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

Oscillating Magnetic Fields

(Table of Contents)

Scope of Deliverables

This section reports the effects of magnetic fields on microbial populations. Mechanisms of inactivation and critical process factors are described. Results of microbial testing experiments are controversial. Consistent results concerning the efficacy of this method are needed before its potential use as a food preservation method is assessed.

1. Definition, Description and Applications

Static (SMF) and oscillating (OMF) magnetic fields have been explored for their potential as microbial inactivation methods. For SMF, the magnetic field intensity is constant with time, while an OMF is applied in the form of constant amplitude or decaying amplitude sinusoidal waves. The magnetic field may be homogeneous or heterogeneous. In a homogeneous magnetic field, the field intensity B is uniform in the area enclosed by the magnetic field coil, while in a heterogeneous field, B is nonuniform, with the intensities decreasing as distances from the center of the coil increases. OMF applied in the form of pulses reverses the charge for each pulse, and the intensity of each pulse decreases with time to about 10% of the initial intensity (Pothakamury and others 1993).

Preservation of foods with OMF involves sealing food in a plastic bag and subjecting it to 1 to 100 pulses in an OMF with a frequency between 5 to 500 kHz at temperatures in the range of 0 to 50 ^{o}C for a total exposure time ranging from 25 to 100 ms. Frequencies higher than 500 kHz are less effective for microbial inactivation and tend to heat the food material (Barbosa-Cánovas and others1998). Magnetic field treatments are carried out at atmospheric pressure and at moderate temperatures. The temperature of the food increases 2-5 ^{o}C. According to Hoffman (1985) exposure to magnetic fields causes inhibition in the growth and reproduction of microorganisms. OMF of intensity of 5 to 50 telsa (T) and frequency of 5 to 500 kHz was applied and reduced the number of microorganisms by at least 2-log cycles. Within the magnetic field of 5-50 T, the amount of energy per oscillation coupled to 1 dipole in the DNA is 10^{-2} to 10^{-3} eV (Hoffman 1985). OMF of this intensity can be generated using: (1) superconducting coils; (2) coils which produce DC fields; or (3) coils energized by the discharge of energy stored in a capacitor (Gersdof and others 1983). Inhibition or stimulation of the growth of microorganisms exposed to magnetic fields may be a result of the magnetic fields themselves or the induced electric fields. The latter is measured in terms of induced electric field strength and induced current density. To differentiate between electric field and magnetic field effects, a cylindrical enclosure containing cells and a medium that can be adapted to in vitro studies employing uniform, single-phase, extremely low frequency (ELF) magnetic fields is recommended.

2. Inactivation of Microorganisms

Yoshimura (1989) classified the effects of magnetic fields on microbial growth and reproduction as (1) inhibitory, (2) stimulatory and (3) none observable. Pothakamury and others (1993) summarized the effect of magnetic fields on microorganisms as shown in Table 1.

Table 1. Effect of magnetic fields on microorganisms.

Microorganism	Type of Magnetic filed[a]	Field Strength (T)	Frequency of pulse (Hz)	Effect	Reference
Wine yeast cell	Heterogeneous Smagnetic field	0.04	0	Growth inhibited when exposed for 5, 20, 25, 60, 120, or 150 min; no inhibition for 10, 15, 17 min exposure	Kimball (1937)
Wine yeast cell	Heterogeneous Smagnetic field	1.1	0	No effect for 5, 10, 20, 40 or 80 min exposure	Kimball (1937)
Serratia marcescens	Heterogeneous Smagnetic field	1.5	-	Growth rate remains same as in controls up to 6 h; growth rate decreases between 6	Gerenscer and others (1962)

				and 7 h and again increases between 8 and 10 h; at 10 h cell population same as in controls	
Staphylococcus aureus	Heterogeneous Smagnetic field	1.5	0	Growth rate increases between 3 and 6 h; then decreases between 6 and 7 h; cell population at 7 h is same as controls	Gerenscer and others (1962)
Saccharomyces cerevisiae	Heterogeneous Smagnetic field	0.465	0	Rate of reproduction reduced, incubated for 24, 48 or 72 h	Van Nostrand and others(1967)
Escherichia coli	Smagnetic field	0.3	0	Growth simulated	Moore (1979)
Halobacterium halobium, Bacillus subtilis	Smagnetic field	0.015 0.03 0.06	0	Growth inhibited	Moore (1979)
Pseudomonas aeruginosa, Candida albicans	Omagnetic field	0.015 0.03 0.06	0.1-0.3	Growth simulated; stimulation increases with increase in frequency	Moore (1979)
E. coli	Omagnetic field	0.15	0.05	Inactivation of cells when concentration	Moore (1979)

