BIOLOGICAL EFFECTS OF ELECTROMAGNETIC FIELDS

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INTRODUCTION

The effects of electromagnetic (em) fields on biological systems were first observed and exploited well over a century ago. Concern over the possible health hazards of human exposure to such fields developed much later. It is now well known that excessive exposure to em fields may have in undesirable biological consequences. Standards were introduced to determine what constitute an excessive exposure and how to avoid it. Current concern over the issue of hazards stems mainly from recent epidemiological studies of exposed populations and also from the results of laboratory experiments in which whole animals are exposed in vivo or tissue and cell cultures exposed in vitro to low levels of irradiation. The underlying fear is the possibility of a causal relationship between chronic exposure to low field levels and some forms of cancer. So far the evidence does not add up to a firm statement on the matter. At present it is not known how and at what level, if at all, can these exposure be harmful to human health. This state of affair does not provide a basis for incorporating the outcome of such research in exposure standards.

This paper will give a brief overview of the research in this field and how it is evaluated for the purpose of producing scientifically based standards. The emphasis will be on the physical, biophysical and biological mechanisms implicated in the interaction between em fields and biological systems. Understanding such mechanisms leads not only to a more accurate evaluation of their health implications but also to their optimal utilisation, under controlled conditions, in biomedical applications.

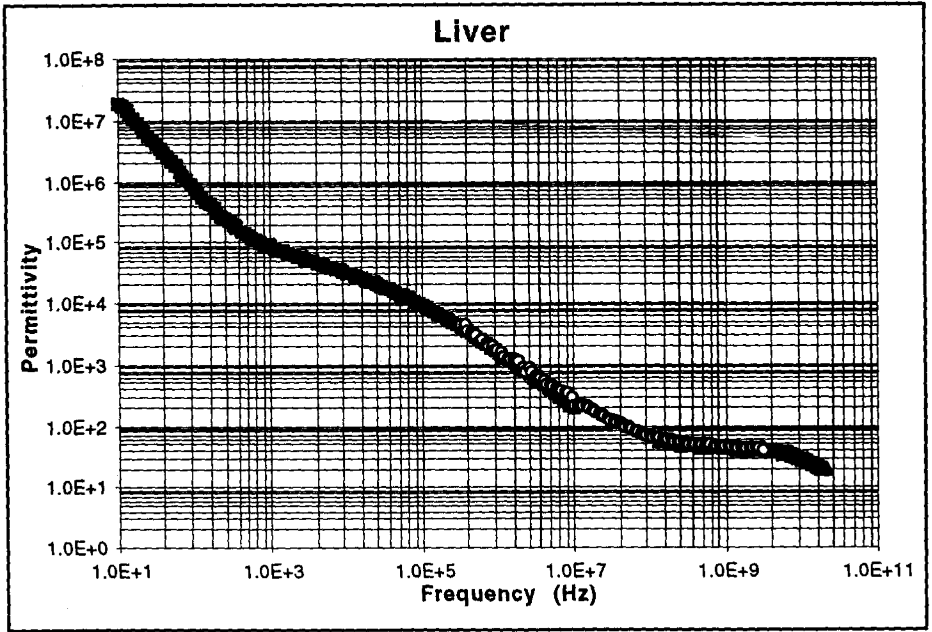
INTERACTION OF EM FIELDS WITH PEOPLE

Interactions between em fields and people occur at all levels of organisation. The coupling of external fields with the body is the first step leading to further interactions at the cellular and molecular level. The initial coupling is a function of numerous parameters including field characteristics as well as the size and shape of the body and its electrical properties. The coupling is most efficient when the size of the body is of the same order of magnitude as the wavelength of the field and when the long axis of the body is in the direction of the field. This statement is based numerous dosimetric exercises in which the shape of the body was approximated to a geometric form such as a homogeneous ellipsoid to facilitate calculations and on later verifications using more realistic models (1). A consequence of the primary interaction is that internal fields are induced inside the body. The quantification of these fields and their spatial distribution is the concern of dosimetry.

