Review

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

Toru HAYASHI

National Food Research Institute, Ministry of Agriculture, Forestry and Fisheries, Kannondai, Tsukuba, Ibaraki 305-8642, Japan

Received January 16, 1998; Accepted February 10, 1998

Electrons with energies of 300 keV or lower (soft-electrons) reduced microbial loads of grains, pulses, spices, dehydrated vegetables and seeds to levels lower than 10 CFU/g. The viscosity of gelatinized grain powder suspension (parameter for starch degradation) showed no significant difference between untreated grains and soft-electron treated ones, which indicated that soft-electrons did not significantly degrade the starch molecules of grains. Electrons with a higher energy with a higher penetration capacity resulted in a higher thiobarbituric acid value (TBA, parameter for lipid oxidation) of brown rice. Milling rice at a yield of 90% or 88% after electron treatment made the TBA of rice treated with electrons at 65 keV almost the same as that of untreated rice. The results indicated that the milling process removed the portion of brown rice exposed to soft-electrons. Seeds which were exposed to soft-electrons showed the same sprouting capacity as untreated seeds. Soft-electrons could eradicate microorganisms on the surface of dry food ingredients and seeds with little adverse effects on quality and sprouting capacity.

Keywords: grain, pulse, spice, dehydrated vegetable, seed, decontamination, electron

Dry food ingredients such as grains, pulses, spices and dehydrated vegetables are frequently contaminated with heat-resistant bacterial spores. Heating processes such as steaming and boiling on a large scale at food processing plants do not inactivate all the microorganisms, especially bacterial spores, because of the uneven temperature inside the heating vessels. Thus, dry ingredients for food processing should be decontaminated to prevent food spoilage and food-borne diseases. Fumigation with ethylene oxide, irradiation with ionizing radiation and treatment with super-heated steam are applicable to the decontamination of such dry food ingredients. However, fumigation with ethylene oxide gas is prohibited in Japan. Irradiation with ionizing radiation can effectively decontaminate spices and dehydrated vegetables and is widely used for their decontamination in various countries (WHO, 1994). However, irradiation of food other than potato is not approved in Japan. Irradiation at high doses for decontamination cannot be applied to grains such as rice and wheat, because ionizing radiation causes oxidation and degradation of components such as lipid and starch molecules (Diehl, 1990; Urbain, 1986; WHO, 1994). In Japan, treatment with super-heated steam is the only method widely used for decontaminating dry ingredients. However, super-heated steam sometimes brings about changes in flavor and color. The food industry is interested in the development of new methods to decontaminate dry food ingredients.

Most microorganisms contaminating dry food ingredients reside on their surfaces, so their inner parts do not need to be exposed to heat, gas or radiation in the decontamination

process. The penetration capacity of an electron beam is dependent upon the energy; the penetration capacity of electrons decreases with decreasing energy (Hayashi, 1991). We have defined low-energy electrons at 300 keV or lower as "soft-electrons." It is expected that soft-electrons penetrate only the surface of food (Fig. 1) and that the changes in quality of the food caused by such electrons are much smaller than those caused by gamma-rays or high-energy electrons with much higher penetration capacities, if the size of the food sample is much larger than the penetration depth of soft-electrons. We will review the results of our studies on the efficacy of soft-electron treatment as a means of decontaminating dry food ingredients.

Equipment for soft-electron treatment

Dry ingredient samples were treated with soft-electrons while under rotation to expose all the sample surfaces to electrons with low-penetration capacities. A grain rotator was developed which enabled the samples to rotate by simultaneously shaking and vibrating them at variable speeds (Fig. 2). The rotator was placed under the window of a Van de Graaff electron accelerator (Nissin High Voltage Engineering Co., Ltd., Kyoto), which generated electrons at acceleration voltages of 170-300 kV. The distance between the window of the electron accelerator and the grain rotator was 17 cm.

Penetration capacity of soft-electrons

Several pieces of radiochromic film dosimeter (RCF) (5.94 mg/cm², FWT-60-00, Far West Technology Inc., Goleta,

Fig. 1. Penetration of soft-electron.

Fig. 2. 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.

