Food Irradiation

Dose Rate Effect

Dose Rate Effect in Food Irradiation

- Aim of all food processing methods is to minimize damage to the nutrients while maximizing damage to microoganisms
- Codex Alimentarius Commission concluded that nutrient losses insignificant up to 10 kGy
- Losses may be even lower, if irradiation done at high dose rates (Brasch and Huber, 1947; Singh, 1991)

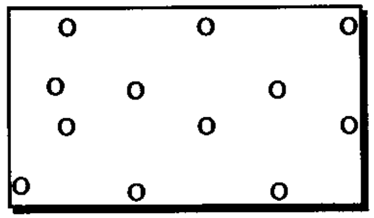
Typical Irradiators and Their Dose Rates[1]

Irradiator[2]	Beam Voltage (MeV)	Dose Rate ($Gy \cdot s^{-1}$)
High Voltage Engineering Corporation	0.3 to 3.0	2.5×10^4 to 2.5×10^6
Nissin High Voltage	0.5 to 3.0	8×10^5
Radiation Dynamics	0.4 to 4.5	10^6
AECL, I-10/1	10	2×10^3
AECL, I-10/50	10	10^5
Nordion, Co-60	1.17, 1.33	4 to 10

[1] Singh, 1991; [2] Electron accelerators, except for the last item

Transition From Inhomogeneous to Homogeneous Distribution of Free Radicals in Liquid Water

(i) γ- Irrad $\sim 10^{-12}$s



[Spur] -Low number

$[e^-_{aq}] \approx [\cdot OH] \approx 0.1$ mol.dm^{-3}(Av)[a]

$[\cdot OH] \approx 2$ mol.dm^{-3} (Spur Core)[b]

(ii) $G(e^-_{aq})$ ~2.7

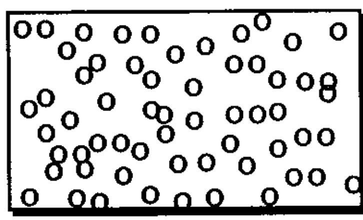
$G(\cdot OH)$ ~2.7

Homogeneous Distribution ($\cdot OH$, e^-_{aq}, $\cdot H$)

$[e^-_{aq}] \approx [\cdot OH] \approx 10^{-9}$ mol.dm^{-3}(γ)[c]

$\approx 10^{-3}$ to 10^{-6} mol .dm^{-3} (e^-)[d]

(iii) e^- Irrad $\sim 10^{-12}$ s



[Spur] -Very high number

$[e^-_{aq}] \approx [\cdot OH] \approx 0.1$ mol.dm^{-3}(Av)[a]

$[\cdot OH] \approx 2$ mol.dm^{-3} (Spur Core)[b]

a. Averaged over total spur volume; b. Initial Concentration within the spur core; c. γ- Irradiation; d. e^-- Irradiation

Transition From Inhomogeneous to Homogeneous Distribution of Free Radicals in Liquid Water

(i) Represents spur formation on energy absorption from a single gamma photon in 10^{-12} s or less

(ii) Shows homogeneous distribution of reactive species on diffusion of spurs in about 10^{-7} s

(iii) Represents spur formation on energy absorption from a single electron in 10^{-12} s or less. The higher spur concentration [spur] on electron irradiation is not drawn to scale

Singh (1991)

Dose Rate Effect on Product Formation from Linoleic Acid[1]

Dose Rate[2] (Gy/min)	Product (10^{-5} mol.dm^{-3})
~ 0.10	28.2
~ 0.33	11.8
~ 0.98	5.0
~ 5.40	2.0