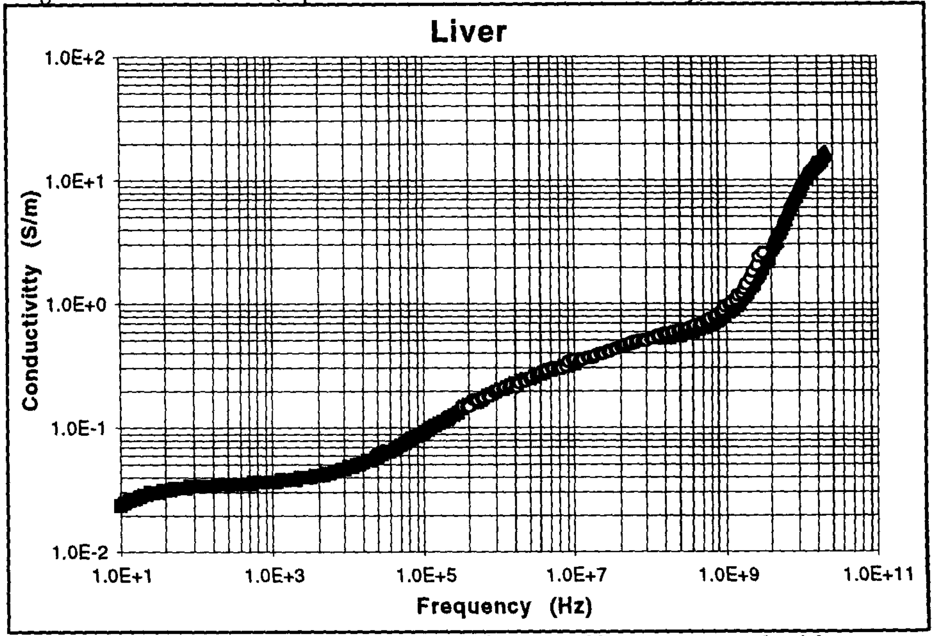
The internal fields will, in turn, induce local fields at the level of the cells, in the extracellular space, within cells and across cell membranes (2). The quantification of these fields and the determination of local current pathways is termed microdosimetry (3). Microdosimetry can be extended to include interactions at the molecular level using concepts of em energy absorption and the establishment of internal thermal gradients (4).

Electromagnetic fields interact with matter through forces generated on charges. Internal electric fields act on bound and free charges in the body tissue causing polarisation, molecular orientation and the establishment of ionic currents. There is little, if any, direct interaction with a magnetic field, instead, time varying magnetic field generate electric fields with the usual consequences.

The electrical properties of tissues (relative permittivity ε' and total conductivity σ) can be considered a measure of the interaction of the tissue with an electric field. For most tissues, the relative permittivity is highly frequency dependent from hertz to gigaherts with values reaching 10^7 below 100 Hz decreasing to less than 50 above 1 GHz (Fig. 1). The corresponding conductivity values (Fig. 2) increase with frequency is steps that mirror the fall in permittivity. Implicit in this qualitative analysis is that strong direct interactions are likely at low frequencies (high permittivity and low conductivity) while at high frequencies, the interactions are dominated by the high conductivity of tissues making energy absorption from ionic and polarisation currents the main outcome.



Figures 1: Permittivity of ovine liver tissue at 37°C presented here as an example of the spectrum of a high water content tissue (experimental data from author's laboratory).



Figures 2: Conductivity of ovine liver tissue at 37°C presented here as an example of the spectrum of a high water content tissue (experimental data from author's laboratory).

