ESTABLISHED BIOLOGICAL EFFECTS OF EXTREMELY LOW FREQUENCY (ELF) FIELDS, CURRENT PROTECTION CONCEPTS AND RESEARCH NEEDS

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INTRODUCTION

Public concern about possible health hazards from exposure to electromagnetic fields is growing. However, although several epidemiological studies suggest a weak association between the exposure to extremely low-frequency (ELF) fields and an increase in various kinds of cancer, a final risk assessment of long-term continuous exposure to ELF fields is not possible so far. There has not been a definite proof yet that the electric and especially magnetic ELF fields occurring at working places or in every-day life are mutagenic or carcinogenic. Questionable points are those concerning statistical evaluation, insufficient determination of the field strength during exposure, dose-effect relationship, inadequate demarcation of concomitant factors, and - most important - the absence of known interaction mechanisms (for further details see contribution of J. Stolwijk in this book). A final clarification of the question of possible late effects requires further elucidation. The non-stochastic ELF field effects, therefore, are of major importance for the derivation of standards (7).

INTERACTION MECHANISMS

Direct coupling mechanisms: Electric fields

Biological material is a much better conductor than air, therefore an electric field is distorted by the presence of a living being in the field.

Due to polarisation effects electric fields act on the outer surface of the body and lead to hair movements and sensory effects. In addition, time varying electric fields induce surface charges on an exposed body which result in currents inside the body, the magnitudes of which are related to the surface charge density. Depending on the exposure conditions, the surface charge density can vary greatly resulting in a non-uniform distribution of currents inside the body. For sinusoidal electric fields the magnitude of the currents inside the body increases proportionally with frequency. The induced current density distribution varies inversely with the body cross-section and may be relatively high in the neck and ankles of people.

In a wide variety of materials the current density $\underline{J}$ is directly proportional to the field strength $\underline{E}$, $\underline{\mathbf{J}} = \sigma \underline{\mathbf{E}}$, σ is the frequency dependent electrical conductivity of the medium.

Direct coupling mechanisms: Magnetic fields

The permittivity of biological material and air is about the same, therefore magnetic fields, unlike electric fields, penetrate biomaterial without any loss. Time varying magnetic fields induce electric fields and those cause currents inside the body. The internal tissue current density $\underline{J}$ is related to the external magnetic induction $\underline{B}$, using the Maxwell equations, its absolute value can be approximated by : $\mathbf{J = 0.5\, R\, \sigma\, dB/dt}$, where R is the radius of the inductive loop perpendicular to the direction of the magnetic induction.

The appropriate inductive loop radius depends on the orientation of the magnetic field relative to the body. Theoretically, the largest current densities will be induced in the peripheral tissues and will decrease linearly towards the center of the body as the inductive loop radius decreases.

Indirect coupling mechanisms

ELF electric fields interact with biological bodies through electric charges induced on ungrounded metallic objects, such as cars, trucks, cranes, wires and fences. Two types of interaction may occur:

- a spark discharge between the object and the person touching the object;
- the passage of current to ground through a person coming into contact with such an object; the magnitude of the current depends on the total charge on the object and on the person's impedance to ground. This charge, in turn, depends on the frequency, the electric field strength, the object geometry and its capacitance.

Interferences with medical devices

In addition to direct and indirect coupling mechanisms of low frequency fields, interference with active and passive medical devices has to be taken into account. For persons with implanted electronic devices, such as pacemakers, insulin pumps or cochlea implants and for persons with ferromagnetic implants, e.g aneurysm clips or protheses, magnetic fields may pose potential health risks. For example pacemakers in demand-mode may be activated; if the pacemaker rhythm then is asynchronos to the heart activity, this may pose a certain risk. For worst case situations the interference field strengths for 50 Hz fields were determined to be 1.7-6.8 kV m^{-1} resp.13.8-55 μT (8). Very slow fields may also inhibit continuously working pacemakers, especially for frequencies of some Hz, which is close to the heart activity.

BIOLOGICAL EFFECTS

Cellular Studies

Extremely low frequency electromagnetic fields induce time varying distributions of electric charges in tissues and electrical currents. The local electrical field strength respectively the local current density are responsible for any possible effects. Basically all organisms can be influenced by charges, because all molecules contain charged groups and the change of electric potentials plays an important role during chemical and biochemical reactions. In order to examine the interaction of electromagnetic fields and biological systems, the cell, the cell membrane or molecules are possible sites to be inspected.