California, USA) were stacked together in layers on the bottom of the plastic tray of the grain rotator (C of Fig. 2), 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 mA; 180 kV, 8 mA; 190 kV, 10 mA; 200 kV, 14 mA). 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 McLaughlin *et al.* (1979).

The energies of the electrons at a distance of 17 cm from the window (50 mm 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 powers of air and titanium (ICRU, 1984; Tabata & Tanaka, 1990).

Depth-dose curves of electrons at various energies were

Fig. 3. Depth-dose curves of electrons determined with radiochromic film dosimeter (RCF).

developed by plotting all absorbed doses determined with RCF films (Fig. 3). The penetration depth of electrons increased with electron energy; the electrons at 60 and 75 keV did not penetrate more than 2 films, and those at 90 and 100 keV did not penetrate more than 3 films. The results indicated that the penetration capacities of electrons at 60 and 75 keV were lower than 11.88 mg/cm² (5.94 mg/cm² × 2 pieces) and those at 90 and 100 keV were lower than 17.82 mg/cm² (5.94 mg/cm² × 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. 3) (Hayashi *et al.*, 1998).

Sterility and viscosity of grains exposed to soft-electrons

Energies of electrons necessary to reduce microorganisms to levels lower than 10 CFU/g were 75 keV for brown rice, 160 keV for rough rice, 75 keV for wheat and 160 keV for buckwheat (Table 1) (Hayashi *et al.*, 1997). Gamma-rays at 7.5–12.5 kGy were necessary to achieve the same levels of sterility.

The viscosities of grain suspensions decreased with the energy of the electrons (Table 2) (Hayashi *et al.*, 1997). The viscosities of brown rice and wheat treated with electrons at 75 keV were almost the same as those of the untreated samples. Viscosities of rough rice and buckwheat exposed to electrons at 130 keV were slightly lower than those of the untreated samples, but much higher than those 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 (Hayashi *et al.*, 1993; 1996). The results suggested that electrons with minimum energy for decontamination did not degrade starch molecules inside the grains (Hayashi *et al.*, 1997).

The applicability of soft-electrons to wheat was dependent upon the variety of wheat. Soft-electrons could decontaminate wheat grains of varieties of Australian Standard White (ASW), Shirogane and Western White (WW), but could not decontaminate varieties of Dark Northern Spring (DNS), Norin No.61 and No.1 Canadian White (ICW) (Table 3). There was no relationship between the applicability of soft-electrons and the sensitivity to gamma-rays. The differ-

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 μ A, 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 μ A, 20 min	<100	—	$2.3 \times 10^2 \pm 1.6 \times 10^2$	—
75 keV, 8 μ A, 30 min	<10	—	<100	—
75 keV, 8 μ A, 40 min	<10	—	<10	—
100 keV, 14 μ A, 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 μ A, 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 μ A, 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 μ A, 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 μ A, 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 μ A, 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 μ A, 4 min	<10	$1.0 \times 10^4 \pm 6.6 \times 10^3$	<10	<10
130 keV, 22 μ A, 6 min	<10	<100	<10	<10
160 keV, 40 μ A, 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 μ A, 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 μ A, 2 min	<10	$2.2 \times 10^2 \pm 2.0 \times 10^2$	<10	<10
160 keV, 40 μ A, 3 min	<10	<10	<10	<10
210 keV, 40 μ A, 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 μ A, 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 μ A, 2 min	<10	<10	<10	<10
210 keV, 40 μ A, 3 min	<10	<10	<10	<10
Gamma-ray, 2.5 kGy	$2.2 \times 10^4 \pm 3.6 \times 10^3$	$3.2 \times 10^5 \pm 4.2 \times 10^4$	$2.5 \times 10^4 \pm 4.7 \times 10^3$	$2.0 \times 10^3 \pm 1.2 \times 10^3$
Gamma-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
Gamma-ray, 7.5 kGy	$5.8 \times 10^2 \pm 1.9 \times 10^2$	$7.4 \times 10^3 \pm 3.2 \times 10^3$	$7.5 \times 10^2 \pm 6.3 \times 10^1$	<10
Gamma-ray, 10.0 kGy	<10	$6.3 \times 10^2 \pm 3.2 \times 10^2$	<10	<10
Gamma-ray, 12.5 kGy	<10	<100	<10	<10

