Potential Concerns Associated with Irradiated Foods

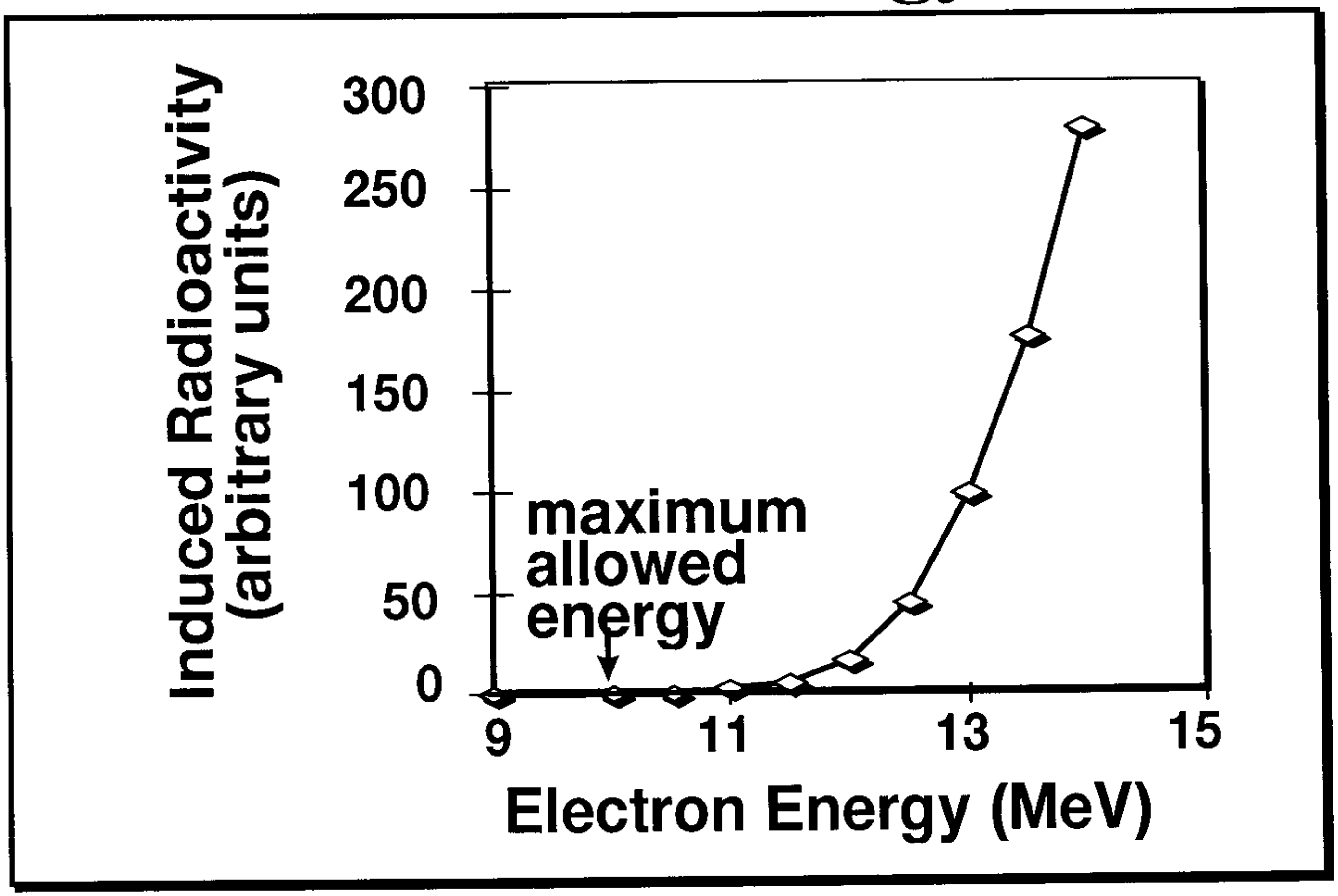
1. Induced radioactivity
2. Microbiological safety
3. Nutritional loss
4. Toxicological safety
5. Miscellaneous

1. Induced Radioactivity

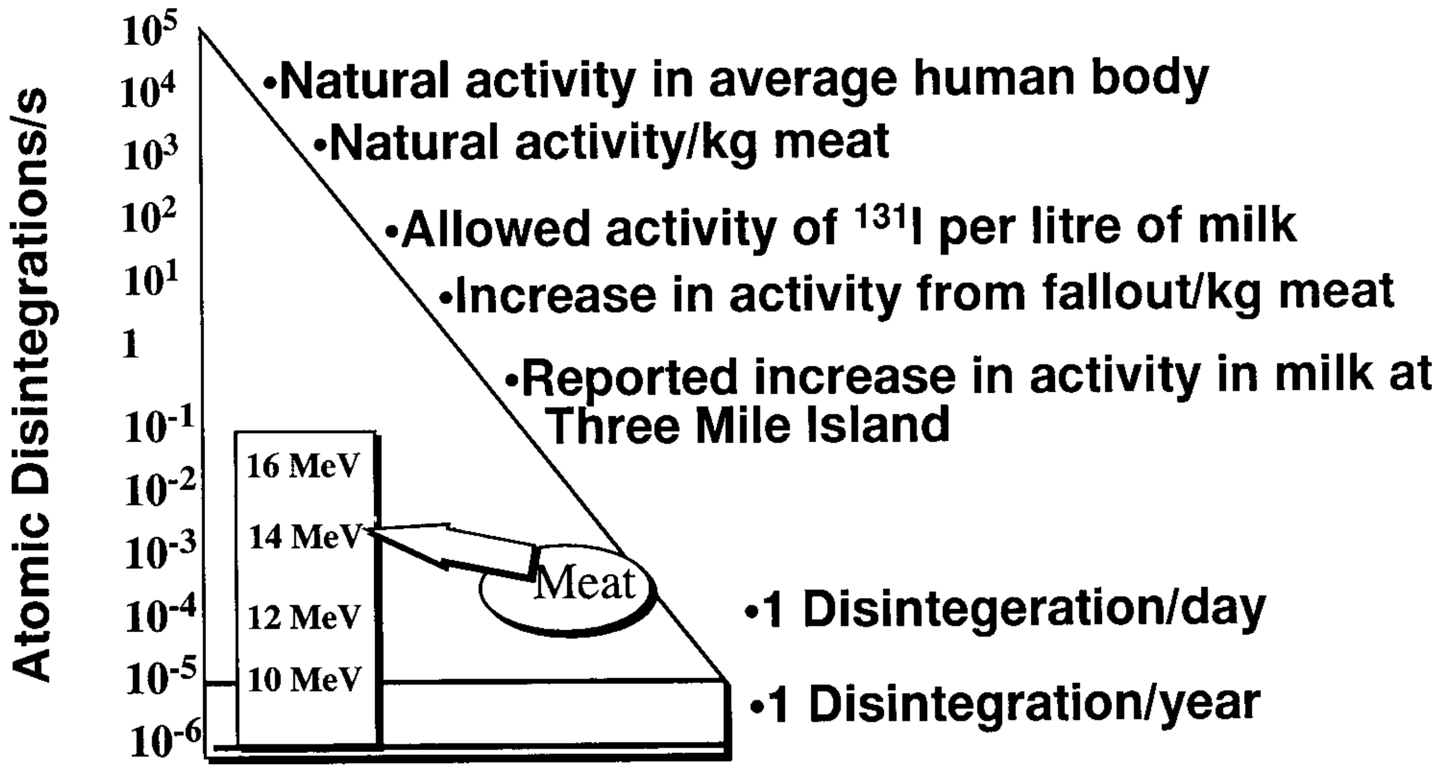
- Should not be a concern
- The energy levels permitted for use in food irradiation are specifically selected to avoid any conditions which could induce significant levels of radioactivity in the treated commodity
- The permitted energy levels are