The cell membrane is a barrier between the cytoplasm with a specific composition of ions and the extracellular medium. The lipid bilayer therefore shields chemical substances and charges. The cell has a negative potential with respect to the extracellular side, in most cases the potential difference is about -70 mV. Consequently there is an electric field strength of about 10 V m^{-1} across the 8 nm of the membrane. Natural biogenic electrical fields result from potential differences at cell membranes e.g. action potentials of nerves and muscle cells. Close to such cells, field strengths up to 200 V m^{-1} can be measured. In the periphery of the heart or brain even a field strength of 50 mV m^{-1} or current densities of 10 mA m^{-2} are possible. It is speculated that these relatively large natural fields are part of an extracellular communication between electrically excitable cells (10).

If the current densities in tissue, induced by electromagnetic fields, are large enough to depolarize the membrane potential up to the excitation threshold, a well defined biological reaction will follow. The mechanisms and thresholds of nerves and muscles are well known in classical electrophysiology. At levels of induced current density exceeding 100 to several hundred mA m^{-2} for frequencies between about 10 Hz and 1 kHz, thresholds for neuronal and neuromuscular stimulation are surpassed. The stimulation for single nerve- and cardiac muscle cells are well above 1 A m^{-2} (11). The threshold current densities increase progressively at frequencies below several Hz and above 1 kHz.

In contrast there is little known about the consequences and the possible mechanisms of interactions between induced, weak electrical fields and biological systems. The induced fields are permanent present and often possess higher frequencies than endogenous fields do (4).

At the moment the hypothesis is that the extracellular surface of the membrane is the target for interaction, it is based on the results of numerous cellular studies using weak magnetic field exposures. It is agreed that receptors in the membrane will be influenced and highly specialized transduction pathways can transform information into the cell. The primary process of the field - protein - coupling mechanism in not understood.

The membrane receptors are specified to transduce one single input signal (e.g. enzyme molecule) to a dominant output message. This unique biological amplification of small signals, lead to the development of many different specific receptor types. Therefore field induced modulation of this transduction pathway leads to different types of reactions without systematical relation.

In experiments, with current densities above 10 mA m^{-2} the following basic effects were produced

- influence of regulation and messenger systems of the cells,
- interference with protein synthesis,
- influence on cell growth and differentiation,
- complex physiological phenomena.

But also exposure with weak magnetic fields below 100 μT (inducing current densities less than 2 mA m^{-2}) may modulate some biological reactions. An evaluation of the various studies with weak fields, is difficult as the results of other labs were not reproduced and the effect found do not differ clearly enough from normal biological variations. Additionally, other experimental parameter proofed to be more effective stimulants.

Animal studies

Many biological endpoints have been examined using exposed rodents or other mammals. There is little evidence to suggest that low level exposure causes any consistent effect on the heart, lungs or immune system.

Various investigations have shown that power frequency fields may affect circadian rhythms via the hormone melatonin (12, 18).

There is some concern about the possible adverse effects of exposure to fields on reproduction and development of embryos and fetuses of chickens but not of mammals (9).

It has been suggested that magnetic fields may increase the risk of cancer incidence by reducing the oncostatic potential of melatonin (14, 18). Studies on carcinogenesis excluded the possibility of initialising cancer by electromagnetic fields, however fields may have a promoting or a co-promotor capacity leading to increased cellular proliferation (9).

Electric Fields - Studies On Volunteers

ELF electric fields can be perceived because of the field-induced vibration of body hair, or the occurrence of spark discharges on contact with clothes or grounded objects. The threshold for perception by hair vibration shows wide individual variation: Only 5% of exposed subjects are able to detect fields as low as 3-5 kV m^{-1} (2, 16). The threshold depends on the relative positions of the head, trunk and limbs, simply as a consequence of the different perturbations of the incident field.

Above a certain threshold, the current to ground is perceived by the person as a tingling or prickling sensation in the finger or hand touching the charged object, for frequencies below about 100 kHz, and as heat at higher frequencies. Although these effects are not considered to be a hazard, hair vibration and tingling if sustained can become an annoyance (5).

A severe shock can be experienced at levels much higher than threshold. The threshold current depend on frequency and on surface of contact area. The thresholds for women are about one third lower and the thresholds for children about 50% lower than the equivalent thresholds of men (3).

Of greater biological significance may be the occurrence of capacitive spark discharges (microshocks) which are generated when two objects of different potential come into close proximity and the electric breakdown field strength of the air is exceeded. These spark discharges will continue as long as the air gap and the potential difference is maintained. The current flows across a very small area of skin and results in a high current density which may be perceptible, irritating or painful. Exposed people may demonstrate stress reactions in the presence of repeated spark discharges with increased nervousness and inability to continue to work.