1 Linoleic acid, 5.8×10^{-3} mol•dm^{-3} in borate buffer, pH 9, containing 5% CH_3OH

2 Total dose ~10 Gy

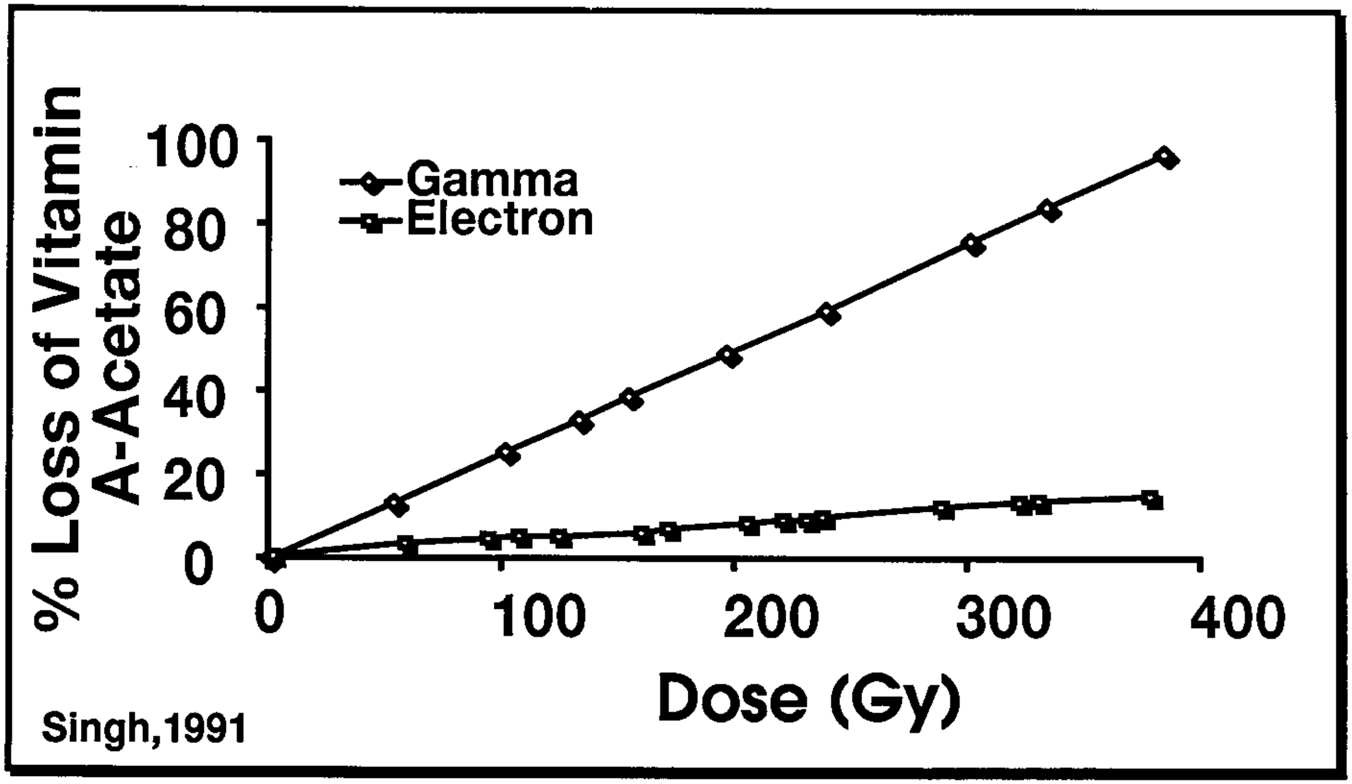
$\cdot OH + CH_3OH \longrightarrow \cdot CH_2OH + H_2O$

$\cdot H + CH_3OH \longrightarrow \cdot CH_2OH + H_2$

$\cdot CH_2OH$ + Linoleic Acid $\longrightarrow$ Reaction Products

$\cdot CH_2OH + \cdot CH_2OH \longrightarrow (CH_2OH)_2$

Effect of Dose Rate on Vitamin A-Acetate in Isopropanol Solution



- Dose Rate: Electron, ~10^4 and Gamma ~10 Gy/s

Dose Rate Effect on α-Tocopherol in Sunflower Oil

Radiation Source	Dose (kGy)	Dose Rate (Gy/s)	Tocopherol Loss (%)	
			In Nitrogen	In Air
^{60}Co	1 10	1.8 1.8	30.1 89.4	36.5 94.6
X-ray (5 mA) (20 mA)	1 10	4 16	30.1± 1.0 86.0± 1.3	34.8± 0.6 90.7 ± 1.2
Van de Graaff (1 MeV)	1 10	2.5×10^4 2.5×10^4	27.8± 0.4 91.1± 1.4	33.5± 0.3 95.9± 0.5
Linear accelerator (10MeV)	1	10^7	27.0	32.2