				was 100 cells/mL	
Streptococcus themophilus in milk	Omagnetic field	12.0	6,000 (1 pulse)	Cell population reduced from 25,000 cells/ml to 970	Moore (1979)
Saccharomyces in yogurt	Omagnetic field	40.0	416,000 (10 pulses)	Cell population reduced from 3,500 cells/ml to 25	Hofmann (1985)
Saccharomyces in orange juice	Omagnetic field	40.0	416,000 (1 pulse)	Cell population reduced from 25,000 cells/ml to 6	Hofmann (1985)
Mold spores	Omagnetic field	7.5	8,500 (1 pulse)	Population reduced from 3,000 spores/ml to 1	Hofmann (1985)
Saccharomyces cerevisiae	Smagnetic field	0.56	0	Decreased growth rate; interaction between temperature and magnetic field only during the logarithmic phase	Van Nostrand and others (1967)

[a]Smagnetic field = static magnetic field; Omagnetic field = oscillating magnetic field

Hoffman (1985) reported on the inactivation of microorganisms with OMF in milk, yogurt, orange juice, and bread roll dough. According to Hoffman (1985) only 1 pulse of OMF was adequate to reduce the bacterial population between 10^2 and 10^3 cfu/g. The intensity of the magnetic field required to achieve these effects varied between 2-25 T and a frequency range from 5-500 Hz.

A review of the literature shows that inconsistent results have been obtained on the effect of OMF on microbial growth (Table 1). In some cases OMF stimulated or inhibited microbial growth and, in others, it had no effect on microbial growth. The results presented in Table 1 show that, although not well understood, the effect of magnetic fields on the microbial population of foods may depend on the magnetic field intensity, number of pulses, frequency and property of the food (that is, resistivity, electrical conductivity, and thickness of the foodstuff).

3. Mechanisms of Microbial Inactivation

SMF or OMF may have some potential to inactivate microorganisms in food. Pothakamury and others (1993) reported 2 theories to explain the inactivation mechanisms for cells placed in SMF or OMF. The first theory stated that a "weak" OMF could loosen the bonds between ions and proteins. Many proteins vital to the cell metabolism contain ions. In the presence of a steady background magnetic field such as that of the earth, the biological effects of OMF are more pronounced around particular frequencies, the cyclotron resonance frequency of ions (Coughlan and Hall 1990).

An ion entering a magnetic field B at velocity v experiences a force F given by:

$$F = q \vec{v} \, x \, \vec{B} \quad (1)$$

Figure 1 shows the movement of a charged particle in a magnetic field. When v and B are parallel, F is zero. When v is normal to B, the ion moves in a circular path (Fig. 2). For other orientations between n and B, the ions move in a helical path (Fig. 3). The frequency at which the ions revolve in the magnetic field is known as the ion's gyrofrequency n , which depends on the charge/mass ratio of the ion and the magnetic field intensity:

$$n = q B / (2 \pi m) \quad (2)$$

where q is the charge and m is the mass of the ion. Cyclotron resonance occurs when n is equal to the frequency of the magnetic field. At 50 μ T, the resonance frequency of Na^+ and Ca^+ is 33.33 and 38.7 Hz, respectively. At cyclotron resonance, energy is transferred selectively from the magnetic field to the ions with n equivalent to frequency of the magnetic field. The interaction site of the magnetic field is the ions in the cell, and they transmit the effects of magnetic fields from the interaction site to other cells, tissues, and organs.

A second theory considers the effect of SMF and OMF on calcium ions bound in calcium-binding proteins, such as calmodulin. The calcium ions continually vibrate about an equilibrium position in the binding site of calmodulin. A steady magnetic field to calmodulin causes the plane of vibration to rotate, or proceed in the direction of magnetic field at a frequency that is exactly = of the cyclotron frequency of the bound calcium. Adding a "wobbling" magnetic field at the cyclotron frequency disturbs the precision to such an extent that it loosens the bond between the calcium ion and the calmodulin (Pothakamury and others 1993).

Hoffman (1985) suggested that the inactivation of microorganisms may be based on the theory that the OMF may couple energy into the magnetically active parts of large critical molecules such as DNA. Within 5-50 T range, the amount of energy per oscillation coupled to 1 dipole in the DNA is 10^{-2} to 10^{-3} eV. Several oscillations and collective assembly of enough local activation may result in the breakdown of covalent bonds in the DNA molecule and inhibition of the growth of microorganisms (Pothakamury and others 1993).

