TOPIC #4: EXPOSURE SYSTEMS

SYNOPSIS

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Purpose

To describe the state of knowledge in the design, construction and operation of EMF exposure systems

Many of the features and physical considerations that must be taken into account when developing state-of-the-art exposure systems for power-frequency and other ELF magnetic and electric fields are presented in this synopsis. Magnetic-field exposure systems for *in-vivo* and *in-vitro* studies are considered first, followed by a more brief account of *in-vivo* electric-field exposure systems.

Summary: Magnetic-field Exposure Systems

Historically, Helmholtz coils and pairs of rectangular or square coils have been used to generate known values of approximately uniform magnetic fields in relatively small volumes. As the need for greater volumes of approximately uniform fields developed for animal studies and some *in-vitro* studies, the size and the number of loops of wire have increased. Other needs related to conducting well-characterized biological effects studies also developed. Features that have been considered when designing modern *in-vivo* and *in-vitro* exposure systems include those discussed below.

Field Uniformity

Magnetic-field nonuniformities of less than ± 10% and ± 5% have been considered acceptable for most *in-vivo* and *in-vitro* studies, respectively. Research that considers resonance mechanisms for biological effects may require more uniform fields.

Coil Systems

Design features of coil systems that generate linearly polarized magnetic fields and that are optimized for use in bioeffects studies include quadrupole designs to reduce stray fields, the use of Merritt coils to maximize the volume of nearly uniform field, and the use of bifilar windings to provide equal currents (and power dissipation) to coil systems used for exposure and sham exposure (Stuchly et al., 1991; Wilson et al., 1994). For coil systems that are operated at a single frequency, the introduction of series capacitors to cancel the inductive impedance of the coils reduces the voltage necessary for energizing the coils (Baum et al., 1991), reduces electric fields produced by the coils, and minimizes the introduction of harmonics in the magnetic field.

Field Magnitude

Magnetic fields that range in magnitude from about 0.5 microtesla (μT) to 2 mT have been used for exposure purposes. While larger fields have been used, their relevance to environmental exposures experienced by most humans (even with rough scaling across different animal species) is limited.

Current Sources

Stable currents with small harmonic content can be provided for magnetic-field coils using combinations of function generators and power amplifiers, and with line conditioners and variable autotransformers. Current to the coils can be monitored by measuring the voltage across a resistor (of adequate power rating) in series with the coils. Computer control of these sources is a characteristic of some modern exposure systems.

Polarization

Elliptically, circularly, and linearly polarized magnetic-field exposure can occur in many settings, e.g., near power lines, in residences (Silva et al., 1989), and in some occupational environments. Two-coil systems with axes that are orthogonally oriented have been used with phase-shifted current sources to produce circularly polarized magnetic fields for exposure purposes during human, *in-vivo,* and *in-vitro* studies (Ahlbom et al., 1987; Cohen et al., 1992). Electric fields and currents induced in biological systems by circularly and linearly polarized magnetic fields can have significantly different properties. However, only limited comparisons of experimental results obtained with linearly and circularly polarized magnetic fields have been reported in the archival literature (Kato et al., 1993; Kato et al., 1994).

Stray Fields/Sham Exposure

Background and stray magnetic fields (from energized exposure systems) experienced by sham-exposed animals and cell cultures are typically about 0.2 μT or less. The use of quadrupole coil designs (e.g., vertically stacked or nested Merritt coils) with reduced stray fields permits closer proximity between exposed and sham-exposed biological systems, a generally desirable result.

Vibrations

The influence of wire vibrations in magnetic-field coil systems has been minimized by mechanically decoupling the coils from platforms occupied by test animals or cell cultures, and by impregnating the wires with commercial resin potting compounds with good thermal conductivity. Bifilar coil windings, when operated in the “bucked configuration,” do not control for vibrations because of differences in the vibration frequency spectrum when compared to coils that are used for generating the field (Jones et al., 1996).

Continuous/Intermittent Exposures

Current to the magnetic-field coils can be made continuous or intermittent (i.e., periodically turned on and off) to test the efficacy of continuous or intermittent exposure to cause a biological effect.

Transients

Transients in the magnetic field, events that occur rapidly compared to the period of the exposure field (e.g., "spikes," chopped waveforms), are avoided when the field is turned-on/turned-off by appropriate circuitry in the power supply. For example, magnetic-field coils can be energized or de-energized at "zero crossings" in the current, or the magnetic field can be made to reach its steady state or zero value gradually over several cycles of the ELF field.

Electric Fields

Electric fields produced by magnetic-field coils because of electric potential differences between the loops of wire can be shielded with metal foil connected to ground.

Computer Control

The setting, monitoring, and correcting for drifts in the magnetic field by computer is common to modern exposure systems. Other parameters such as temperature, lights-on/lights-off (*in-vivo* studies), "blind" operation of the exposure system, and periods of field-on/field-off can be monitored and/or controlled by computers.

Incubators

During *in-vitro* studies, the influence of incubators on exposure fields as well as on other physical parameters must be considered. For example, the introduction of magnetic shielding or modification of the incubator may be required to prevent alternating magnetic fields produced by the incubator from reaching sham-exposed cell cultures. In some cases, the confinement of the coil system by the incubator may require measures to prevent heating effects by the coils. Modifications of incubators should not introduce significant gradients in the temperature, humidity, or CO_2 , as the case may apply. The perturbation of the static geomagnetic field by the incubator may be a valid consideration in some experiments, e.g., tests of resonance theories.