Singh (1991)

- The losses are rather similar, with a hint of lower losses at higher dose rates

Effect of Gamma and Electron Irradiation on Ascorbic Acid (Vitamin C) Content of Citrus Fruit Section[1]

Treatment	Ascorbic Acid Content (mg per fruit section) Dose (kGy)			
	1	2	3	5
Unirradiated (control)	16.6	21.2	18.9	18.6
Electron irradiation (1 MeV,0.4 μA/cm²)	17.0	22.5	18.9	17.9
Gamma irradiation (0.6-2.3 kGy/h)	17.2	21.2	18.6	17.2

1 Singh (1991)

- At low doses, vitamin C loss appears to be insignificant

Dose Rate Effect on Vitamins in Sweet Potatoes[1]

Dose Rate (Gy/s)	Time of Irrad[2] (min)	Thiamin	Riboflavin	Ascorbic Acid	Carotenoids
		mg/100 g (fresh weight)			
3.75	4.4	0.016[a]	0.036[a]	16.43[a b c]	11.4[a b]
2.88	5.7	0.015[a]	0.036[a]	16.34[a b c]	12.8[a]
2.06	8.0	0.017[a]	0.03[a]	16.93[a b]	7.7[c]
1.37	12.1	0.016[a]	0.04[a]	15.05[c]	8.6[b c]
0.27	60.0	0.017[a]	0.04[a]	14.65[c]	7.6[c]
0	-	0.018[a]	0.026[a]	17.30[a]	12.6[a]

1 Singh (1991)

2 Time of irradiation (^{60}Co source) at 24°C for a total dose of 1 kGy

3 Mean values with the same superscripts (a, b, c) in the same column are not significantly different at the 5% level

Dose Rate Effect on Water-Soluble Vitamins in Enzyme-Inactivated Radappertized Chicken[1] (45-68 kGy at -25 ± 15°C)

Vitamin	Frozen Control	Gamma	Electron
Biotin[2]	93.0 (100)[3]	98.0 (105)[3]	103.0 (111)[3]
Choline	952.4 (100)	1096.0 (115)	1001.0 (105)
Folic Acid	0.8 (100)	1.3 (152)	1.5 (177)
Niacin (bound)	218.6 (100)	209.8 (96)	212.1 (97)
Niacin (free)	212.9 (100)	197.9 (93)	208.2 (98)
Pantothenic acid	24.0 (100)	23.5 (98)	24.9 (104)
Riboflavin	4.3 (100)	4.5 (103)	4.9 (113)