X-rays, γ-rays	$\leq$ 5 MeV
Electrons	$\leq$ 10 MeV

Induced Radioactivity vs Electron Energy



Natural and Induced Radioactivity from Various Sources (Becker, 1979)



- In "pure" organic polymers, induced radioactivity should be lower than in foods; in metals it would be higher

Potential Concerns Associated with Irradiated Foods (contd)

1. Induced radioactivity
2. Microbiological safety
3. Nutritional loss
4. Toxicological safety
5. Miscellaneous

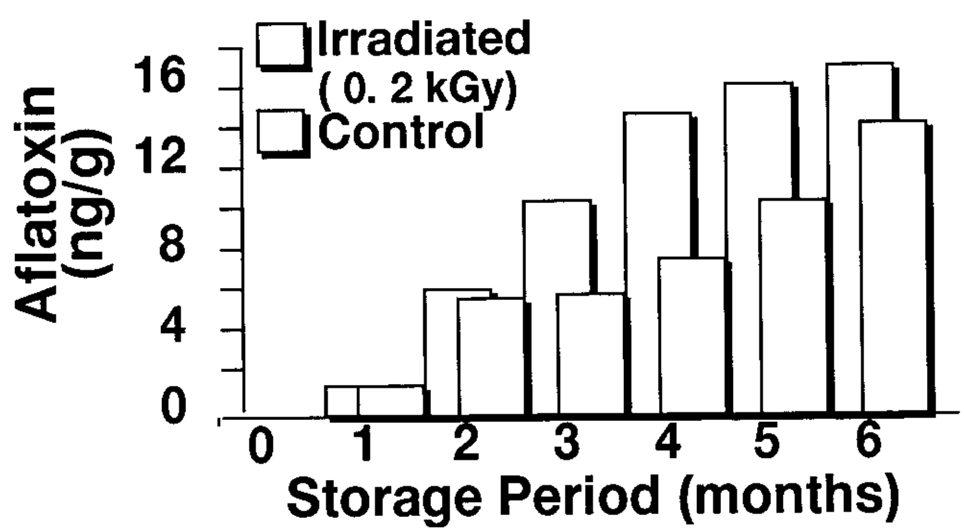
2. Microbiological Safety Concerns and Assessment

(i) Changed Microbial Ecology and Selective Effects

- Changes in microbial population do occur (as in other processing methods) but no evidence of any problems
- Most pathogens are quite sensitive to radiation e.g., a 5 kGy dose would reduce *Salmonella* serotypes, *S. aures, Shigella, E. coli, Vibrio, C. Jejuni, Yersinia* species by at least 6 log cycles
- Some spore-forming pathogens (e.g., *C. botulinum* species A to E) are more resistant to radiation and could conceivably survive a non-sterilizing dose, germinate, grow and produce toxin unless the food was stored at the required low temperature
- Recent model (inoculation pack) studies on several meats suggest that at low dose irradiation, spoilage precedes germination at abuse temperatures

(ii) Enhanced Potential for Mycotoxin Production

- Potential for enhanced mycotoxin production is associated with perturbation of microbial ecology by many agents, including commonly used fumigants as well as by irradiation
- Decades of experience with fumigants has revealed no significant mycotoxin hazard arising from the use of fumigants. Under some conditions irradiation actully reduces the potential for mycotoxin production



Aflatoxin levels in wheat at 90% relative humidity and 28^{o}C (Diehl,1990)

(iii) Increased Radiation Resistance

- Concern that pathogens could develop radiation resistance

- Radiation resistance can be compared with heat resistance. Resistance is generally achieved under very special conditions (e.g. hot springs) and requires those conditions for survival

- The fact that very radiation-tolerant strains are obtained under special laboratory conditions has no bearing on practical food irradiation

Some of the Foodborne Pathogens of Concern

- *Salmonella enteritidis*
  - Incidences tripled in past decade in US (USDA APHIS March 1990)
  - 13-fold increase between 1980-89 in UK (estimate 500,000 cases in 1988)
  - Outbreaks commonly associated with poultry and hamburger
- *Enteropathogenic E. coli*
  - O157:H7 most famous member of this group
  - Causes severe illness (hemorrhagic cloitis, kidney failure in children)
  - Outbreaks commonly associated with hamburger

