U. S. Food and Drug Administration
Center for Food Safety and Applied Nutrition
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Kinetics of Microbial Inactivation for Alternative Food Processing Technologies

Pulsed X-rays

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Scope of Deliverables

This section reviews current applications of X-ray technology for food processing. The advantages of X-rays over other types of radiation are described. A study on the inactivation of *Escherichia coli*, a pathogen of concern, with pulsed X-rays in ground meat is described. Little is known about the inactivation kinetics when X-rays or pulsed X-rays are used for microbial inactivation. Comprehensive research needs to be done to validate the potential use of X-rays in food preservation.

1. Definition, Description and Applications

1.1. X-rays

Several studies have compared the effects of electron beam, gamma rays and X-rays, but comparison between these technologies is inconclusive due to differences in the doses applied (Thorne 1991). It has been suggested that there may be differences in the free radicals formed by these different processes (Taub and others 1979). Electrons have a limited penetration depth of about 5 cm in food (Josephson and Peterson 1982), while X-rays have significantly higher penetration depths (60 - 400 cm) depending upon the energy used (Curry and others 1999).

1.2. Pulsed X-rays

Pulsed X-ray is a new technology that utilizes a solid state-opening switch to generate electron beam X-ray pulses of high intensity. The Institute of Electrophysics in Russia developed a novel nanosecond opening switch in the late 1980□s that could deliver power pulses in the gigawatt range, open at voltages of 100s of kV, and operate repetitively (Curry and others 1999). Opening times range from 30 ns down to a few nanoseconds. Repetition rates have been demonstrated up to 1000 pulses/s in burst mode operation. The specific effect of pulsed in contrast to non-pulsed X-rays has yet to be investigated.

Electrically driven radiation sources that switch off when the radiation is no longer needed are easier to incorporate into existing food processing plants (Martens and Knorr 1992). In contrast, radionuclide sources require permanent massive concrete shielding to protect workers and the environment from their permanent radiation. The practical application of food irradiation in conjunction with existing food processing equipment is further facilitated by: (1) the possibility of controlling the direction of the electrically produced radiation; (2) the possibility of shaping the geometry of the radiation field to accommodate different package sizes; and (3) its high reproducibility and versatility.

Potentially, the negative effects of irradiation on the food quality can be reduced. The radionuclides Co-60 and Cs-137 are produced by neutron bombardment of Co-59 and Cs-136 as a fission fragment of a nuclear power reactor operation. They emit g -radiation of discrete energy. By contrast, the linear induction electron acceleration (LIEA) generates broad spectrum ionizing radiation by targeting the accelerated electron beam to collide with a heavy metal converter plate. This plate converts the electron beam in X-rays with a broad-band photon-energy spectrum. Then, by filtering the energy spectrum of the radiation, high-energy, highly penetrating radiation is produced, resulting in smaller variations in dose uniformity of food packages (Mertens and Knorr 1992) and higher quality. LIEA can deliver dose rates many orders of magnitude higher than possible with Co-60 sources. Consequently, ultra-short, high-intensity radiation treatments can be applied, resulting in higher local radical concentrations and favoring radical-radical recombination reactions. This reduces the diffusion of radical species, which are thought to be responsible for undesirable effects of irradiation on food quality.

Curry and others (1999) used pulsed X-rays to produce up to a 3-log reduction of *E. coli* O157:H7 in ground beef. The system consists of an X-ray accelerator with a thyristor-charging unit, a magnetic pulse compressor, a solid state opening switch, an electron beam diode load and an X-ray convertor (Fig. 1). The thyristor charging unit converts 3 phase (f), 240 V - 440 V power to direct current. A thyristor capacitor charging circuit is used to charge the magnetic pulse compressor (Fig. 2). A 2-stage circuit compresses and sequentially steps-up the voltage pulse before it is used to charge an inductive load or inductance L- as illustrated in Fig. 2. Energy from capacitor C3 is transferred from the inductive load in approximately 100 ns. Upon current reversal through L-, the reverse current through the solid state-opening switch (SOS) rises to tens of kiloamperes. At current reversal, the SOS opens 5-10 ns, generating a 220 keV pulse. The 220 keV, 500 A, 40 ns pulse is delivered to a field emission diode. A prototype accelerator was constructed to operate only on X-ray mode, even though it can be operated either in the pulsed X-ray mode or electron beam mode. A convertor was installed on the accelerator, and the electron beam was converted to pulsed X-rays to allow thick samples to be processed.

