TIME VARYING MAGNETIC FIELDS AND DOSIMETRIC PRINCIPLES

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INTRODUCTION AND BASIC PRINCIPLES

In a broad sense, the term "dosimetry" is used to quantify an exposure to radiation. Quantitative descriptions of an exposure for the purpose of formulating protection standards and exposure limits require the use of adequate quantities. "Adequate" means that the quantities should represent, as well as possible, those physical processes which are closely linked to the biological effects of the fields.

From the analysis of established mechanisms it can be concluded that for time-varying magnetic fields the induction is predominant. The appropriate dosimetric quantity which represents the physical processes that are closely linked to the biological effects of time-varying magnetic fields is the induced electric field strength at the cellular level in the living tissue or - connected with the specific conductivity of the medium - the induced eddy current density (Bernhardt, 1979, 1985). By comparing the current densities, it may be possible to predict effects in human beings from those found in studies on animals and isolated cells. In this context, it is irrelevant whether the current density surrounding a cell is introduced into the body through electrodes or induced in the body by external magnetic fields. However, the current paths within the body may be different. The evaluation of human exposure using current densities is based primarily on a concept of "dose" to the critical organs. Basic protection limits can be expressed in permissible current densities; derived protection limits can be expressed as exposures to external magnetic fields. To fully assess the data obtained in bioeffects research, exposure conditions must be well controlled and measured. In this case, the "dosimetry" in bioeffects research with magnetic fields is very complex, since all relevant factors must be taken into account. Factors affecting interaction of magnetic fields are (UNEP 87):

- Parameters of the magnetic field source (frequency, modulation (pulse, AM, FM), rise and decay times (dB/dt), polarisation, field strength, field pattern (uniformity), surrounding material properties);
- Parameters related to exposure (tissue properties (conductivity, anisotropy, permeability), size, geometry, orientation relative to polarization, mode of exposure (partial; whole body));
- extraneous factors (metal implants (ferromagnetic), metal objects in the field, drugs (medications), chemical pollutants).

INDUCED ELECTRIC FIELDS AND CURRENT DENSITIES; RESPONSE OF BIOLOGICAL SYSTEMS

In accordance with Faraday's law, magnetic fields that vary in time will induce potentials and circulating currents in biological systems:

$$J = \sigma E = \frac{1}{2} r \sigma \frac{dB}{dt}$$

where

J = current density (A/m^2),
E = induced electric field strength (V/m),
r = radius of the loop (m),
σ = tissue conductivity (S/m),
$\frac{dB}{dt}$ = rate of change of magnetic flux density B (T/s).

For sinusoidal fields of frequency f the equation reduces to $J = \pi r \sigma f B_o$, where B_o is the magnetic field amplitude.

Thus, the magnitude of the induced electric fields and current densities is proportional to the radius of the loop, the tissue conductivity and rate of change of magnetic flux density. The dependence of the induced field and current on the radius of the loop through which magnetic flux linkage occurs is an important consideration for biological systems. The magnetically-induced electric field strengths and corresponding current density are greatest at the periphery of the body where the conducting paths are longest, whereas microscopic current loops anywhere within the body would have extremely small current densities. The magnitude of the current density is also influenced by tissue conductivity where the exact paths of the current flow depend in a complicated way on the conducting properties of the various tissues. Different authors give different values for the low-frequency conductivity, e.g., for the myocardial tissue and the nerve tissue (white and grey cerebral substance). Additionally, high ratios of the transverse to longitudinal impedance up to 7:1 were observed. The anisotropy of tissue conductivity makes the applicability of phantom techniques using isotropic tissue substitutes questionable. It should be remembered that the current tends to follow routes of least resistance and that the exact current paths of the magnetically induced currents and the exact magnitudes of the current densities are not known and that only rough approximations can be made.

An important factor to be considered in the response of biological systems to the time-varying magnetic field is the waveform. Many different types of magnetic field waveform are used in practice, including sinusoidal, square-wave, saw tooth, and pulsed fields. For these fields, the two parameters of key importance are the rise and decay times of the signal, which determine the maximum time rates of change of the field (dB/dt) and hence the maximum instantaneous current densities induced in tissues. Rms values are often used in the context of electric current effects to give an "effective" value for a variety of waveforms. The peak instantaneous field strengths appear to be important for nerve and muscle cell stimulation, or for perturbing cell functions. The effects strongly depend on the frequency.