Some of the Foodborne Pathogens of Concern (contd)

- *Listeria monocytogenes*
  - Foodborne pathogen of growing importance especially as ready-to-eat, refrigerated meals gain in popularity
  - Very high mortality associated with infection
  - Very serious for pregnant women (abortion to stillbirth)

Recent Outbreaks

Salmonella

- Two outbreaks of *salmonella* gastroenteritis occurred at the Grey-Bruce Regional Health Centre (GBRHC) in Canada between September 1991 and January 1992
- In all, there were 95 confirmed cases of infection by *Salmonella enteritidis* phage type 13
- The source of both outbreaks is considered to have been ready-to-eat food contaminated by raw food processed in the same vertical blade mixer

Listeria

- An outbreak of *listeriosis* in France, 1995 was attributed to a raw milk soft cheese (Brie de Meaux). 20 cases, including 11 pregnant patients, were attributed to the consumption of the cheese

Recent Outbreaks (contd)

E. Coli O157:H7

Place/Agent	Food	Year	Sick	Deaths
Jack in the Box (fast food)	Hamburger	1993	700	4
Beef Processor, Nebraska	Hamburger	1994	21	
Meat Plant, Scotland	Meat	1996	12000	10-15
Hudson Foods, Colorado	Hamburger	1997		
Virginia Grocery Store	Ground Beef			

Relative Radiation Sensitivities of Different Classes of Microorganisms[a]

Microorganisms	Approximate D_{10} Value (kGy)
Bacteria (vegetative form)	0.2 to 1.0
Bacterial spores	2 to 4
Mould spores	1 to 1.5
Yeasts	0.6 to 1.0
Viruses	5
Trichinella spiralis	0.15 to 0.30

[a] Diehl (1989); Urbain (1986)

Factors Affecting Radiation-Sensitivity of Microorganisms

- Presence of oxygen
  D_{10} generally lower in O_2
- Temperature
  D_{10} decreases with increasing temperature
- Growth Medium
  D_{10} depends on the growth medium
- Dose Rate
  D_{10}-values could vary somewhat between γ- and e^--irradiation