The threshold for the perception of spark discharges by 10 % of a group of volunteers close to an earthed object has been reported to be 0.6 to 1.5 kV m^{-1} at 50 to 60 Hz, with a similarly defined threshold for annoyance of 2 to 3.5 kV m^{-1} (2). Sensitivity appears to depend on such factors as skin hydration, body location and skin temperature.

There are also extensive laboratory tests on volunteers with better defined exposure conditions, but limited exposure time. The laboratory tests include field exposure times from 3 h to 1 week and field strengths of up to 20 kV m^{-1}. The variables examined were reaction time to optic and acoustic stimulation, physiological factors, EEG, ECG, blood pressure, pulse frequency, body temperature, blood status, biochemical parameters of blood and urine, enzymes and metabolic factors. No significant changes were found.

Magnetic Fields - Studies On Volunteers

At frequencies below approximately 100 kHz, interactions of time varying magnetic fields with biological systems and potential hazards can be considered in terms of induced currents and current densities. The use of induced current densities, is appropriate for the assessment of acute, immediate effects, while it may have some limitations for the complete evaluation of long-term effects. The waveform of the electromagnetic field and peak instantaneous field strengths are important factors to be considered in the response of biological systems. Generally, for frequencies above 100 to 1000 Hz, the thresholds for stimulation effects increase with frequency, up to frequencies where thermal effects dominate (> 100 kHz).

The ability of people to perceive 50 or 60 Hz magnetic fields has been studied by several groups. Visual phenomena (magnetophosphenes) caused by magnetic fields depend not only on the frequency and flux density of the magnetic field, but - with eyes open - also on adaption condition or background illumination. The sensitivity thresholds were found to be frequency dependent with a minimum threshold (maximum sensitivity) of approximately 5 mT at 20 Hz, although threshold values as low as 2 mT have been quoted, rising at lower and higher frequencies. The threshold current density at 20 Hz is estimated to be 10 mA m^{-2}. The investigations indicate that visual phenomena are not released by the magnetic field, but rather by the induced currents influencing the bipolar ganglion cells of the retina. This also explains the agreement between magneto- and electrophosphenes which may result from alternating currents produced by electrodes (5).

Following the development of clinical magnetic resonance imaging (MRI) diagnostic techniques, patients are routinely exposed during examination to intense (up to several mT), time-varying longitudinal and transverse gradient magnetic fields, pulsed at frequencies below about 10 kHz. Experiments have been carried out using volunteers in order to identify thresholds for peripheral nerve stimulation. Small, involuntary muscular twitches of the nose, and sometimes of the lower back and thigh, were reported. Threshold values depend on the orientation of the magnetic field relative to the body and have been estimated to range between about 25 and 60 T s^{-1}, the lower values corresponding to transverse magnetic field orientation and to current densities exceeding 500 mA m^{-2} (5).

The exposure of volunteers for several hours to 50 or 60 Hz fields of up to 5 mT had no effect on a number of clinical and physiological tests, including haematology and blood biochemistry, ECG, heart rate, blood pressure and body temperature; elevated triglyceride levels were ascribed to other, confounding factors (5, 17).

It may be assumed on the basis of all known effects that man is influenced by low-frequency magnetic fields (50/60 Hz) of more than 5 mT. Volunteers exposed to intense ELF magnetic fields (up to 100 mT) at frequencies between 5 and 50 Hz have reported „indisposition and headaches" during exposure above 60 mT. Changes were also recorded in the visually evoked potential response at this magentic flux density (corresponding current densities of 100 mA m^{-2}, although visual acuity itself was apparently unaffected. Reversal of VEP's were observed that are reported not to be immediately reversible.

CURRENT PROTECTION CONCEPTS

Health implications and basic restrictions

Any discussion on the restriction of exposure has to be built on a certain protection concept. For non-ionizing electromagnetic fields usually the health threshold based system is applied: that is adverse health effects are identified together with the type and magnitude of the fields which cause this effect.

Given the inadequacy of the available data on carcinogenicity, exposure limits for electric and magnetic fields are currently based on well established mechanisms and experimental findings related to acute effects. The published guidelines are based on the limitation of electric fields or current densities induced in the body by exposure to electric or magnetic fields. Nevertheless, by considering the merits of the induced current approach for risk assessment, one should not mistakenly conclude that alternative explanations for other phenomena are impossible.