^{a)}untreated sample.^{b)}data not obtained.Hayashi *et al.*, 1997.**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 ^{a)}	211.1 $\pm$ 12.5 ^{c)}	149.5 $\pm$ 7.7 ^{c)}	287.4 $\pm$ 18.2 ^{bc)}	211.3 $\pm$ 21.6 ^{c)}
75 keV, 8 μ A, 40 min	206.0 $\pm$ 3.5 ^{c)}	— ^{d)}	293.6 $\pm$ 12.5 ^{bc)}	—
100 keV, 14 μ A, 20 min	185.9 $\pm$ 8.6 ^{ac)}	147.3 $\pm$ 8.9 ^{c)}	246.6 $\pm$ 10.8 ^{ac)}	199.9 $\pm$ 25.4 ^{c)}
130 keV, 22 μ A, 6 min	146.7 $\pm$ 11.9 ^{ab)}	137.3 $\pm$ 7.3 ^{c)}	206.4 $\pm$ 3.5 ^{ab)}	192.5 $\pm$ 6.4 ^{c)}
160 keV, 40 μ A, 3 min	136.2 $\pm$ 4.6 ^{abc)}	133.4 $\pm$ 4.8 ^{abc)}	192.8 $\pm$ 8.0 ^{abc)}	165.6 $\pm$ 7.5 ^{abc)}
210 keV, 40 μ A, 3 min	88.5 $\pm$ 3.0 ^{abc)}	105.5 $\pm$ 6.8 ^{ab)}	133.6 $\pm$ 3.6 ^{abc)}	108.7 $\pm$ 10.9 ^{abc)}
Gamma-ray, 0.1 kGy	198.4 $\pm$ 4.1 ^{c)}	138.3 $\pm$ 5.6 ^{c)}	246.5 $\pm$ 3.4 ^{ac)}	189.6 $\pm$ 12.2 ^{c)}
Gamma-ray, 0.5 kGy	160.8 $\pm$ 8.3 ^{ab)}	117.9 $\pm$ 5.5 ^{ab)}	211.3 $\pm$ 4.7 ^{ab)}	143.2 $\pm$ 8.3 ^{ab)}
Gamma-ray, 10.0 kGy	21.1 $\pm$ 1.0 ^{abc)}	31.9 $\pm$ 4.9 ^{abc)}	34.6 $\pm$ 1.7 ^{abc)}	26.8 $\pm$ 4.6 ^{abc)}

^{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.Hayashi *et al.*, 1997.**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)}	$2.7 \times 10^4 \pm 1.2 \times 10^4$	$3.5 \times 10^4 \pm 1.5 \times 10^4$	$3.3 \times 10^5 \pm 3.7 \times 10^5$	$9.0 \times 10^4 \pm 5.1 \times 10^4$	$6.0 \times 10^4 \pm 2.1 \times 10^4$	$2.8 \times 10^5 \pm 1.1 \times 10^5$
75 keV, 4 μ A, 45 min	<10	<10	$2.2 \times 10^4 \pm 8.9 \times 10^3$	$3.0 \times 10^3 \pm 1.8 \times 10^3$	<10	$1.8 \times 10^4 \pm 7.3 \times 10^3$
75 keV, 4 μ A, 90 min	<10	<10	$3.6 \times 10^4 \pm 1.7 \times 10^4$	$2.1 \times 10^3 \pm 1.1 \times 10^3$	<10	$2.1 \times 10^4 \pm 8.9 \times 10^3$
100 keV, 14 μ A, 15 min	<10	<10	$1.8 \times 10^4 \pm 1.7 \times 10^4$	$3.6 \times 10^3 \pm 1.2 \times 10^2$	<10	$2.2 \times 10^4 \pm 5.4 \times 10^3$
100 keV, 14 μ A, 30 min	<10	<10	$2.7 \times 10^4 \pm 1.4 \times 10^4$	$9.1 \times 10^2 \pm 7.7 \times 10^2$	<10	$1.7 \times 10^4 \pm 7.9 \times 10^3$
210 keV, 40 μ A, 2 min	<10	<10	$1.4 \times 10^4 \pm 1.1 \times 10^4$	$6.5 \times 10^3 \pm 8.0 \times 10^2$	<10	$2.3 \times 10^4 \pm 1.3 \times 10^4$
210 keV, 40 μ A, 4 min	<10	<10	$1.4 \times 10^4 \pm 1.1 \times 10^4$	$3.8 \times 10^3 \pm 1.7 \times 10^3$	<10	$1.9 \times 10^4 \pm 9.5 \times 10^3$
400 keV, 40 μ A, 2 min	<10	<10	<10	<10	<10	<10
Gamma-ray, 2.5 kGy	$2.5 \times 10^4 \pm 4.7 \times 10^3$	$3.2 \times 10^3 \pm 7.0 \times 10^2$	$2.8 \times 10^4 \pm 7.7 \times 10^3$	$7.3 \times 10^2 \pm 2.3 \times 10^2$	$3.9 \times 10^3 \pm 5.4 \times 10^2$	$5.2 \times 10^2 \pm 9.2 \times 10^1$
Gamma-ray, 5.0 kGy	$4.6 \times 10^3 \pm 1.4 \times 10^3$	$1.3 \times 10^2 \pm 5.7 \times 10^1$	$1.2 \times 10^4 \pm 3.3 \times 10^3$	<100	$1.3 \times 10^2 \pm 4.5 \times 10^1$	<100
Gamma-ray, 7.5 kGy	$7.5 \times 10^2 \pm 6.3 \times 10^1$	<100	$6.5 \times 10^2 \pm 3.2 \times 10^2$	<10	<100	<10
Gamma-ray, 10.0 kGy	<10	<10	<10	<10	<10	<10