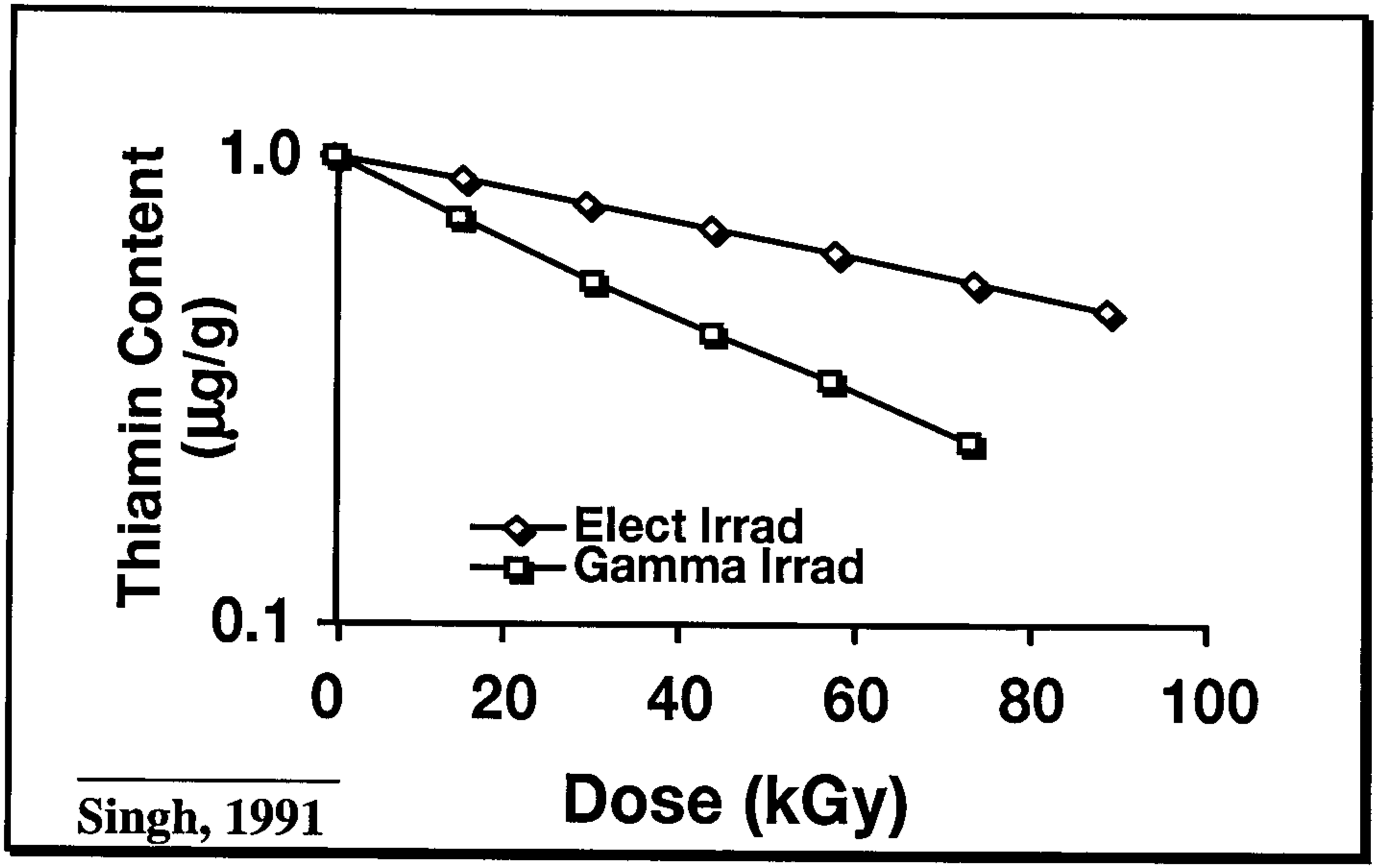
1 Singh (1991)
2 Biotin content given in µg/kg chicken (dry weight), other data mg/kg
3 Values in brackets give percentage of frozen control

Dose Rate Effect on Vitamins in Meat (-30 ± 10°C)

Vitamin	System	Average Total Dose (kGy)	Gamma	Electron
			Percent Retention	
Thiamin	Beef	58[1]	23	44
	Chicken	58[1]	26	66
	Chicken	45-68[2]	~68	~86
Pyrid-oxine	Chicken	58[1]	50	62
	Chicken	45-68[2]	73	93

1. Gamma and electron dose rates assumed to be ~14 Gy/s and ~10^6 Gy/s respectively (Singh, 1991)
2. Gamma and electron dose rates 9.6 and ~10^6 Gy/s, respectively (Thayer, personal communication)

Effect of Dose Rate on Thiamin in Pork Irradiated at -45°C



- Initial thiamin concentration about 9 µg/g in pork
- Dose Rate: Electron, ~106 and Gamma ~14 Gy/s