The following observations can be made for induced current density ranges and magnetic flux densities induced by sinusoidal homogeneous fields (17):

- Below 10 mA m^{-2} are the naturally occurring endogeneous currents of the body.
- Between 10 mA m^{-2} and 100 mA m^{-2} there are well established effects on the visual and nervous system.
- Between 100 mA m^{-2} and 1000 mA m^{-2} changes in the excitability of nerveous tissue is observed and there are possible health hazards.
- Above 1000 mA m^{-2} nerve stimulation and stimulation of the heart including extrasystoles and ventricular fibrillation can occur (acute health hazards).

Based on these data, levels of exposure are recommended which lie well below the levels of nerve excitation. In order to chose an approriate safety margin for such a recommendation, the following factors have to be considered:

- It is difficult to correlate precisely tissue current densities with external fields.
- There is a wide difference in perception thresholds, e.g. between children and grown-ups.
- Extrapolation from acute short term effects to long term exposure.
- Combined effects of exposure to fields and other chemical or physical agents of the environment.
- Medicated persons may have different responses.

Furthermore, experiments are conducted for specific frequencies only so that the whole frequency range and especially all possible modulations cannot be covered with sufficient data. The available set of data mostly is not obtained from experiments with human beings.

In the frequency range between 10 Hz and 10 kHz, for levels of induced current densities above 100 mA m^{-2} the thresholds for possible acute health hazards are surpassed. Given the considerations above a safety factor of 10 was chosen and it was decided, that for human exposure only current densities below 10 mA m^{-2} should be allowed.

This basic restriction is a factor of 10 below serious acute effects like reversal of VEP and below the lowest threshold of changes in central nervous system excitability. Furthermore this basic restriction is a factor of 100 below the threshold of definite health hazards (ventricular fibrillation).

Then there are additional reasons to adopt lower exposure limits for the exposure of the population than for the ocupationally exposed persons. The main reason are the following: the general public comprises individual persons of all ages and different health status, individuals or groups with particular health susceptibility may be included in the general population. Exposure of the general public may last all day long, where as occupational exposure is restriced, usually to 8 hours a day for 5 days a week. Finally the public cannot be expected to take any risks or to accept any annoyances e.g. from contact currents. Thus for the exposure of the general public another factor of 5 was chosen, which leads to maxium current densities of 2 mA m^{-2}, corresponding to the current densities naturally occurring in the tissues and organs of the body.

The current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction. This averaging seems to be sufficient to include spatial peak values due to differences in the conductivity and in view of the fact that the effects of current densities are occuring at the cellular levels and that the safety zone from stimulating effects is sufficiently large.

Derived exposure levels

In practice, values of „field" quantities are required since the basic quantities cannot be measured directly in the human body. The derived exposure levels is the permissible value for the electric or magnetic field strength which is derived from basic restrictions. Derived exposure levels are given to provide a method of assessment for the effect of electromagnetic fields and to demonstrate compliance with the basic restrictions of exposure. Said exposure levels have been specified in such a manner that the basic restrictions are not exceeded even if the most unfavourable conditions of field exposure are taken as a basis.

Since the first attempt to relate external exposure to internal current densities (1) several numerical and measuring methods were developed for the derivation of field strength exposure limits from the basic restriction. For both methods considerable simplifications have been used up to now that did not account for phenomena such as the inhomogeneous distribution and anisotropy of the electric conductivity and other factors.

Magnetic field models assume that the body has a homogeneous and isotropic conductivity and apply simple circular conductive loop models to estimate induced currents in organs and body regions, i.e., for the head by using the relation $\mathbf{J} = \pi \mathbf{R} \sigma \mathbf{f} \mathbf{B_o}$ (amplitude of the field $\mathbf{B_o} = \sqrt{2} \cdot \mathbf{B_{rms}}$). More complex models use an ellipsoidal-shaped model (11) to represent the trunk or the whole body for the estimation of induced currents resulting in higher current densities which occur at the periphery of a body. Results are summarized in table 1 for 50 Hz. The exposure level of 0.5 mT for occupational exposure or 100 µT for general public exposure recommended by (7) corresponds to maximum current densities of about 8 mA m^{-2} or 1.6 mA m^{-2}, respectively, in peripheral regions of the trunk. Referring to more realistic calculations based on an anatomically and electrically enhanced model (15) result in higher current densities (i.e., 0.5 mT induce 12 mA m^{-2} at 60 Hz).