^{a)}untreated sample.

ence in the applicability of soft-electrons was ascribed to the structure of wheat grain. In the varieties such as DNS, Norin No.61 and 1CW, microorganisms reside where soft-electrons did not reach. On the contrary, no such variety-specific applicability of soft-electrons was observed in rice. Brown rice samples of both Koshihikari and Nihonbare could be decontaminated with soft-electrons at 60 keV (Table 4) (Hayashi *et al.*, 1998).

Effects of milling on brown rice exposed to soft-electrons

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; milling rice grains at a yield of 88% made the difference in the viscosity between the untreated sample and the 100 keV-electron treated sample insignificant (Table 5) (Hayashi *et al.*, 1998). However, milling did not influence the viscosity of rice irradiated with gamma-rays. The results suggested that soft-electrons degraded the starch molecules near the surface of rice grains, which could be

Table 4. Microbial load of brown rice exposed to low-energy electrons or gamma-rays (CFU/g).

	Koshihikari ^{b)}	Nihonbare ^{b)}
Control ^{a)}	$2.8 \times 10^5 \pm 5.6 \times 10^4$	$1.8 \times 10^6 \pm 2.4 \times 10^5$
60 keV, 4 μ A, 15 min	$2.8 \times 10^2 \pm 3.5 \times 10^1$	$3.4 \times 10^3 \pm 5.2 \times 10^2$
60 keV, 4 μ A, 30 min	<100	$2.1 \times 10^2 \pm 5.6 \times 10^1$
60 keV, 4 μ A, 45 min	<10	<10
60 keV, 8 μ A, 10 min	$1.1 \times 10^2 \pm 2.4 \times 10^2$	$1.2 \times 10^3 \pm 6.6 \times 10^2$
75 keV, 8 μ A, 20 min	<100	<100
75 keV, 8 μ A, 30 min	<10	<10
90 keV, 10 μ A, 10 min	$2.6 \times 10^2 \pm 6.5 \times 10^1$	$3.5 \times 10^2 \pm 1.0 \times 10^2$
90 keV, 10 μ A, 20 min	<100	<10
90 keV, 10 μ A, 25 min	<10	<10
100 keV, 14 μ A, 5 min	$4.5 \times 10^2 \pm 3.8 \times 10^1$	$6.0 \times 10^2 \pm 1.0 \times 10^2$
100 keV, 14 μ A, 10 min	<100	<100
100 keV, 14 μ A, 15 min	<10	<10
Gamma-ray, 2.5 kGy	$1.0 \times 10^4 \pm 5.6 \times 10^3$	$7.9 \times 10^3 \pm 3.2 \times 10^3$
Gamma-ray, 5.0 kGy	$2.5 \times 10^2 \pm 7.5 \times 10^1$	$2.8 \times 10^2 \pm 1.3 \times 10^2$
Gamma-ray, 7.5 kGy	<10	<10
Gamma-ray, 10.0 kGy	<10	<10

^{a)}untreated sample.