Amino Acid Content (g/100g Protein) of Irradiated Enzyme-Inactivated Chicken at High Doses (45-68 kGy at -25 ± 15°C)

Amino Acid	Frozen Control	Electron (10^6 Gy/s)	Gamma (9.6 Gy/s)
Alanine	5.76	5.85	5.84
Arginine	6.24	6.38	6.37
Aspartic acid	8.94	8.84	8.98
Cysteine	0.91	0.93	0.96
Glutamic acid	14.33	14.37	14.19
Glycine	5.83	5.87	4.21
Histidine	4.05	4.36	5.96
Hydroxyproline	0.28	0.28	0.27
Isoleucine	4.51	4.67	4.70
Leucine	7.53	7.64	7.69
Lysine	8.34	8.49	8.55
Methionine	2.52	2.57	2.48
Phenylalanine	3.78	3.79	3.74
Proline	4.02	4.34	4.45
Serine	3.72	3.60	3.73
Threonine	4.11	3.94	4.14
Tryptophan	1.16	1.20	1.25
Tyrosine	3.38	3.22	3.34
Valine	4.79	4.93	5.02

Singh (1991)

Dose Rate Effect on the Amino Acid Content (g/100g Protein) of Raw Beef at Low Dose (6 kGy)

Amino Acid	Control	^{60}Co Irradiation	Electron Irradiation 2 MeV		Electron Irradiation 4 MeV	
	Dose Rate (Gy/s)					
	0	5.3	2×10^2	2×10^3	2×10^2	2×10^3
Cystine	0.72	0.86	0.71	0.87	0.65	0.62
Lysine and histidine	15.42	14.95	13.46	15.07	14.29	13.79
Arginine	7.95	7.23	7.72	8.09	7.32	7.65
Aspartic acid	7.04	7.15	6.85	6.65	6.41	6.78
Serine	2.82	2.79	2.97	2.60	3.04	2.96
Glycine	3.37	3.42	3.39	3.61	3.91	3.75
Glutamic acid	11.82	11.50	11.75	11.11	12.04	11.72
Threonine	4.64	4.67	4.23	4.52	4.52	4.54
Alanine	4.64	4.82	5.10	4.95	5.12	5.19
Tyrosine	2.84	3.03	2.74	2.89	3.02	2.77
Methionine	2.48	2.52	2.38	2.46	1.91	2.30
Valine	5.35	5.15	5.21	5.08	5.71	5.63
Phenylalanine	4.10	4.15	4.57	4.90	4.69	4.96
Leucine and isoleucine	9.19	9.32	10.04	9.74	9.96	9.93

Singh (1991)

Dose Rate Effect on Selected Amino Acids in Enzyme-Inactivated Beef (-40°C)

Amino Acid	Frozen Control	^{60}Co (47-71 kGy)	e^-, 10 MeV (47-71 kGy)
Cystine	0.28	0.26	0.28
Methionine	0.53	0.57	0.59
Tryptophan	0.25	0.25	0.26

Singh (1991)

- The data suggest absence of a dose rate effect

Some Volatile Radiolysis Products Isolated from Irradiated (45 kGy at -30°C) Chicken Meat

	Frozen Control		Gamma Irrad		Electron Irrad	
	No. 1[b]	No. 2[b]	No. 1[b]	No. 2[b]	No. 1[b]	No. 2[b]
Ethane	-	-	110	134	161	196
N-Pentane	2	3	107	138	157	191
N-Hexane	9	5	173	219	248	301
N-Nonane	-	-	101	131	153	187
Ethylene	-	-	13	21	21	26
Nonene	-	-	51	55	79	86
Methyl alcohol	-	-	31	35	48	52
Ethyl alcohol	-	-	50	55	77	84
Acetone	1	1	41	43	63	69
Ethyl mercaptan			6	7	3	6
Dimethyl sulfide	+	+	3	4	4	3
Tetradecadiene			17	17	26	28

