EXPOSURE PARAMETERS DURING STUDIES WITH ELF MAGNETIC AND ELECTRIC FIELDS

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INTRODUCTION

At the present time, mechanisms for explaining reported biological effects following in vivo and in vitro exposures to extremely low frequency (ELF) magnetic and electric fields are unclear. One consequence of this situation is the uncertainty in determining what characteristics of the field, e.g., magnitude, frequency content, polarization, etc., are the active agents responsible for the reported effects. Therefore characterization of one or more of these characteristics and how they might relate to human exposure may serve as possible goals of a research program[1].

At yet another level of analysis regarding interactions between ELF fields and biological systems, one might consider the induced current density and electric fields, or surface electric fields (for the case of electric field exposure in air) as being important in explaining the reported effects.

Following brief remarks regarding the terminology that describes power frequency and other ELF magnetic and electric fields, a short survey is given of methods for simulating and measuring in a laboratory setting fields encountered by humans in the environment. The remainder of the paper will briefly consider a few of the candidate exposure parameters which might be responsible for reported biological effects. For example, the possible exposure parameters for animals exposed to electric fields include the surface electric field and induced (internal) electric field and current density, and the candidate exposure parameters during animal and cell culture studies with magnetic fields include the induced electric field and current density as well as the alternating and static magnetic fields.

LINEAR AND CIRCULAR POLARIZATION

While concepts of terms such as magnitude and frequency as they are used to describe magnetic and electric fields are familiar to many readers, the concept of field polarization is perhaps less familiar. Magnetic fields produced by single sources consisting of currents in straight or loops of wire (one or more turns) can be represented at a point in space by a vector that oscillates in magnitude and direction along a straight line. Such fields are produced by some grounding systems and electrical appliances and are said to be linearly polarized. Multiple sources of magnetic fields, in which the currents are out of phase with respect to one another, can also be represented at a point in space with a vector. In contrast to the case of linear polarization, however, the vector rotates and in general traces an ellipse. For some conditions, the trace can be approximately a circle. Such fields are said to be elliptically or circularly polarized. Both types of fields have been used during in vivo and in vitro bioeffects studies and will be referred to again later in this paper.

Electric fields also can be linearly, elliptically or circularly polarized. The largest most likely encountered electric fields occur near ground level in the vicinity of power lines. Because the electric fields near ground level are approximately linearly polarized, such electric fields normally have been used for exposure purposes. Further discussion of ELF field polarization is provided in the IEEE standard for ELF measurement instrumentation, IEEE Std 1308-1994[2].

Electricity and Magnetism in Biology and Medicine
Edited by Bersani, Kluwer Academic/Plenum Publishers, 1999

PRODUCING ELECTRIC AND MAGNETIC FIELDS FOR EXPOSURE PURPOSES

Electric Fields

Known electric fields for conducting in vivo bioeffects studies have typically been produced using parallel plates energized with high voltage, with test animals normally confined in plastic enclosures placed on the bottom plate. Issues that may need to be resolved include adequate field uniformity over the volume occupied by the animals (field non-uniformities of 10% or less have been acceptable), proximity effects (shielding) by nearby animals, adequate spacing of the parallel plates, contamination of the plastic enclosures, and elimination of corona. Additional discussion of these parameters and characterization of the fields are given in an NBS primer and the references cited therein[3].

Electric field exposure of cells during in vitro studies is most efficiently implemented by placing the field generating electrodes in culture medium. Agar barriers are normally placed between the electrodes and the culture medium where the cells are located. Discussions of in vitro electric field exposure systems and characterization of fields in culture medium are described in a Bioelectromagnetics journal primer[4].

Magnetic Fields

Linearly polarized magnetic fields can be produced with circular or square Helmholtz coils and multiple rectangular coils (with a common axis). In recent years, rectangular coil systems in a quadrupole arrangement[5] and nested 4-coil Merritt coils[6] have been employed to reduce stray magnetic fields reaching the sham exposed test animals or cells.

Circularly polarized magnetic fields have been produced by two coil systems with their axes orthogonal to one another. The currents in the two coil systems are made to differ in phase by 90 degrees[3]. Non-uniformities in the field of less than 5% and 10% have been considered acceptable for most in vitro and in vivo exposures, respectively. However, if a resonance mechanism is being investigated, greater field uniformity may be required.

Modern magnetic field exposure systems that operate under computer control are now commercially available.

INSTRUMENTATION FOR MEASURING ELECTRIC AND MAGNETIC FIELDS

Electric Field Meters

Three types of electric field meters have been used to characterize power frequency and other ELF electric fields: free-body meters, ground reference meters, and electro-optic meters. Free-body meters are usually battery operated, electrically isolated from ground potential, and supported in the field at the end of a long insulating rod. Ground referenced meters are normally used with the probe or sensor located on grounded surfaces, e.g., the bottom plate of a parallel plate exposure system. The underlying physics for measurements with electro-optic meters differs from that of free-body meters, but it is used in a similar fashion. Discussions of the various types of electric field meters, their principles of operation, calibration procedures, sources of measurement uncertainty, etc., are found in the IEEE standard for instrumentation, IEEE Std 1308-1994[2].