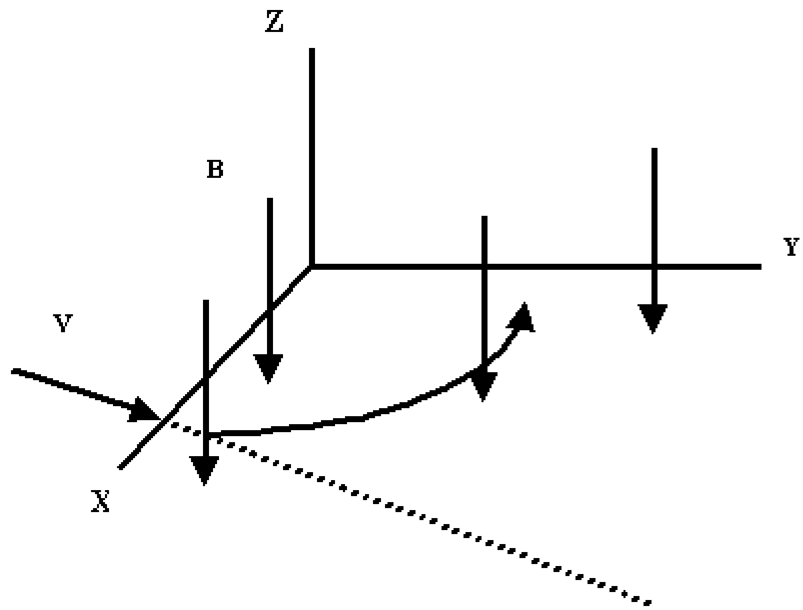

Figure 1. Charged particle in a magnetic field.

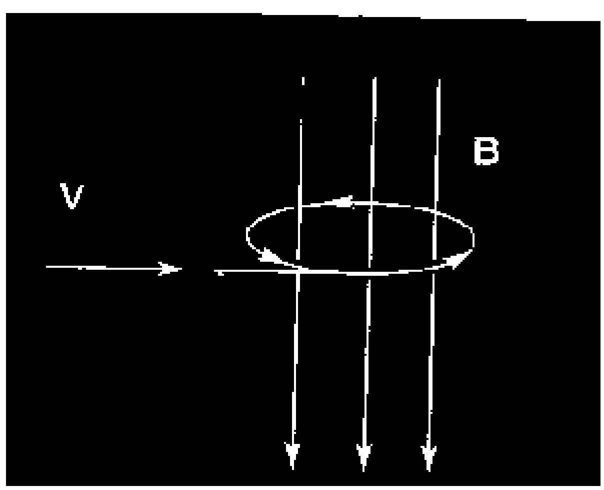

Figure 2. Charged particle in a magnetic field when V is normal to B.

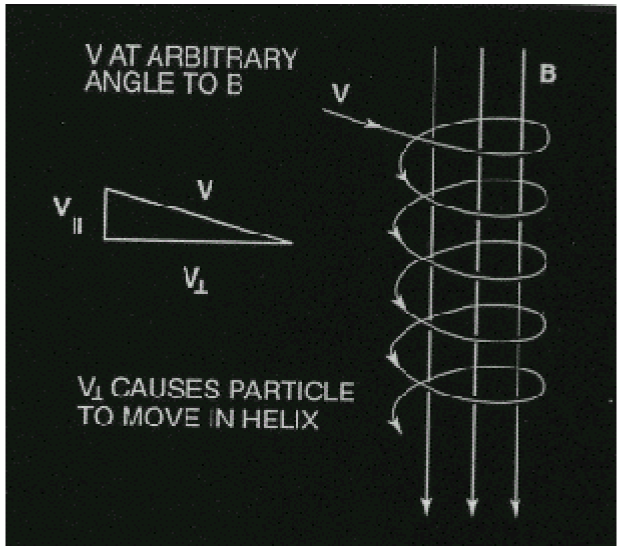

Figure 3. Charged particle in a magnetic field when V makes an arbitrary angle with B.

The work of San-Martin and others (1999) shows that an externally applied electromagnetic signal at frequencies close to a given resonance and parallel to an SMF (Fig. 4) may couple to the corresponding ionic species in such a way as to selectively transfer energy to these ions and thus indirectly to the metabolic activities in which they are involved. The earth's total field ranges from 25 to 70 μ T. Most of the slightly and double charged ions of biological interest have corresponding gyrofrequencies in the ELF range 10 to 100 Hz for this field strength.

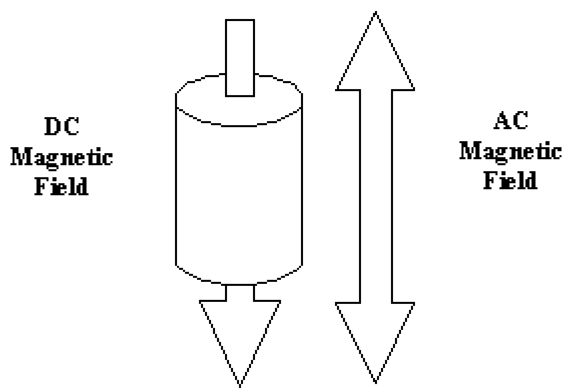

Figure 4. Required AC and DC magnetic field orientation to achieve ion cyclotron.