Static Magnetic Fields

Well-defined static magnetic fields are required to test various resonance theories. The coil designs for generating static magnetic fields can be the same as those for alternating fields. Static fields parallel to the alternating field can be produced by mounting coils for both fields on the same frame or routing the AC and DC currents through the same coil system (assuming the absence of capacitors). Static fields orthogonal to the alternating field are produced with an orthogonally oriented coil system.

Summary: Electric-field Exposure Systems

Well-characterized electric-field exposure systems used for *in-vivo* studies are briefly considered. Electric-field exposure systems for conducting *in-vitro* studies, without the presence of significant magnetic fields, are described in the primer by Misakian et al. (1993) and are not considered here. Generation of approximately uniform ELF electric fields for laboratory studies with small animals has normally been done using parallel plate systems and with the animals confined in plastic enclosures located on the bottom plate. Exposure systems for larger animals and humans are described in Kaune et al. (1980), Cohen et al. (1992), and Rogers et al. (1995). Most 60-Hz electric field biological studies were conducted during the 1970s and 1980s without the use of computer controls found in modern magnetic-field exposure systems.

Well-characterized electric-field exposure systems take into consideration several factors, described below.

Field Uniformity

Electric-field nonuniformities of ±10% or less are considered acceptable.

Field Magnitude

Electric-field levels from a few kilovolts per meter to 100 kV/m have been used for small animal exposures. The higher fields can be justified by scaling arguments for equivalent surface fields across different animal species and humans.

Animal Proximity Effects

Mutual shielding effects by rats because of their close proximity during field exposure can be as large as 35% under certain conditions (Kaune, 1981). An experimental technique to insure that all animals receive comparable exposures is described in Creim et al. (1984).

Contamination of Plastic Enclosures and Shielding

When test animals contact the surfaces of the plastic enclosures, the surfaces are soiled. The combined effects of soiling and relative humidity can approximate the shielding effects of a Faraday cage. For example, under certain conditions, the electric-field attenuation can reach 40% (Patterson and Dietrich, 1987). Periodic cleaning of the enclosures minimizes the shielding effects.

Stray Electric Fields and Shielding

Unlike that for magnetic fields, shielding of stray electric fields from parallel-plate exposure systems is readily accomplished with coarse wire mesh, which has negligible effect on other physical parameters (e.g., air circulation, lighting) in the laboratory.

Parallel-plate Spacing

Parallel-plate spacing that is too large (relative to plate side dimensions) can lead to unacceptable field nonuniformity in the test animal region; the perturbing influence of nearby ground planes also increases (Misakian, 1984). Parallel-plate spacing that is too small can lead to animal surface fields and induced currents that are greater than that resulting from the shape of the animal in a uniform field (Kaune, 1981).

Electric Field Perturbation by Nearby Ground Planes

Proximity effects of nearby ground planes (e.g., metal walls) can reduce the electric field along grounded plate surfaces. Electric-field measurements provide a convenient means for characterizing the field distribution (Misakian, 1984).

Corona

When parallel plates are energized with the high voltages necessary for producing electric fields in the kV/m range, sharp metal edges can produce corona. Audible noise, chemical products such as ozone, and radio-frequency radiation are all possible byproducts of corona and must be controlled, e.g., by increasing the radius of curvature of energized and nearby grounded conductors.

Location of Food and Water

When food and water are inappropriately placed between the parallel plates, the field can be significantly perturbed. If they are placed above the test animals, spark discharges can occur when the animal drinks water, and low-field regions are created in the space below the food (Misakian, 1984). Control of electric currents through the animal's mouth when it is drinking water is discussed by Kaune (1979) and Kaune et al. (1980).

Quality of Exposure Systems

The quality of exposure systems that have been used in biological effects research supported by the Federal Government (Department of Energy (DOE), National Institute of Environmental Health Sciences (NIEHS)), EPRI, and the New York State Power Lines Project (in the 1980s) has benefited from periodic site visits by a quality control team (supported by DOE) with expertise in the biological and engineering sciences. These site visits, which often included field measurements, were supplemented on some occasions by characterizations of the fields by staff from the National Bureau of Standards/National Institute of Standards and Technology (NIST). While the research results with ELF magnetic and electric fields have been controversial at times, the controversy most often has not been related to the field conditions during exposure. This favorable situation has resulted in part from the site visits noted above, and in part from the efforts of engineers/physicists who have been part of the interdisciplinary teams conducting the research.

Implications for Risk Assessment

As part of the risk assessment process, the existence of quality assurance procedures related to engineering is one criterion that should be considered when evaluating the validity of laboratory studies with magnetic and electric fields.

Remaining Engineering Questions

Our lack of knowledge of how the various parameters that characterize magnetic and electric fields may or may not interact with biological systems (i.e., what constitutes “dose”) influences comments about “remaining engineering questions” related to exposure systems. What can be said is that there are no major engineering questions that would prevent the development of systems that would expose humans and animals to the various field parameters that characterize fields experienced by most people. For example, magnetic-field exposure systems that produce harmonics of the power frequency and circularly polarized magnetic fields have been used during bioeffects research.

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