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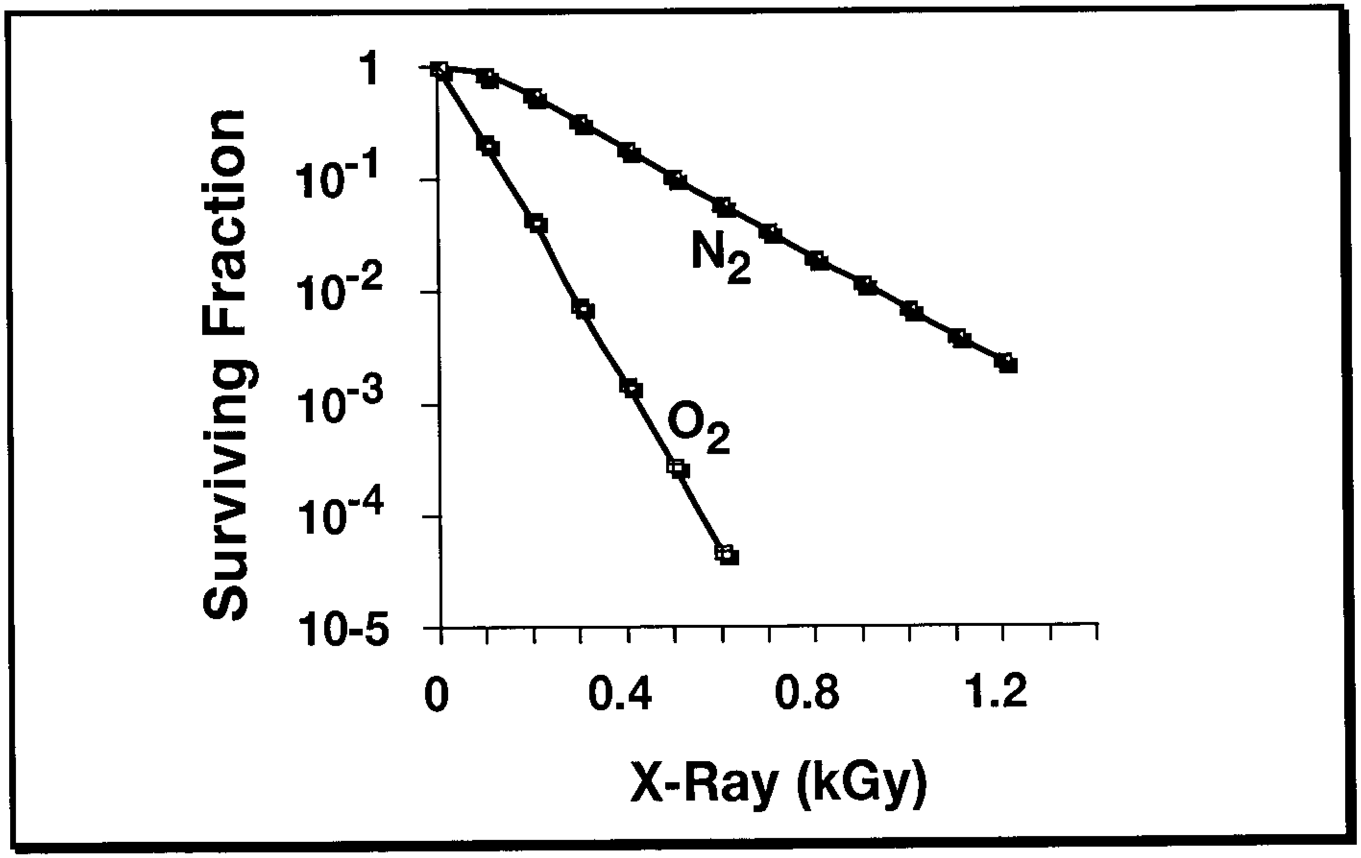
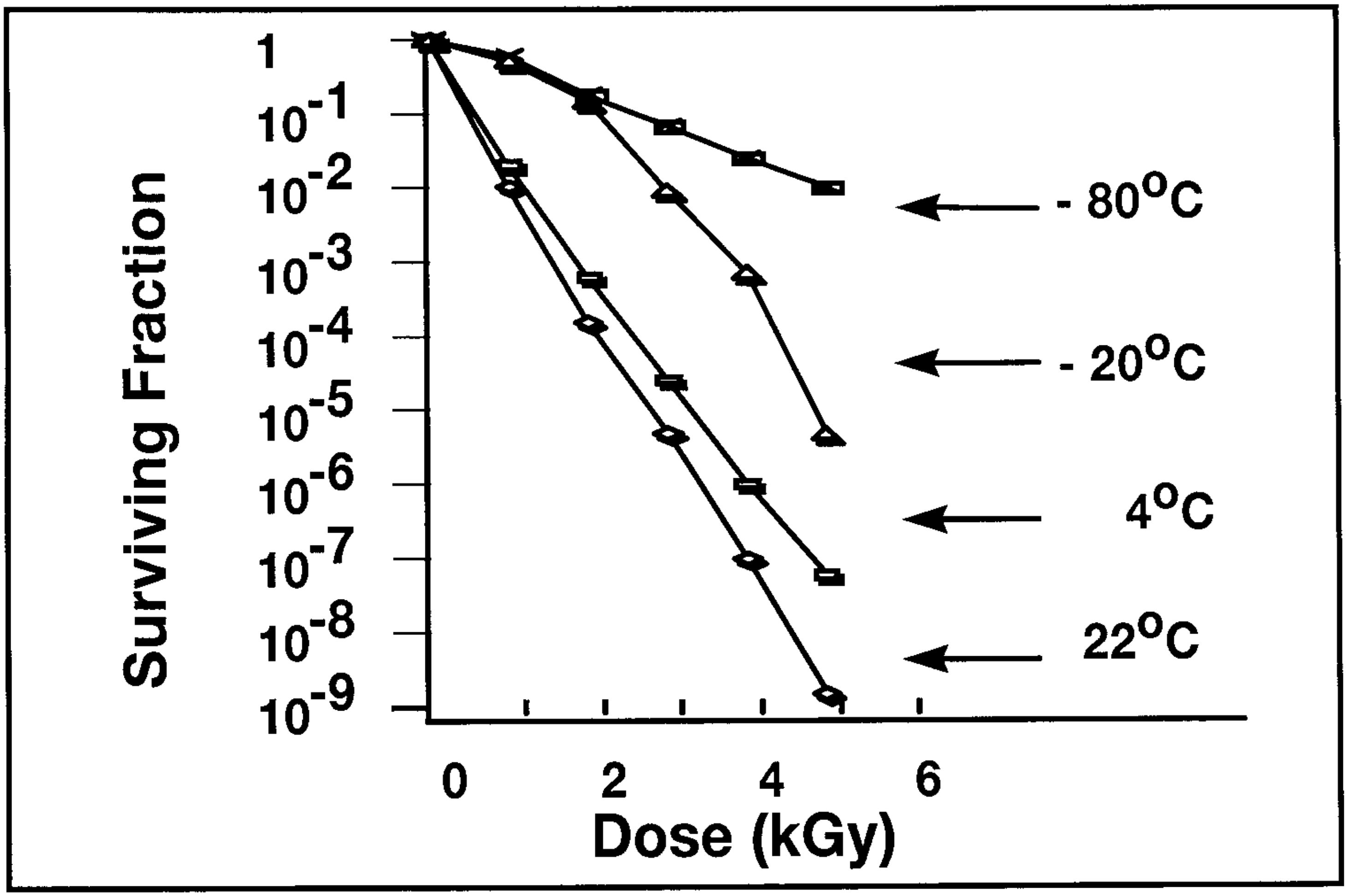
D_{10}-value is defined as the dose required to reduce the number of colony-forming units by 90%

Radiation-Inactivation of *E. coli*



E.coli cultured aerobically in broth and irradiated in O_2-saturated or N_2-saturated buffer (Casarett,1968)

Effect of Temperature



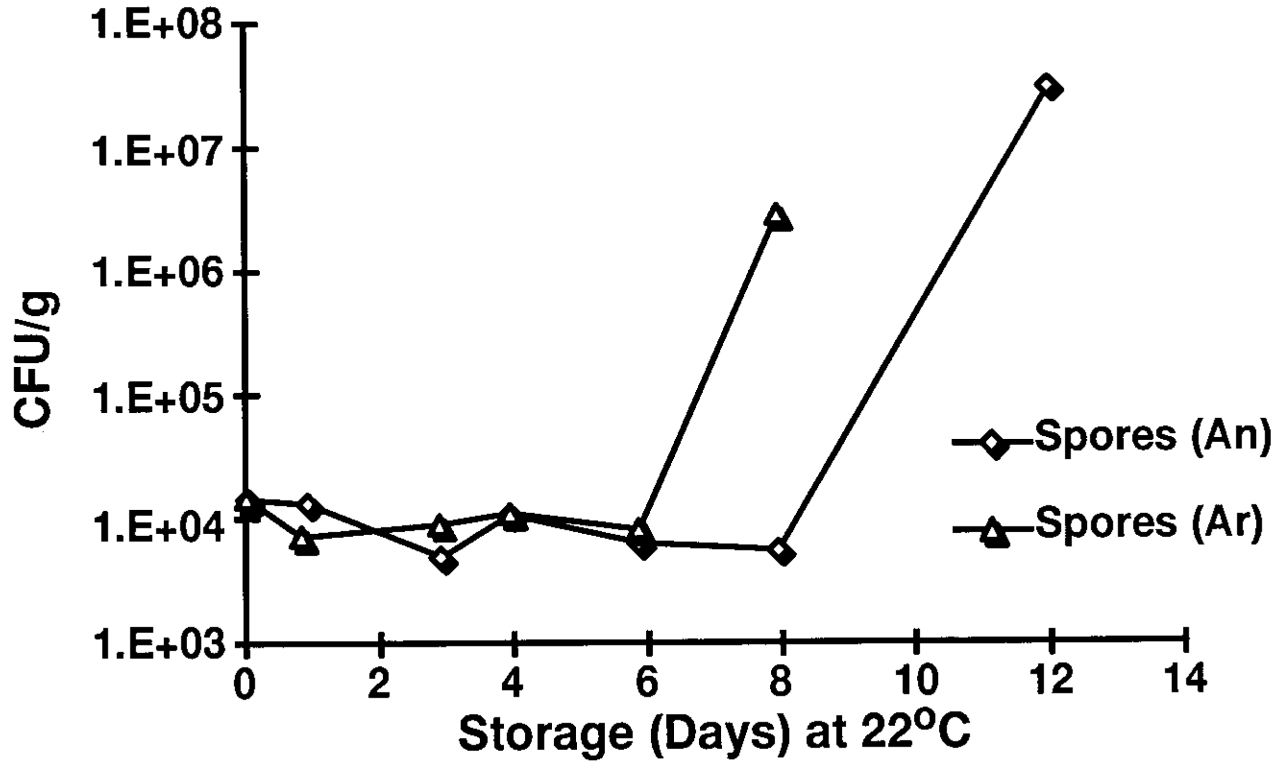
Radiation survival curves for *S.typhimurium,* RIA.The cells were inoculated onto chicken before irradiation (Previte et al.,1970)