Magnetic Fields Meters

Magnetic field meters are available with single- and three-axis coil probes or sensors. Fluxgate magnetometers, capable of measuring the static and ELF magnetic field, are also available with single- and three-axis sensors. Further details of their operation, calibration procedures, sources of measurement uncertainty, etc., are given in the IEEE standard cited above[2].

ELECTRIC FIELDS IN AIR: SURFACE ELECTRIC FIELDS AND INDUCED CURRENT DENSITY

Normally, the unperturbed electric field is measured when characterizing exposure. This practice has been followed because of the existence of "enhancement factors" (the ratio of the perturbed electric field at the surface of the body to the unperturbed electric field) which permits the determination of the electric field strength at the surface of humans[7,8]. Information is also available, given the unperturbed electric field, which permits the determination of the average induced current density over different parts of the body[8]. The reader is referred to reference 8 for a graphic illustration of how the surface electric fields and induced current densities scale across two animal species and humans. Estimates of the average induced electric field can be made by dividing the current density by the average conductivity in the region of the body under consideration. Yet another reason for measurement of the unperturbed electric field is that exposure limits in several documents have been expressed in terms of the unperturbed electric field strength[9,10].

MAGNETIC FIELDS: INDUCED ELECTRIC FIELDS AND CURRENT DENSITY

Electric Fields and Current Densities in Animals Induced by Magnetic Fields

Electric fields and currents induced by external vertical linearly polarized electric fields (the power line case) tend to have paths that go from the top of humans and some animal species to the bottom or feet, which are typically in contact with a ground plane (or nearly so). In contrast to this pattern, electric fields and currents induced by an external magnetic field, regardless of direction, form closed loops in portions of the body. Illustrations of this difference can be found in a paper by Miller and Creim[11] and the references cited therein. Reference 4 in this paper discusses relations between in vivo and in vitro exposure conditions.

Electric Fields and Current Densities Induced By Magnetic Fields in Cell Culture Media

Electric fields and currents induced in cell cultures are highly dependent on geometrical factors, i.e., the shape and volume of the culture medium and the direction of the magnetic field with respect to the culture medium[12]. Perhaps the simplest geometry for discussing induced currents or electric fields is that of a vertical linearly polarized magnetic field and culture medium in a circular dish. The induced electric field or current density vanishes at the center of the dish, increases linearly as a function of radial distance, and is independent of culture medium depth. This geometry can be used to give cells a range of exposures and also to explore the possibility that an observed biological effect is due to, in part, the induced electric field or is solely a magnetic field effect[13].

Figure 1 compares current densities induced along the bottom surface of cell culture media by linearly and circularly polarized magnetic fields in the horizontal plane. One of the major differences between the two cases is that the induced current density (or electric field) never vanishes as a function of time for the circularly polarized magnetic field[14].

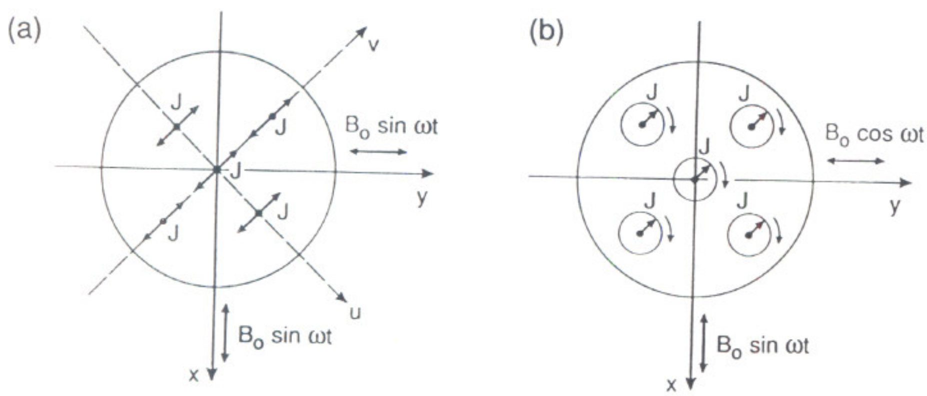

Figure 1. (a) Induced current sheet oscillates along fixed direction for linearly polarized magnetic field, (b) Induced current sheet rotates with constant magnitude for circularly polarized magnetic field.

A recent study that examined electric fields induced in cell culture media by a circularly polarized magnetic field in the *vertical plane* revealed a more complicated picture than Figure 1, and demonstrated that it would be unsuitable for investigating biological effects due to induced electric fields[15].

A complication not considered in the above discussions for induction effects in culture media is the proximity effects due to nearby cells as confluence is approached.

Acknowledgement

This work is supported by the U.S. Department of Energy, Office of Energy Management.

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