A potentially important target of ELF magnetic field interactions is the nervous system. From a consideration of the naturally occurring fields in the central nervous system, it can be concluded that magnetic fields in the 1-100 Hz frequency range, which can induce current densities in tissue of approximately 1 mA/m^2 or smaller, should not have a direct effect on the brain's electrical activity (Bernhardt, 1979). Induced fields sufficient to exceed a threshold depolarisation value can result in an action potential. These effects are well understood. ELF magnetic fields inducing such large depolarisations may result in nerve stimulation or muscle contraction, or even in fibrillation. ELF magnetic fields inducing weak electric fields may also interact with, or modulate, nervous system activity in a manner less well understood, resulting in changes in electrical excitability. Such interactions may be involved in, for example, magneto-phosphenes. These interactions show frequency threshold characteristics of nervous tissue, and have been documented (Bernhardt 1979, 1985). With regard to "hazardous values" and the upper limit of the field strength that leads to injury, the ultimate criterion for the definition of injury may be the initiation of heart fibrillation. The threshold for extrasystole induction at 60 Hz is estimated to be above 300 mT for stimulation times of 1 second or longer, and the threshold for ventricular fibrillation is higher by a factor of 3 - 5 (Bernhardt, 1985). For shorter exposure times, higher field strengths are necessary to produce similar biological effects.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

As stated above, it is difficult to correlate external magnetic field strengths with induced tissue current densities. However, using "worst case" assumptions, an estimate of the order of magnitude for "safe" and "dangerous" magnetic field strengths and their frequency dependence can be made, especially for the critical organs brain and heart (Bernhardt, 1985).

The table summarizes induced current density ranges between 3 and 300 Hz for producing biological effects (UNEP, 87) and values for the magnetic flux density for inducing approximately these current densities at 50 or 60 Hz

Current density mA/m^2	Effects	Magnetic flux density mT
> 1000	extra systoles and ventricular fibrillation possible; definite health hazards	> 500
100 - 1000	Changes in central nervous system excitability established; range, where stimulation of excitable tissue is observed; possible health hazards.	50 - 500
10 - 100	well established effects, evident visual (magnetophosphenes) and possible nervous system effects; induction of bone reunion reported	5 - 50
1 - 10	minor biological effects reported	0.5 - 5
< 1	absence of well established effects	< 0.5

More experimental data are necessary, which include

- the influence of the anisotropy and of inhomogeneities of the tissue conductivity on the induced current densities;
- influences of field gradients on the induced current densities in homogeneous and inhomogeneous tissues;
- specification of the "worst case" conditions and which current densities and current loops are maximally possible;
- the frequency dependence of threshold values for current densities which produce significant biological effects;
- threshold for modulation of nervous systems activity and excitation thresholds especially for single unidirectional pulses or pulse sequences and

connection between the duration of pulses and the rates of change of the magnetic flux density.

On the other hand, several recent epidemiological reports suggest an association of exposure to very weak magnetic field with an increase of the incidence of cancer among children, adults and occupational groups. These correlations cannot be explained by the present knowledge for interaction mechanisms of magnetic fields. Because up to now the available data are inadequate to conclude that magnetic field exposure alone is the reason for the observed cancerogenic effects there must be considerable further study before these reports can be accepted. Similar conclusions can be performed with regard to reports describing teratogenic effects of pulsed magnetic fields on chicken embryos or describing an increase in external malformations among mice exposed to weak pulsed magnetic fields. Although other groups found similar results we are far away from understanding these effects especially the causal relationship with the exposure to magnetic fields.

REFERENCES

Bernhardt, J.H. (1979). The direct influence of electromagnetic fields on nerve- and muscle cells of man within the frequency range of 1 Hz to 30 MHz. Rad. and Environm. Biophys. 16:309-323

Bernhardt, J.H. (1985). Evaluation of human exposure to low frequency fields. AGARD Lecture Series No. 138: The impact of proposed radio frequency radiation standards on military operations, pp. 8.1-8.18.

Tenforde, T.S. (1985). Mechanisms for biological effects of magnetic fields. In: "Biological effects and dosimetry of static and ELF electromagnetic fields (Grandolfo, M., et al., eds.) Plenum Press, New York and London. pp. 71-92

UNEP (1987). United Nations Environmental Programme; Environmental Health Criteria 69, Magnetic Fields. WHO, Geneva.