^{b)} $n=3$; mean $\pm$ standard deviation.

Hayashi *et al.*, 1998.

Table 5. Viscosity of 7% aqueous suspensions of rice which were exposed to low-energy electrons or gamma-rays followed by milling (mPa·s).

	Milling yield			
	100% ^{b)}	92% ^{b)}	90% ^{b)}	88% ^{b)}
Control ^{a)}	181.4 $\pm$ 9.3	188.9 $\pm$ 10.9	202.4 $\pm$ 10.7	203.9 $\pm$ 10.7
60 keV, 4 μ A, 45 min	182.5 $\pm$ 11.5	188.4 $\pm$ 8.5	201.2 $\pm$ 11.5	205.8 $\pm$ 9.2
75 keV, 8 μ A, 30 min	183.9 $\pm$ 14.0	187.4 $\pm$ 17.4	198.0 $\pm$ 15.1	206.8 $\pm$ 6.3
90 keV, 10 μ A, 25 min	172.9 $\pm$ 12.3	179.9 $\pm$ 9.6	187.2 $\pm$ 12.9	199.8 $\pm$ 7.9
100 keV, 14 μ A, 15 min	149.9 $\pm$ 2.6 ^{c)}	171.4 $\pm$ 9.4 ^{c)}	175.2 $\pm$ 10.5 ^{c)}	187.0 $\pm$ 8.0
Gamma-ray, 7.5 kGy	30.1 $\pm$ 1.2 ^{c)}	30.9 $\pm$ 1.5 ^{c)}	30.9 $\pm$ 0.9 ^{c)}	32.4 $\pm$ 0.8 ^{c)}

^{a)}untreated sample.

^{b)} $n=3$; mean $\pm$ standard deviation.

^{c)}significantly different from control ($p < 0.05$).

Hayashi *et al.*, 1998.

Table 6. TBA values of rice which were 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 $\pm$ 1.55	4.95 $\pm$ 0.38	4.75 $\pm$ 0.69	4.23 $\pm$ 0.81
60 keV, 4 μ A, 45 min	29.68 $\pm$ 2.66 ^{c)}	7.98 $\pm$ 0.20 ^{c)}	5.18 $\pm$ 0.70	4.75 $\pm$ 0.57
75 keV, 8 μ A, 30 min	34.21 $\pm$ 0.49 ^{c)}	9.05 $\pm$ 0.83 ^{c)}	8.37 $\pm$ 0.80 ^{c)}	5.43 $\pm$ 0.77
90 keV, 10 μ A, 25 min	41.45 $\pm$ 0.90 ^{c)}	15.55 $\pm$ 3.96 ^{c)}	9.47 $\pm$ 0.71 ^{c)}	9.43 $\pm$ 0.93 ^{c)}
100 keV, 14 μ A, 15 min	57.66 $\pm$ 2.47 ^{c)}	19.74 $\pm$ 0.67 ^{c)}	14.33 $\pm$ 0.28 ^{c)}	13.70 $\pm$ 0.74 ^{c)}
Gamma-ray, 7.5 kGy	60.59 $\pm$ 5.64 ^{c)}	46.59 $\pm$ 3.96 ^{c)}	43.83 $\pm$ 3.08 ^{c)}	43.23 $\pm$ 4.70 ^{c)}

^{a)}untreated sample.

^{b)} $n=3$; mean $\pm$ standard deviation.

^{c)}significantly different from control ($p < 0.05$).

Hayashi *et al.*, 1998.