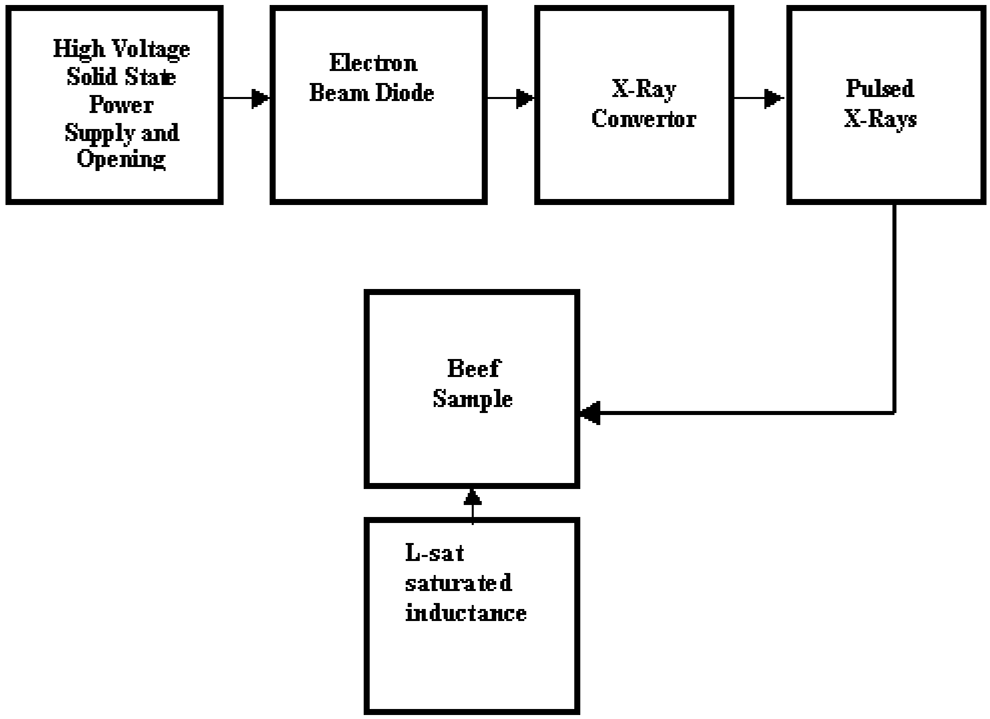

Fig. 1. Schematic flow diagram for pulsed X-rays.

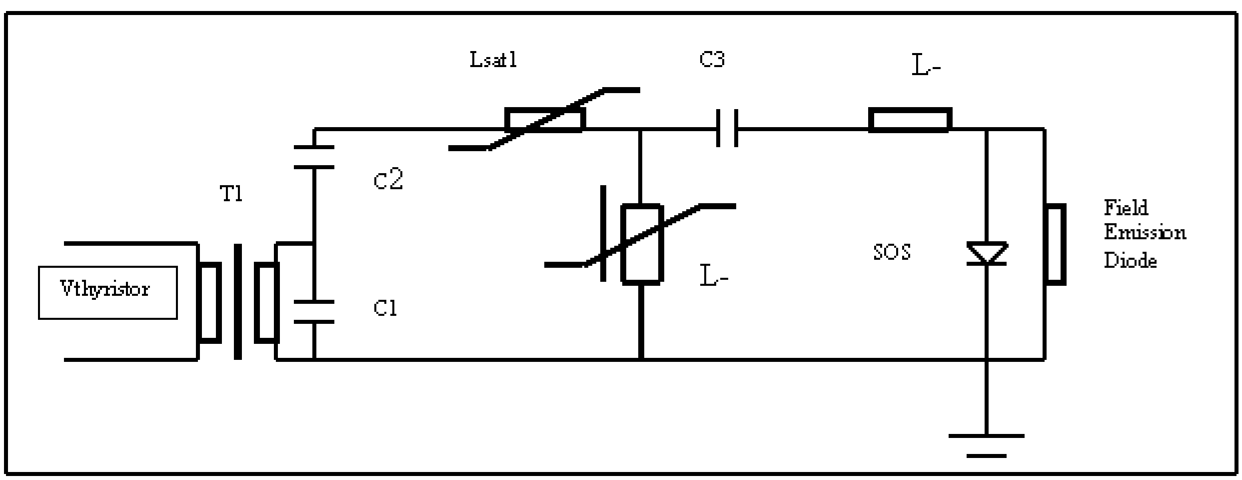

Fig. 2. Electrical circuit for solid state opening switch accelerator system. L-sat, saturated inductance; L, inductance C1,2,3, capacitors; T1, transformer; SOS, switch

2. Pathogens of Public Health Concern

Bremssthrahlung X-rays have been used to eliminate 99.9% of *E. coli* O157:H7 added to ground beef prior to treatment (Curry and others 1999). A high peak rate of 10^7 - 10^8 rads/sec X-ray pulses were used. The study compared X-rays with gamma rays from a cobalt-60 source. Doses in the range of 0.2 to 0.4 and 0.7 to 0.9 KGy were used. The results showed a slighly higher inactivating rate (6%) per log of reduction for X-rays in contrast to gamma radiation.