[a] Based on data of Merritt (1984), µg/kg chicken meat
[b] Samples of two different production lots (No. 1 and No. 2) were processed simultaneously; experimental error high

Dose Rate Effect on Percentage of Tuber Sprouting in Two Varieties of Potatoes

Potato Variety	Total Dose (Gy)	Dose Rate (Gy/min)		
		0	2.5	30
		Percent Sprouting		
Gola	60	100	15	0
Up-to-Date	90	100	20	0

Singh (1991)

- The higher dose rate appears to be more efficient in perventing tuber sprouting

Sensory Evaluation of Gamma- and Electron-Irradiated Walla Walla Onions[1]

Irradiation Treatment	Fresh				Cooked[2]		
	Dose (kGy)	Firmness	Flavour	Taste	Firmness	Flavour	Taste
Electron (2 MeV, ~10^5 Gy/s)	0	7.0[a]	6.7[a]	6.4[a]	6.4[a]	4.8[b]	4.9[c]
	0.1	6.1[a]	7.3[a]	6.8[a]	7.3[a]	7.3[a]	7.0[a]
	1.0	6.6[a]	6.7[a,b]	6.6[a]	5.9[3]	5.5[a,b]	5.4[b,c]
	2.0	6.8[a]	5.6[b]	6.4[a]	7.0[a]	6.5[a,b]	7.0[a]
Gamma (22.8 Gy/s)	0	6.6[a,b,c]	6.4[a]	6.6[a,b]	7.1[a]	6.5[a]	7.0[a]
	0.1	6.2[a,b,c]	6.0[a]	6.0[b]	6.8[a,b]	6.3[a]	6.5[a]
	1.0	7.0[a,b]	7.2[a]	7.1[a,b]	6.4[a,b]	5.5[a]	5.9[a]
	2.0	6.8[a,b,c]	6.6[a]	6.5[a,b]	6.7[a,b]	6.2[a]	5.9[a]

[1] Singh (1991). A nine-point hedonic scale: 9=like extremely; 1 = dislike extremely Mean values with the same superscripts (a,b,c) in the same columns are not different ($P < 0.05$)

[2] Chopped onions cooked for 2 min at 250°C

Expert Panel Evaluation of Dose Rate Effect on the Sensory Characteristics of Enzyme-Inactivated Radappertized Chicken Meat[1]

Treatment	Overall Score[2]			
	Colour	Odour	Flavour	Texture
Gamma[3]	6.28[b] ± 0.73[b]	6.04[a] ± 0.53[6]	5.43[a] ± 0.38[6]	5.40[b] ± 0.58[6]
Electron[4]	6.30[b] ± 0.73	5.98[a] ± 0.58	5.40[a,b] ± 0.56	5.35[b] ± 0.54
FC[5]	6.45[b] ± 0.44	6.68[b] ± 0.48	6.40[b] ± 0.47	6.11[c] ± 0.42

1 Singh (1991)
2 Expert panel, n= 10; average data for 4 storage times x preparations for serving (n=80)
3 ^{60}Co, dose rate ~ 5 x 10^2 Gy/s
4 10-MeV LINAC, ~10^6 Gy/s
5 Frozen control
6 Mean values with different superscripts in the same column (a,b,c) are significantly different ($P < 0.05$)

Consumer Preference Ratings of Irradiated Roast Beef[1]

Experiment No.	No. of Raters	Average Preference Rating[2]		
		^{60}Co[3]	Electron[3]	Control[3]
1	32	5.5	5.4	5.5
2	32	6.2	5.6	6.1
3	32	5.4	5.8	6.0
4	32	6.6	5.9	6.2
5	32	5.6	6.3	6.0
6	30	5.0	5.6	4.8
7	30	5.8	6.3	5.4

[1] Singh (1991)

[2] Nine-point hedonic scale: 9=like extremely; 5=neither like nor dislike extremely

[3] Dose 47 to 71 kGy at $-30 \pm 10^{\circ}C$