Table 7. 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 $\pm$ 0.57	2.13 $\pm$ 0.28	2.03 $\pm$ 0.25	4.88 $\pm$ 0.49
60 keV, 4 μ A, 45 min	6.94 $\pm$ 0.48	1.94 $\pm$ 0.23	1.99 $\pm$ 0.33	5.03 $\pm$ 0.41
75 keV, 8 μ A, 30 min	7.08 $\pm$ 0.56	2.09 $\pm$ 0.28	1.99 $\pm$ 0.21	4.83 $\pm$ 0.38
90 keV, 10 μ A, 25 min	6.74 $\pm$ 0.44	1.64 $\pm$ 0.29 ^{d)}	1.71 $\pm$ 0.18	4.76 $\pm$ 0.72
100 keV, 14 μ A, 15 min	6.57 $\pm$ 0.51	1.59 $\pm$ 0.19 ^{d)}	1.52 $\pm$ 0.13 ^{d)}	4.81 $\pm$ 0.48
Gamma-ray, 7.5 kGy	4.89 $\pm$ 0.89 ^{d)}	0.77 $\pm$ 0.17 ^{d)}	1.06 $\pm$ 0.14 ^{d)}	4.46 $\pm$ 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 $\pm$ standard deviation.

^{d)}significantly different from control ($p < 0.05$).

Hayashi *et al.*, 1998.

Table 8. Sterility of dehydrated vegetables exposed to low-energy electrons (CFU/g).

	Orange peel	Green laver	Parsley	Leak	Onion	Burdock	Carrot	Mushroom
Control	$4.8 \times 10^5 \pm 2.6 \times 10^5$	$1.6 \times 10^7 \pm 2.5 \times 10^6$	$2.7 \times 10^4 \pm 1.1 \times 10^4$	$9.0 \times 10^4 \pm 5.1 \times 10^4$	$1.2 \times 10^3 \pm 6.4 \times 10^2$	$9.0 \times 10^3 \pm 1.4 \times 10^3$	$8.7 \times 10^4 \pm 4.5 \times 10^4$	$2.4 \times 10^5 \pm 7.6 \times 10^4$
100 keV, 15 min	$2.8 \times 10^4 \pm 3.1 \times 10^3$	$7.3 \times 10^6 \pm 2.9 \times 10^5$	<100	$5.0 \times 10^2 \pm 2.8 \times 10^1$	<100	<100	$1.2 \times 10^2 \pm 8.2 \times 10^1$	$2.5 \times 10^2 \pm 5.7 \times 10^1$
100 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
100 keV, 45 min	<100	$1.3 \times 10^5 \pm 2.4 \times 10^4$	<10	<10	<10	<10	<10	<10
100 keV, 60 min	<10	$2.8 \times 10^4 \pm 1.1 \times 10^4$	<10	<10	<10	<10	<10	<10
100 keV, 90 min	<10	$1.5 \times 10^3 \pm 1.2 \times 10^3$	<10	<10	<10	<10	<10	<10
100 keV, 120 min	<10	<100	<10	<10	<10	<10	<10	<10
100 keV, 150 min	<10	<10	<10	<10	<10	<10	<10	<10
γ -ray, 2.5 kGy	$1.9 \times 10^4 \pm 9.0 \times 10^3$	$3.3 \times 10^6 \pm 1.6 \times 10^5$	$1.2 \times 10^3 \pm 2.6 \times 10^2$	$4.3 \times 10^2 \pm 9.6 \times 10^1$	<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

easily removed by the milling process, and that gamma-rays degraded all the starch molecules in rice grains, most of which could not be removed by milling.

The TBA of brown rice increased with the energy of the electrons. TBA values of brown rice samples exposed to electrons at 60–100 keV were significantly higher than those of the untreated control (Table 6) (Hayashi *et al.*, 1998). Gamma-rays at 7.5 kGy resulted in a higher TBA than electrons with energies of 60–100 keV. Milling decreased the TBA values of all samples, especially those of the electron-treated samples. Accordingly, the differences in TBA between the control and the electron-treated rice grains greatly decreased after milling. The difference in TBA between the control and the rice exposed to electrons at 60 keV was insignificant at a milling yield of 90% or lower, and the difference between the control and the rice exposed to electrons at 75 keV was insignificant at a milling yield of 88%. The results suggested that most of the lipids oxidized by electrons at 60 keV and 75 keV were removed by milling at yields of 90% and 88%, respectively (Hayashi *et al.*, 1998).