X-ray irradiation has been used to eliminate *Salmonella* Senftenberg 775W from turkey carcass. The food was irradiated using a General Electric Maxitron 300 X-ray machine, operated at 300 kV peak, 20 MA with a half layer 2.8 mm copper, delivering 268 rads/min at an effective energy of 49 kV (Teotia and Miller 1975). Each carcass or drumstick was placed in the center of the X-ray beam to obtain as complete irradiation of the carcass or drumstick as possible. Each carcass or drumstick was irradiated continuously for 2 h to give a total exposure of 30,000 to 80,000 rads. The temperature in the X-ray room varied between 20 and 24 ° C. Results showed that 80,000 rads of X-ray failed to eliminate the test organism on whole turkey carcasses but reduced the test organism to an undetectable level on turkey drumsticks. Each irradiated carcass or drumstick was aseptically transferred from its packaging to a sterile stainless steel container. As the drumsticks or carcasses were removed from its packaging, they were examined, and no change in appearance of the skin or meat was observed (Teotia and Miller 1975).

3. Mechanisms of Microbial Inactivation

To inactivate surface and subsurface bacteria, fully packaged foods are sterilized by X-ray treatment (Brynjolfsson 1979). X-ray treatment reduces or eliminates *Salmonella* serovars in poultry, mold growth on strawberries and sprout development in potatoes. *Salmonella* serovars have been found to be the most radiation sensitive of all pathogenic organisms on foods (Teotia and Miller 1975). As a method of food preservation, X-ray treatment has low energy requirements.

Radionuclides emit gamma radiation with discrete energy levels (1.17 MeV and 1.3 MeV for Co-60 and 0.67 MeV for Cs-137), while X-ray spectra (from a 5 MeV electron accelerator) have broad energy distributions spanning the same general energy levels (Martens and Knorr 1992). Given these overlapping energy distributions, it is reasonable to assume that mechanisms for microbial inactivation are also similar.

Microbial inactivation by all types of ionizing radiation is thought to happen through 2 main mechanisms: direct interaction of the radiation with cell components and indirect action from radiolytic products, such as the water radicals $^{\cdot}H^{+}$, $^{\cdot}OH^{-}$ and e_{aq}- (Farkas 1997). The primary target of ionizing radiation appears to be chromosomal DNA, although effects on the cytoplasmic membrane may also play a role (Grecz and others 1983). Changes to chromosomal DNA and/or cytoplasmic membrane can cause microbial inactivation or growth inhibition. Many studies have shown that ions, excited atoms and molecules generated during irradiation have no toxic effect on humans.

4. Research Needs

Research needs include:

- Identifying pathogens of concern resistant to the technology and validating surrogates.
- Understanding mechanisms of inactivation.

- Understanding critical process factors and how they affect microbial inactivation.
- Identifying process deviations and how to correct them.
- Investigating the specific effects of pulsed X-rays in contrast to X-rays.

Glossary

A complete list of definitions regarding all the technologies is located at the end of this document.

Bremsstrahlung. One of the 3 possible ways to generate X-rays, and the one commonly used to create X-rays for food irradiation. Literally translated from the German it means "breaking" (brems) "radiation" (strahlung). Bremsstrahlung X-rays are generated when electrons accelerate on coulomb collision with other particles or when a beam of particles decelerates on encountering an obstacle. Synchrotron radiation or Compton scattering can also generate X-rays.

Converter Plate. A heavy metal (usually Pb) plate that converts an electron beam into Bremsstrahlung X-rays with a broad band photon energy spectrum.

LIEA. Linear Induction Electron Accelerator.

SOS. For X-rays technology, solid state opening switch. It can deliver pulses in the gigawatt range.

Thyristor. Charging unit used to convert 3-phase power to direct current.

REFERENCES

Brynjolfsson, A. 1979. Food irradiation and nutrition. The Professional Nutritionist. 11(4):7-10

Curry, R., Unklesbay, N., Clevenger, T., Brazos, B., Mesyats, G. and Filatov, A. 1999. The effect of high doses rate X-rays on E. coli O157:H7 in ground beef. IEEE on Plasma Science. in print.:

Farkas, J. 1997. Physical methods of food preservation. Food Microbiology. Fundamentals and Frontiers. M.P. Doyle, L.R. Beauchat, T.J. Montville(eds.). Washington, D.C. ASM Press. 497-519.

Josephson, E.S. and Peterson, M.S.(Eds.) 1982. Preservation of food by ionizing radiation. I, II, III. CRC Press. Boca Raton, FL

Martens, B. and Knorr, D. 1992. Developments of nonthermal processes for food preservation. Food Technol. 46(5):124, 126-133

Taub, I. A., Kaprielian, R. A., Halliday, J. W., Walker, J. E., Angelini, P. and Merrit Jr, C. 1979. Factors affecting radiolytic effects in food. Radiated Physical Chemistry. 14:639-653

Teotia, J. S. and Miller, B. F. 1975. Destruction of salmonellae on poultry meat with lysozyme, EDTA, X-ray, microwave and chlorine. Poul Sci. 54:1388-1394

Thorne, S.(Ed.) 1991. Food Irradiation. Elsevier Applied Science. London.

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