4. Validation/Critical Process Factors

The critical process factors affecting the inactivation of microbial populations by magnetic fields are not completely understood. Some factors believed to influence microbial inactivation include magnetic field intensity, electrical resistivity, and microbial growth stage.

4.1. Magnetic Field

Exposure to a magnetic field may stimulate or inhibit the growth and reproduction of microorganisms. A single pulse of intensity of 5 to 50 T and frequency of 5 to 500 kHz generally reduces the number of microorganisms by at least 2-log cycles (Hoffman 1985). High intensity magnetic fields can affect membrane fluidity and other properties of cells (Frankel and Liburdy 1995). Inconsistent results of other inactivation studies (see Table 1), however, make it impossible to clearly state the microbial inactivation efficiency of magnetic field or to make any predictions about its effects on microbial populations.

4.2. Electrical Resistivity

For microorganisms to be inactivated by OMF, foods need to have a high electrical resistivity (greater than 10 to 25 ohms-cm). The applied magnetic field intensity depends on the electrical resistivities and thickness of the food being magnetized, with larger magnetic fields intensities used with products with large resistivity and thickness.

4.3. Microbial Growth Stage

Tsuchiya and others (1996), working with homogeneous (7 T) and inhomogeneous (5.2 to 6.1 T and 3.2 to 6.7 T) magnetic fields, found a growth stage dependent response of Escherichia coli bacterial cultures. The ratio of cells under magnetic field to cells under geomagnetic field was less than 1 during the first 6 h of treatment and greater than 1 after 24 h. These authors also found that cell survival was greater under inhomogeneous compared with homogeneous fields. Based on the assumption that magnetic fields could act as a stress factor, cells collected after 30 min of incubation under magnetic field treatment (lag or early lag growth phase) or in the stationary phase after long-term magnetic field treatment were heated to 54 ^{o}C. No differences were observed between the treated and control samples. Little else is known about the effect of microbial growth stage on susceptibility to magnetic fields.

5. Process Deviations

Data acquisition systems must be installed in the processing area to monitor and control the power source, number of pulses, and frequencies applied to the food. Food composition, temperature, size of unit, among other factors also would require control and monitoring to assure constant treatments. Any deviation from the specified conditions such as temperature changes must be continuously recorded and appropriate responses taken. If the system shuts down or fails to deliver the described treatment during processing, the food must be reprocessed to assure quality and safety.

6. Research Needs

There is a significant lack of information on the ability of OMF treatment to inactivate pathogenic microorganisms and surrogates. A main area that needs to be elucidated is the confirmation that magnetic field treatment is an effective process to inactivate microbes. Once this is established, significant data gaps still must be closed before this technology can be safely and practically applied to food preservation. Some of the more significant research needs are:

- Identify key resistant pathogens.
- Establish the effects of magnetic fields on microbial inactivation.
- Elucidate the destruction kinetics of magnetic fields.
- Determine the mechanism of action of magnetic fields.
- Determine critical process factors and effects on microbial inactivation.
- Validate the process and evaluate indicator organisms and appropriate surrogates.
- Identify process deviations and determine ways to address them.

GLOSSARY

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

Cyclotron resonance. Phenomenon that occurs when the frequency of revolving ions induced by a specific magnetic field intensity is similar to the frequency of that magnetic field and parallel to it. In these instances, energy may be transferred to the ions, affecting cell metabolic activities.

Cyclotron. An accelerator in which particles move in spiral paths in a constant.

Dipole. For oscillating magnetic fields, a magnetic particle that contains a *north* and *south* magnetic pole.

Gyrofrequency. Frequency at which the ions revolve in a magnetic field.

Heterogeneous magnetic field. Magnetic field that exhibits a gradient depending on the nature of the magnet.

Homogeneous magnetic field. Magnetic field with a constant strength over space.

Magnetic flux density. Force that an electromagnetic source exerts on charged particles. Magnetic flux density is measured in Telsa (1 Telsa =104 gauss).

Oscillating magnetic field. Fields generated with electromagnets of alternating current. The intensity varies periodically according to the frequency and type of wave in the magnet.

Sinusoidal Wave. A mode of propagation of the magnetic field.

Static magnetic field. Magnetic fields with a constant strength over time.

Telsa. Unit to express magnetic flux density (B). 1 Telsa (T) = 104 gauss.

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