Effect of Media on D_{10}-Values of Two *Salmonella typhimurium* Nal^R Strains[a]

Strain	Suspension Medium/Support	D_{10}-Value (kGy)	Number of Determinations
ATCCC 13311 Nal^R	Nutrient broth	0.571 ± 0.035	8
	Phosphate buffer	0.198 ± 0.013	5
	Chicken drumstick	0.534 ± 0.006	2
K1-2B Nal^R	Nutrient broth	0.398 ± 0.035	4
	Phosphate buffer	0.212	1
	Chicken drumstick	0.318 ± 0.014	3

[a] Shamsuzzaman et al. (1989)

Inoculation (*C. sporogenes*) Pack Study
Ground Beef Patties



- Germination of *C. sporogenes* spores on storage at 22°C starts after day 6 in air, and after day 8 under vacuum
- Out-growth follows the same pattern

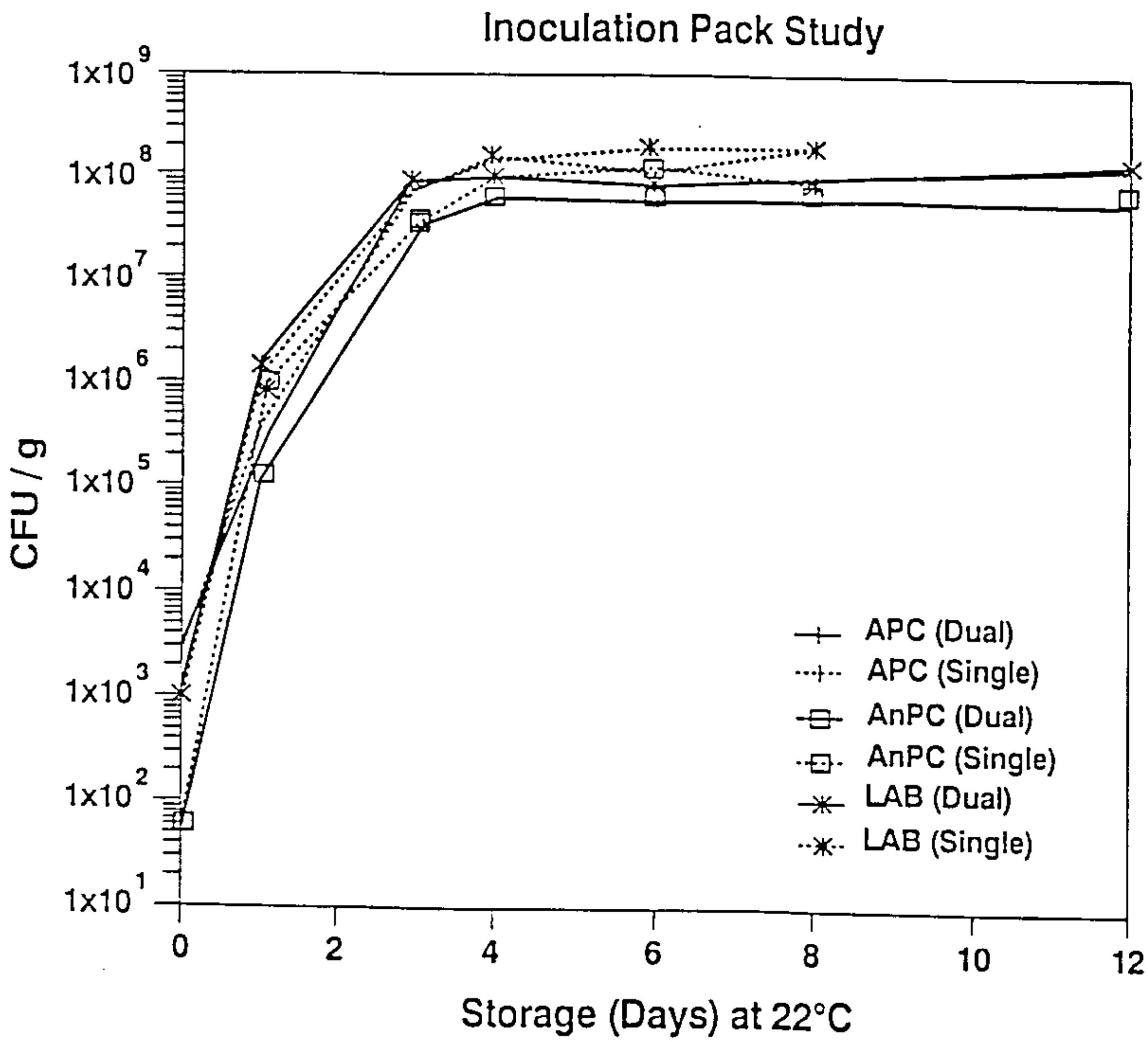


Figure 2. Effect of gamma irradiation (2.5 kGy) and storage (22°C) on C. sporogenes in inoculated fresh ground beef patties in single (aerobic) and dual (anaerobic) bags; (Tot. Clost., total Clostridium cell growth) [92,93].