Hardness and stickiness at low compression and stickiness at high compression of cooked rice grains (90% milling yield) exposed to electrons at 60–75 keV were almost the same as those of the control (Table 7) (Hayashi *et al.*, 1998). The hardness at high compression of grains exposed to electrons at 60–100 keV was almost the same as that of the control. The hardness and stickiness at low and high compressions of gamma-irradiated samples were lower than those of the control. The hardness and stickiness at low compression are parameters for the rheological properties of the surface of cooked rice grains, and those at high compression are parameters for the properties of overall cooked rice grains (Okadome *et al.*, 1996). The results shown in Table 7 indicate that rice grains which were exposed to electrons at 60–75 keV and milled at a yield of 90% had the same rheological properties as the control.

The results shown in Tables 5–7 indicate that milling at yields of 88–90% removed the portion of rice exposed to electrons at 60 keV which could eradicate most of the microorganisms contaminating brown rice. Milling brown rice grains which have been decontaminated with soft-electrons under aseptic conditions will result in milled rice with low levels of microbial contamination. Thus, soft-electrons with an energy of 60 keV enable the preparation of milled rice with low levels of microbial contamination and quality deterioration.

Decontamination of other food ingredients

Soft-electrons at 100 keV reduced microbial loads of shredded dehydrated vegetables to levels lower than 10 CFU/g, although the time necessary for electron treatment was different, dependent on the kind of dehydrated vegetables (Table 8). A longer time 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. Whole black pepper could be decontaminated with electrons at 210 keV, while whole white pepper, basil leaf and whole coriander could be

Table 9. Sterility of spices exposed to low-energy electrons (CFU/g).

Treatment	White pepper (whole)	Black pepper (whole)	Coriander (whole)	Basil (leaf)
Control ^{a)}	$2.1 \times 10^5 \pm 1.4 \times 10^5$	$2.8 \times 10^7 \pm 1.9 \times 10^6$	$1.0 \times 10^6 \pm 7.8 \times 10^5$	$3.4 \times 10^5 \pm 9.2 \times 10^4$
100 keV, 14 μ A, 15 min	$7.5 \times 10^2 \pm 3.7 \times 10^2$	$3.2 \times 10^6 \pm 1.1 \times 10^6$	$8.1 \times 10^2 \pm 4.7 \times 10^2$	$9.8 \times 10^2 \pm 6.2 \times 10^2$
100 keV, 14 μ A, 30 min	<10	$2.9 \times 10^6 \pm 8.4 \times 10^5$	<10	<10
210 keV, 40 μ A, 1 min	$3.8 \times 10^2 \pm 1.1 \times 10^2$	$3.0 \times 10^5 \pm 1.7 \times 10^4$	$1.1 \times 10^3 \pm 6.8 \times 10^2$	$1.4 \times 10^3 \pm 4.1 \times 10^4$
210 keV, 40 μ A, 2 min	<100	$1.2 \times 10^5 \pm 8.9 \times 10^3$	<100	<100
210 keV, 40 μ A, 5 min	<10	<10	<10	<10
310 keV, 40 μ A, 5 min	<10	<10	<10	<10
400 keV, 40 μ A, 5 min	<10	<10	<10	<10

^{a)}untreated sample.**Table 10.** Sterility of pulses exposed to low-energy electrons (CFU/g).

	Adzuki bean	Black soybean	Soybean
Control	$7.5 \times 10^3 \pm 2.8 \times 10^3$	$1.0 \times 10^3 \pm 6.5 \times 10^3$	$3.2 \times 10^3 \pm 1.3 \times 10^3$
60 keV, 4 μ A, 30 min	<100	<100	<100
60 keV, 4 μ A, 45 min	<10	<10	<10
100 keV, 40 μ A, 2 min	<10	<10	<10

Table 11. Sterility, sproutig and growth of mung beans exposed to low-energy electrons.

Incubation period	Microbial loads (CFU/g)	Sprouting rate of seeds (%)			Volume of sprouts (ml)	
		1 day	2 days	3 days	3 days	4 days
Control	$5.4 \times 10^3 \pm 2.8 \times 10^3$	98.3 $\pm$ 1.4	99.5 $\pm$ 0.7	99.8 $\pm$ 0.5	49.8 $\pm$ 2.3	74.0 $\pm$ 4.7
60 keV	$1.9 \times 10^2 \pm 5.6 \times 10^2$	98.3 $\pm$ 1.8	99.5 $\pm$ 0.7	100.0 $\pm$ 0.0	50.6 $\pm$ 3.2	73.6 $\pm$ 4.3
75 keV	<10	99.8 $\pm$ 0.5	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	50.6 $\pm$ 2.3	73.6 $\pm$ 2.9
90 keV	<10	99.5 $\pm$ 0.7	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	49.8 $\pm$ 3.7	72.6 $\pm$ 3.9
100 keV	<10	99.0 $\pm$ 1.0	99.8 $\pm$ 0.6	100.0 $\pm$ 0.0	46.6 $\pm$ 2.5	65.0 $\pm$ 2.7

