated vegetables exposed to low-energy electrons (CFU/g)

	Orange peel	Green laver	Parsley	Leek	Onion	Burdock	Carrot	Mushroom
Control	$4.8 \times 10^5 \pm 2.6 \times 10^5$	$1.6 \times 10^7 \pm 2.5 \times 10^6$	$2.7 \times 10^4 \pm 1.1 \times 10^4$	$9.0 \times 10^4 \pm 5.1 \times 10^4$	$1.2 \times 10^3 \pm 6.4 \times 10^2$	$9.0 \times 10^3 \pm 1.4 \times 10^3$	$8.7 \times 10^4 \pm 4.5 \times 10^4$	$2.4 \times 10^5 \pm 7.6 \times 10^4$
200 keV, 15 min	$2.8 \times 10^4 \pm 3.1 \times 10^3$	$7.3 \times 10^6 \pm 2.9 \times 10^6$	<100	$5.0 \times 10^2 \pm 2.8 \times 10^1$	<100	<100	$1.2 \times 10^2 \pm 8.2 \times 10^1$	$2.5 \times 10^2 \pm 5.7 \times 10^1$
200 keV, 30 min	$1.4 \times 10^3 \pm 9.1 \times 10^2$	$3.3 \times 10^5 \pm 1.2 \times 10^5$	<10	<10	<10	<10	<100	<100
200 keV, 45 min	<100	$1.3 \times 10^5 \pm 2.3 \times 10^4$	<10	<10	<10	<10	<10	<10
200 keV, 60 min	<10	$2.8 \times 10^4 \pm 1.1 \times 10^4$	<10	<10	<10	<10	<10	<10
200 keV, 90 min	<10	$1.5 \times 10^3 \pm 1.2 \times 10^3$	<10	<10	<10	<10	<10	<10
200 keV, 120 min	<10	<100	<10	<10	<10	<10	<10	<10
200 keV, 150 min	<10	<10	<10	<10	<10	<10	<10	<10
γ-ray, 2.5 kGy	$1.9 \times 10^4 \pm 9.0 \times 10^3$	$3.3 \times 10^6 \pm 1.6 \times 10^6$	$1.2 \times 10^3 \pm 2.6 \times 10^2$	$4.3 \times 10^2 \pm 9.6 \times 10^1$	<100	$1.4 \times 10^3 \pm 2.8 \times 10^2$	$1.0 \times 10^3 \pm 2.2 \times 10^2$	$1.8 \times 10^2 \pm 6.1 \times 10^1$
γ-ray, 5.0 kGy	$1.3 \times 10^3 \pm 9.7 \times 10^2$	$1.1 \times 10^6 \pm 4.4 \times 10^5$	<100	$1.1 \times 10^2 \pm 6.2 \times 10^1$	<10	<100	$1.8 \times 10^2 \pm 5.1 \times 10^1$	<10
γ-ray, 7.5 kGy	<100	$3.4 \times 10^5 \pm 1.9 \times 10^5$	<10	<10	<10	<10	<10	<10
γ-ray, 10.0 kGy	<10	$1.1 \times 10^5 \pm 4.9 \times 10^4$	<10	<10	<10	<10	<10	<10
γ-ray, 20.0 kGy	<10	$9.0 \times 10^3 \pm 2.0 \times 10^3$	<10	<10	<10	<10	<10	<10
γ-ray, 30.0 kGy	<10	<100	<10	<10	<10	<10	<10	<10

exposed to electrons at 60 keV which could eradicate most of the microorganisms contaminating brown rice.

Decontamination of other ingredients

Soft-electrons at 100 keV reduced the microbial loads of shredded dehydrated vegetables to levels lower than 10 CFU/g, although the time necessary for electron treatment was different (Table 6). Longer duration of electron treatment was necessary for dehydrated vegetable samples which required a higher dose of gamma-rays for disinfection. The microorganisms contaminating dehydrated vegetables showed the same resistance to soft-electrons as to gamma-rays. Black pepper could be decontaminated with electrons at 210 keV, while white pepper, basil and coriander could be decontaminated at 100 keV. Pulses such as soybean, adzuki bean and black soybean could be decontaminated with electrons at 60 keV.

Conclusion

Soft-electrons can decontaminate dry food ingredients such as grains, dehydrated vegetables, spices and pulses with minimal quality deterioration. The portion of grains exposed to electrons is removed as husk and bran by dehusking and/or milling. Therefore chemical compounds formed by electron exposure are removed by dehusking or milling and no such compounds occur in the edible parts of grains.

Electrons with such low energies do not require a thick shield due to their low penetration capacity, which enables in-line decontamination at food processing plants. Facility to expose all the ingredient surfaces uniformly to soft-electrons on a large scale in a short period of time should be developed to industrialize this decontamination technique.

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(Received for publication, February 3, 1998)