Potential Concerns Associated with Irradiated Foods (contd)

1. Induced radioactivity
2. Microbiological safety
3. Nutritional loss
4. Toxicological safety
5. Miscellaneous

3. Nutritional Loss Concerns

- Concerns which have been raised include

  (a) Nutrient Destruction, Nutrient Unavailability, Loss of Biological Activity, Altered Digestibility and Reduced Energy Content

  (b) Induction of Anti-Vitamin Activity

  (c) Altered Palatability

  - However, it is known that macronutrients are not significantly affected on food irradiation
  - In the case of micronutrients, some vitamin losses do occur on irradiation but such losses also take place with alternate processing methods
  - From animal feeding studies it is known that there is no significant effect on digestibility, biological activity, nutrient availability, energy content, anti-vitamin activity and palatability

Evaluation of Nutritional Data

Chemical Composition of Enzyme-Inactivated Chicken Meat[a]

Component	Samples	Frozen Control	Thermally Processed	Gamma Irrad	Electron Irrad
H_2O, (%)	12	65.4±0.7	65.3±1.0	65.1±0.8	65.3±0.3
Protein (%)	12	20.2±0.6	19.9±0.7	20.0±0.4	20.4±0.4
Fat (%)	12	12.4±1.1	12.7±1.2	13.0±0.9	12.6±0.3
Ash (%)	12	1.9±0.1	1.9±0.1	1.9±0.1	1.9±0.0
NaCl (%)	12	0.85±0.05	0.87±0.05	0.85±0.08	0.87±0.05
P(mg/100g)	12	265±9	263±9	260 ±10	266±12
NPN[b]	8	0.36±0.02	0.35±0.03	0.38±0.02	0.38±0.02
pH	8	6.39±0.10	6.33±0.08	6.40±0.08	6.39±0.08

[a] Based on data from Wierbicki (1985). Irradiation dose of 45 to 68 kGy

[b] NPN = Non-protein nitrogen as % total N

Evaluation of Nutritional Data

(i) Macronutrients

Metabolizable Energy (cal/g) in Rat Diet[1]

	Metabolizable Energy of Nutrients (cal/g)	
	Unirrad	Irrad
Carbohydrate	3.87 ± 0.20	3.78 ± 0.30
Casein (protein)	4.56 ± 0.30	4.51 ± 0.22
Lard (Fat)	8.82 ± 0.31	8.87 ± 0.39
Rat diet 1	90.0[2]	90.1[2]
Rat diet 2	89.2[2]	89.0[2]
Rat diet 3	92.3[2]	91.4[2]

[1] Singh (1988)
[2] Overall metabolizable energy of rat diet, cal/100 g of diet

- **The metabolizable energy of the macronutrients/ rat diet is not affected on irradiation**

Evaluation of Nutritional Data (Contd)

(a) Amino Acids and Proteins

- The nutritional needs of essential amino acids for humans vary with age and physiological condition of the individual

- The deficiency in nutritional proteins can be very large for some segments of the world population

- It is thus very important that processing methods used for foods do not reduce the nutritional component (essential amino acids) of the proteins

Effect of Irradiation on the Amino Acid Content (g/100 g Dry Weight of Protein) of Raw Beef[1]

Amino Acid	0 kGy	6 kGy (^{60}Co)
Cystine	0.72	0.86
Lysine and histidine	15.42	14.95
Arginine	7.95	7.23
Aspartic acid	7.04	7.15
Serine	2.82	2.79
Glycine	3.37	3.42
Glutamic acid	11.82	11.50
Threonine	4.64	4.67
Alanine	4.64	4.82
Tyrosine	2.84	3.03
Methionine	2.48	2.52
Valine	5.35	5.15
Phenylalanine	4.10	4.15
Leucine and isoleucine	9.19	9.32

[1] Data cited by Josephson et al. 1978

- The effect of low dose irradiation not significant

Amino Acid Analyses of Irradiated and Unirradiated Chicken, Stored for 6 Days at +5°C and Cooked

Amino Acid	0 kGy	3 kGy	6 kGy
	(g/100g protein)		
Isoleucine	4.2	4.2	4.3
Leucine	6.7	6.7	6.8
Lysine	7.1	6.9	7.1
Methionine	2.3	2.3	2.35
Cystine	0.98	1.02	1.02
Phenylalanine	3.6	3.5	3.5
Tyrosine	2.9	2.8	3.0
Threonine	4.0	4.0	4.1
Tryptophan	0.98	0.93	0.96
Valine	4.8	4.8	4.9
Arginine	6.6	6.5	6.6
Histidine	3.4	3.3	3.3
Alanine	6.4	6.5	6.6
Aspartic acid	8.4	8.2	8.4
Glutamic acid	13.6	13.6	13.6
Glycine	8.5	8.8	9.0
Proline	5.5	5.6	5.7
Serine	4.1	4.1	4.2

Singh (1988)

- No significant changes in amino acids in chicken proteins, on irradiation and cooking

Evaluation of Nutritional Quality of Food Proteins

- Net protein utilization
  - Digestibility
  - Biological value

Digestion and Nitrogen Metabolism Data of Raw and Radiation-Sterilized Beef and Mackerel

	Beef		Mackerel	
	Raw	Radiation Sterilized	Raw	Radiation Sterilized
True digestibility (%)	100	100	93.2	98.6
Biological value (%)	78	78	82.6	80.2