decontaminated with electrons at 100 keV (Table 9). Pulses such as soybean, adzuki bean and black soybean could be decontaminated with electrons at 60 keV (Table 10).

Soft-electron treatment of seeds

Seeds of mung bean could be decontaminated with electrons at 75 keV (Table 11). The percentages of sprouting seeds were not affected by electrons at 100 keV, and the volumes of the sprouts of mung bean after incubation for 3 and 4 days at 30°C were almost the same as those of the controls (untreated samples). The results suggested that soft-electrons necessary for decontamination did not adversely affect the sprouting of seeds or the growth of sprouts.

Conclusions

Soft-electrons can eradicate microorganisms on the surface of dry food ingredients such as grains, dehydrated vegetables, spices and pulses with little quality deterioration. The penetration depths of the soft-electrons are too shallow to cause detrimental effects on the ingredients, when the sizes of the ingredients are taken into consideration. Soft-electron treatment is one of the efficacious techniques for decontaminating dry food ingredients, except for powdered products. The portion of grains exposed to electrons are 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 compound resides in the edible parts of grains, which suggests the safety of foods treated with soft-electrons.

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. The facility to uniformly expose all ingredient surfaces to soft-electrons on a large scale during a short period of time should be developed to industrialize this decontamination technique.

References

- Diehl, J.F. (1990). "Safety of Irradiated Foods," Marcel Dekker, Inc., New York, USA.
- Hayashi, T. (1991). Comparative effectiveness of gamma rays and electron beams in food irradiation. In "Food Irradiation," ed. by S. Thorne. Elsevier Science Publisher, Inc., London, UK, pp. 167-216.
- Hayashi, T., Todoriki, S. and Kohyama, K. (1993). Applicability of viscosity measuring method to the detection of irradiated spices. *J. Jpn. Soc. Food Sci. Technol.*, **40**, 456-460.
- Hayashi, T. and Todoriki, S. (1996). Detection of irradiated peppers by viscosity measurement at extremely high pH. *Radiat. Phys. Chem.*, **48**, 101-104.
- Hayashi, T., Takahashi, Y. and Todoriki, S. (1997). Low-energy electron effects on the sterility and viscosity of grains. *J. Food Sci.*, **62**, 858-860.
- Hayashi, T., Okadome, H., Toyoshima, H., Todoriki, S. and Ohtsubo, K. (1998). Rheological properties and lipid oxidation of rice decontaminated with low-energy electrons. *J. Food Protect.*, **61**, 73-77.

- ICRU. (1984). "Stopping Powers for Electrons and Positrons," ICRU Rep. 37, International Commission on Radiation Units and Measurements, Bethesda, USA.
- McLaughlin, W.L., Humphreys, J.C., Radak, B.B., Miller, A. and Olejnik, T.A. (1979). The response of plastic dosimeters to gamma rays and electrons at high absorbed dose rates. *Radiat. Phys. Chem.*, **14**, 535-550.
- Okadome, H., Toyoshima, H. and Ohtsubo, K. (1996). Many-sided evaluation of physical properties of cooked rice grains with a single apparatus. *J. Jpn. Soc. Food Sci. Technol.*, **43**, 1004-1011.
- Tabata, T. and Tanaka, R. (1990). Fundamental data on electron beam dosimetry, In "Radiation Dosimetry of Electron Beams for Radiation Processing," ed. by Y. Moriuchi. Chijinshokan Publisher, Inc., Tokyo, pp. 109-135.
- Urbain, W.M. (1986). "Food Irradiation," Academic Press, Inc., Orlando, USA.
- WHO. (1994). "Safety and Nutritional Adequacy of Irradiated Food," World Health Organization, Geneva, Switzerland.