Electric field models have to take into account that depending on the exposure conditions, size, shape and position of the exposed body in the field, the surface charge density can vary greatly resulting in a variable and non-uniform distribution of currents inside the body. Thus for sinusoidal electric fields below about 10 MHz the factor of proportionality σ between the current density and the external field strength should be replaced, so that, $\underline{J}=A\ f\ \underline{E}_{ext}$, where $\underline{E}_{ext}$ is the external unperturbed electric field strength and A is a „shape factor" for human body parts of specific shape and a specific orientation.

The factor A can be determined by model calculation (including measurements) for different parts of the body: for the trunk (average) about $6.7 \cdot 10^{-9}$ S Hz^{-1} m^{-1}, for the ankle about $40 \cdot 10^{-9}$ S Hz^{-1} m^{-1} for the neck about $10 \cdot 10^{-9}$ S Hz^{-1} m^{-1} and for the head $2 \cdot 10^{-9}$S Hz^{-1} m^{-1}. These numbers show that the induced current density distribution varies with the body cross-section and may be relatively high in the neck and ankles of people. The electric field strengths which approximately procuce current densities of 10 or 2 mA m^{-2}, respectively, in different body parts are listed in Table 1. The exposure level of 5 kV m^{-1} for continuous general public exposure recommended by (7) corresponds to a current density of about 2.5 mA m^{-2} in the neck and about 1.7 mA m^{-2} in the trunk (average) if the E-field vector is parallel to the body axis.

Table 1: 50-Hz-electric field strengths and magnetic flux densities producing approximately current densities of 10 mA m^{-2} or 2 mA m^{-2}, respectively, in different body parts (6)

	Trunk (average)	Head	Neck	Ankles, when both feet are grounded	Whole Body (ellipsoidal model)	Head	Wrist/ Ankle
	Shape factor in 10^{-9} S $Hz^{-1}m^{-1}$				$\sigma = 0.2$ S m^{-1}		
Parameters for calculation	A = 6.7	A = 2	A = 10	A = 40	a =0.2 m b =0.85 m c =0.1 m	R=0.075m	R=0.03m
Current density	Electric field strength (kV m^{-1})				Magnetic flux density (mT)		
10 mA m^{-2}	30	100	20	5	0.6	2.5	6
2 mA m^{-2}	6	20	4	1	0.12	0.5	1.2

RESEARCH NEEDS

Recently research on interaction mechanisms of electromagnetic fields has increased enormously. In spite of the large amount of publications there still is no convincing answer, how weak electromagnetic fields in the body can lead to an interaction even below electric stimulation thresholds.

Based on numerous studies with exposure to weak magnetic fields it is hypothesized by now that the induced currents and voltages in the extracellular medium interact with electrochemical processes at the cell surface.

Some biological effects can only be evoked by fields with a narrow set of parameters therefore reaction windows were postulated. Experimental data then have to be used to test the existence of nonlinear intensity-reaction-relations. Only after the proof of this hypothesis a transfer to other biological systems is possible.

The weak fields obviously do have a very differential interaction with the metabolism of organisms. Various effects only lead to a minor temporal modulation of biological reactions. The measurement of different physiological, parameters showed heterogeneous and contradictory results.

Therefore there still is a need for fundamental research to find and to define one or more primary mechanisms. For example it should be found out, if it is the magnetic field or the induced electric field which is responsible for a reaction.

Only with the knowledge of the primary reactions, a systematic concept of research projects can be established for examining the pathway of the biological signal to the manifested effect and for testing the possibility of transduction with subsequent amplification cascades. It has to be elucidated for example which physiological functions are involved and if cells have different sensibilities.

Studies on immune and nervous systems then have to show if those single cells effects can influence the circulation system or the embryonic development or the whole organism have to be tested with exposure conditions.

Central nervous system responses to induced electric current should be further investigated including, for example, *in vitro* brain slice studies of weak electric current effects.

There is a particular need for studies on the possible carcinogenicity of electromagnetic fields. The experimental work should include co-carcinogenesis experiments, particularly looking at co-promotion in animal and cellular models, studies of effects on cell signalling and proliferation, Ca^{2+} uptake and gene expression, and further study of effects on melatonin and its possible role in the suppression of mammary tumour growth.

Further investigations of possible weak ELF field interaction mechanisms particularly of experimentally testable hypotheses such as magnetic field effects on radical pair interactions have merit as well as studies of weak electromagnetic fields interactions with the optical system, in relation to effects on the production of melatonin by the pineal gland.

After the field induced changes or modulations of biological systems are scientifically established, it has to be found out, whether these evoked effects are potentially pathogenic.

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