Singh (1988)

$$\text{Biological value} = \frac{N_2 \text{ utilized}}{N_2 \text{ absorbed}} \times 100$$

- Biological value of radiation sterilized beef does not show any change, while mackerel shows a very small change which could be within biological variability and analytical error

Effect of Irradiation Dose on Digestibility and Biological Value of Protein Components in Standard Rat Diet

Radiation Dose (kGy)	True Digestibility (%)	Biological Value (%)
0	85.6	80.5
5	83.6	75.8
10	86.5	81.7
25	87.0	78.1
35	84.8	77.3
70	85.3	76.4

From Ley, F.J., Bleby, J., Coates, M.E., and Patterson, J.S., Lab Anim., 3, 221, 1969

- No effect on digestibility
- The apparent reduction in biological value may be within experimental error

Effect of Heat and Radiation Processing on the Nutritive Value of Proteins From Some Foods[1]

Protein source	Raw	Heat Processed	Radiation Processed
Pea protein			
True digestibility (%)	92	91	91
Biological value (%)	58	58	51
Lima bean protein			
True digestibility (%)	68	77	70
Biological value (%)	48	64	47
Milk protein			
True digestibility (%)	98	97	97
Biological value (%)	89	84	82

[1]From Metta, V.C., Norton, H.W., and Johnson, B.C., J. Nutri., 63, 143, 1957 and Metta, V.C. and Johnson, B.C., J. Nutri., 59, 479, 1956

- No significant changes on irradiation in digestibility of these foods
- Radiation treatment does not cause as great an improvement in the biological value of lima bean protein as does heat processing although it is the same in pea and milk protein

Nutritive Value of Protein in Irradiated Chicken Meat Stored at 5°C Before Cooking[1]

Dose (kGy)	Protein Efficiency Ratio[2]
0	2.18
3	2.34
6	2.21

[1] Singh (1988)
[2] Protein efficiency ratio is the weight (grams) gained by rats per gram of protein consumed

- At the radiation doses required for poultry, there is no significant effect on the protein efficiency ratio

Conclusions

- From the available information it can be concluded that radiation treatment of foods, even at the high doses required for sterilization, has very little effect on their amino acid and protein content

- In general, there is no significant change in the digestibility, protein efficiency ratio, and the biological value of proteins, for most foods, on irradiation

Evaluation of Nutritional Data (Contd)

(b) Lipid/Fats

- Most important functions of lipids in diet include
  - Source of energy
  - Required for cell structure and membrane functions
  - Source of essential fatty acids
  - Carrier for oil-soluble vitamins

- Other functions include improvements of food palatability and use in food processing, inlcuding use for heat transfer in cooking

Total Saturated and Unsaturated Fatty Acid Content[a] of Neutral Lipids from Irradiated (-20°C) and Unirradiated Chicken Muscle[1]

Fraction	Radiation Dose (kGy)								
	0	1		3		6		10	
		Air	Vac	Air	Vac	Air	Vac	Air	Vac
From Neutral Lipids									
Saturated									
Identified	29.49	29.84	29.65	29.87	29.95	29.70	29.36	29.49	29.88
Unidentified	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total Unsaturated									
Identified	69.51	69.09	69.25	68.92	69.11	69.08	69.30	69.20	68.71
Unidentified	0.45	0.45	0.45	0.46	0.46	0.44	0.45	0.45	0.43

[a] Tabulated values are average of 4 samples, given as normalized percent

[1] Data taken from Rady et al. (1988)

- **Therefore, irradiation has little or no effect. Very similar results in the major components on irradiation at 2-5°C**

Total Saturated and Unsaturated Fatty Acid Content[a] of Polar Lipids from Irradiated (-20°C) and Unirradiated Chicken Muscle[1]

Fraction	Radiation Dose								
	0 kGy	1 kGy		3 kGy		6 kGy		10 kGy	
		Air	Vac	Air	Vac	Air	Vac	Air	Vac
<u>From Polar Lipids</u>									
Saturated									
Identified	34.03	34.12	34.07	34.07	34.21	34.45	34.51	34.47	34.61
Unidentified	0	0	0	0	0	0	0	0	0
Total Unsaturated									
Identified	65.75	65.56	66.00	65.85	65.70	65.45	65.39	65.45	65.00
Unidentified	1.20	1.35	1.37	1.21	1.20	1.20	1.20	1.25	1.18

[a] Tabulated values are average of 4 samples, given as normalized percent
[1] Data taken from Rady et al. (1988)

- Therefore, irradiation has little or no effect. Very similar results in the major components on irradiation at 2-5°C

Changes Observed in Unsaturated Fatty Acids (FA) From Polar Chicken Muscle Tissue Irradiated at 0-10 kGy in Air at 2-5°C[1]

Unsaturated FA	Dose (kGy) at 2-5°C					Change on Irrad at -20°C
	0	1	3	6	10	
	Percent					
Trans-monoenoic						
16:1ω7t	0.23	0.21	0.25	0.22	0.24	None
18:1ω9t	0.22	0.40	0.45	0.50	0.60	None
Cis-monoenoic						
16:1ω7c	1.59	1.62	1.64	1.69	1.91	Very
18:1ω9c	18.63	18.82	19.09	19.29	19.99	Small
Nondienoic polyenoic						
20:4ω6c	12.01	11.55	11.34	11.13	10.48	None

[1] Data taken from Maxwell and Rady , Radiat. Phys. Chem. 34, 791, 1989

Fatty Acid Composition of Irradiated and Unirradiated Kent Variety of Mangoes[1]

Fatty Acids	0 kGy	0.75 kGy
Heptadecanoic acid $C_{17:0}$	0.5	0.4
Lauric acid $C_{12:0}$	0.4	0.4
Linoleic acid $C_{18:2}$	5.3	5.6
Linolenic acid $C_{18:3}$	29.3[2]	26.7
Myristic acid $C_{14:0}$	4.5	4.4
Oleic acid $C_{18:1}$	19.8	20.8
Palmitic acid $C_{16:0}$	19.8	21.7
Palmitoleic acid $C_{16:1}$	17.0	17.7
Pentadecanoic acid $C_{15:0}$	0.4	0.4
Stearic Acid $C_{18:0}$	0.6	0.6

[1] Data taken from Blakesley et al. (1979); [2] significant differences

- 0.75 kGy dose causes only a small decrease (9%) in the level of linolenic acid. It remains to be determined whether even this small difference is in fact a result of irradiation or is instead due to the delay in ripening

Effect of Irradiation and Storage (-18°C) on Free Fatty Acids from Muscle and Adipose Tissues (g Oleic Acid/100g Lipid Extract)[1]

Muscle Tissue	Dose (kGy)			
Storage Time	0		4	
(days)	χ^2	s[3]	χ	s
2	2.3	0.30	2.4	0.23
30	4.2	0.75	5.6	0.92
150	5.0	0.70	4.9	0.75
Adipose Tissue	Dose (kGy)			
Storage Time	0		4	
(days)	χ	s	χ	s
2	1.9	0.23	2.3	0.26
30	3.0	0.46	2.5	0.30
150	3.5	0.30	3.5	0.30

[1] Data from Gruiz and Kiss , Acta Alimentaria, 16, 11, 1987
[2] Measured value; [3] Value of variance

- The data from the work of Rady et al. (1988) showed increase in the individual free fatty acids (FFA) on irradiation
- However, FFA in themselves are not harmful and do not lower the quality of food

Other Minor Fatty Acids

- Minor food constituents, the polyunsaturated fatty acids, sometimes called vitamin F
- A report by British authors that an irradiated mixture of starch and herring oil had considerable destruction of highly unsaturated fatty acids during post irradiation storage in air, caused some concern that irradiation may generally act destructively on unsaturated fatty acids
- However, there is no food that would correspond to this artifical mixture
- When herring fillets were irradiated, even a dose of 50 kGy did not affect the proportions of the polyunsaturated fatty acids
- When whole grains (rye, wheat and rice) were irradiated, no loss of polyunsaturated fatty acids was observed in the dose range of 0.1 to 1 kGy, and only small losses at 63 kGy (Diehl, 1990)

Conclusion

Overall, under optimum conditions, there are no particular losses of the major lipids but some losses of the minor lipids on irradiation of foods. However, there is no loss of their nutritional value as indicated by the measurements of the metabolizable energy of lipids (fats)

(c) Carbohydrates

- Carbohydrates provide ~80% of caloric intake in humans
- The most abundant carbohydrate in human diet is starch (grains, fruits and vegetables) but all mono and polysaccharides contribute a very large component

Carbohydrate Content of the Irradiated and Unirradiated Papayas[1]

Dose kGy	Total Reducing Sugars				Total Soluble Solids	
	(mg/100g)[2]		(% of control)		(Percent)	
	Day 3	Day 6	Day 3	Day 6	Day 3	Day 6
0	6.3	7.5	100.0	119.5	12.0	12.0
1.0	7.0	6.7	111.3	107.0	11.5	12.3
2.0	6.5	6.6	103.5	105.9	11.1	11.7
3.0	5.8	7.1	92.3	113.6	11.3	12.3
5.0	6.3	7.1	100.9	113.9	10.4	11.7

[1] Data taken from Upadhya et al., 1967
[2] Values rounded off to the first decimal place

- Similar results from irradiated ~~of~~ papayas and mangoes

(c) Carbohydrates (contd)

- The deoxy sugars produced during irradiation of oxygen-free sugar solutions may lead to the formation of α–β unsaturated carbonyls (Schubert and Sanders 1971)

.OH + Sugar ⟶ Ṡugar - OH

↓

α–β Unsaturated Carbonyls
(in air-free solution)

- These carbonyls are cytotoxic *in vitro* but practically non-cytotoxic *in vivo* (Schubert 1974). In the case of straw-berries, little or no α–β carbonyls were formed on irradiation (Schubert et al. 1973)

- Formation of malondialdehyde on radiolysis of some carbohydrates has been reported (Adams 1983). The levels of malondialdehyde seen in irradiated foods are too low (ppb) to be of concern

Malondialdehyde in Various Foods After Irradiation(10 MeV Electrons, in Air) and Storage at Ambient Temperatures[1]

Dose (kGy)	Immediately After Irradiation	After 8 Days	After 30 Days
	µg/100 g		
Wheat Flour			
1	13	0	0
5	49	17	8
10	67	23	20
Corn Starch			
1	22	10	0
5	58	24	8
10	101	35	17
Milk Powder			
1	51	38	30
5	95	104	87
10	163	190	145
Rolled Oats			
1	7	0	0
5	20	0	0
10	32	8	0
Wheat Semolina			
1	7	0	0
5	16	0	0
10	24	0	0
Apple Juice			
1	13	0	0
5	21	0	0
10	40	0	0

[1] Scherz, H., Chem. Mikrobiol. Technol. Lebensm., 1, 103, 1972

Overall Metabolizable Energy of Macronutrients From Unirradiated and Irradiated Rat Diets[1]

	Un-irrad[1a]	Irrad[2a]	Un-irrad[1b]	Irrad[2b]	Un-irrad[1c]	Irrad[2c]
Gross Energy cal/100 g diet	353.6	356.4	213.0	213.3	275.0	276.3
Metabolizable Energy (cal/ 100g gross energy intake)	90.0	90.1	89.2	89.0	92.3	91.4

1 Data taken from Kraybill (1984), for three diets with ratios of casein/lard/ carbohydrate as (a) 30/40/23; (b) 14/10/69; and (c) 20/30/43

2 At sterilizing dose; (a), (b) and (c) as in 1 above

- Results of experiments on overall metabolizable energy of unirradiated and irradiated rat diet show that irradiation has no adverse effect on the metabolizable energy of irradiated food

Conclusions

- The levels of malondialdehyde seen in irradiated foods are too low (ppb) to be of concern

- The concentrations fround even in milk powder are very much lower than the concentrations founds in unirradiated meats due to autoxidation and enzyme activity.