BIOLOGICAL EFFECTS

Cells and tissues exist in a background of bioelectric fields. For example, some electrically active cells sustain a transmembrane potential of up to 0.1 V (inside negative), cell communications initiate action potentials which are pulse like signals lasting a few milliseconds. Currents induced by external fields add to and interfere with these ambient fields. At frequencies below 1 kHz, induced currents flow mainly through the extracellular fluid, they affect the electrical environment of cells, may cause changes in the transmembrane potential, and, if sufficiently intense, stimulate electrically excitable cells. Current densities of the order of 0.1 Am^{-2} are capable of stimulating nerve and muscle cells (5) while higher currents have more serious consequences, this compares with endogenous current densities of between 1 and 10 mAm^{-2}. Interactions at or below the threshold for stimulation are not isothermal, energy is absorbed but the resulting thermal load is negligible by comparison to the thermal fluctuation of the body. The threshold for stimulation increases proportionally with frequency, the energy dissipated by that currents increases at a faster rate. At about 1 MHz, thermal damage to the cells may occur at current densities below the stimulation threshold. Interactions resulting in thermal effects are described in terms of the power absorbed per unit body mass or specific absorption rate (SAR). People are accustomed to receiving thermal stimulation and, provided that these are not too large, the body can deal with them by invoking thermoregulatory responses. The threshold SAR for the onset of thermally induced biological effects is about 4 Wkg^{-1}. This level of SAR may give rise to a temperature elevation of about 1 or 2 degrees and may cause behavioural changes or result in a reduction of performance of learned tasks in experimental animals. These effects are consistent with the rise in temperature. The biological effects associated with higher levels of SAR are well documented and have been extensively reviewed (6, 7) they include modification of the action of drugs, changes in the secretion of hormones, developmental abnormalities as well as transient effects on heat sensitive systems such as spern cells and blood forming tissues. The batabase of biological effects is consistent with a strong correlation between the SAR and the severity of the resulting biological effect.

There is a growing body of evidence describing subtle biological responses to specific low intensity fields below the threshold for thermal manifestations.. A common feature to most of the experimental studies is the lack of dose-response relationship. The concept of low level interactions leading to significant biological effects has been challenged on theoretical grounds (8). The main argument is that such fields are likely to be masked by thermally generated electrical noise. Several non linear interaction mechanisms have been proposed to describe some of the experimental results in terms of signal amplification from resonant or cooperative interactions at the site of the cellular membrane. The absence of dose response relationship together with the lack of well defined mechanism makes it difficult to plan new experiments and even to repeat old ones in different laboratories under identical exposure conditions.

Two examples of well conducted studies will be briefly reported to illustrate the type of research that needs to be replicated in different laboratories. Degenerative changes caused by low level microwave irradiation in the retina, iris and corneal endothelium of primates were first reported in 1985 (9) followed by several studies by the same research group over a number of years (10). The effects were observed with continuous irradiation but pulsed microwaves were found to be as effective at lower power levels. Pre-treatment of the eye with the glaucoma drug timolol maleate further lowered the threshold for damage to an average SAR of 0.26 Wkg^{-1}. Although the authors did not measure intra ocular temperatures in the animals, the results suggest that a mechanism other than significant heating of the eye is involved. Another example of biological effects arising from acute low-level exposure to microwaves involves single-strand breaks in DNA in brain cells from rats (11). No significant effect is observed immediately after irradiation with pulsed microwaves but a dose related effect was observed 4 hours post exposure equivalent to 0.6 and 1.2 Wkg^{-1} whole body SAR. With continuous irradiation increase in DNA single strand breaks were observed immediately as well as 4 hours post exposure. The study suggests that microwave irradiation may increase the rate of DNA breaking or inhibit the repair processes in the cells.

A study by Chou et al (12) illustrates investigations of the effect of chronic exposure to low levels of microwave . The aim of the study was to investigate the effects of long-term exposure to pulsed microwave radiation. An interesting and important feature of the study was the exposure of a large sample of experimental animals (rats) throughout their lifetimes in order to monitor them for effects on general health and longevity. Statistically the results were negative overall for effects on general health, longevity, cause of death, and lesions associated with ageing and the incidence of benign tumours. Some positive results on hormone levels and changes in the immune system were transient. A statistically significant increase of primary malignancies in exposed rats compared to controls was reported but tumour incidence was lower than historically expected in both groups. The authors state that, in the light of other parameters in the study, it is conjectural whether the excess reflects a true biological influence. Moreover, in the absence of reduced longevity, the biological significance of this effect is questionable. Overall, the results indicate that there were no definitive biological effects in rats chronically exposed to microwaves. The cost of repeating lifetime animal studies is not trivial in many respects, nevertheless, such studies need independent verification. A number of long term exposure studies are currently underway, it will be interesting to see if they have sufficient similarities in the experimental design to enable a meaningful comparison of the data output.

Understanding and eventually predicting the biophysical responses to low levels fields is a challenging task. Below 100 kHz, a prerequisite is the quantification of induced currents at the site of interaction. Such currents are different from those calculated in the primary interaction of external fields with the body assuming tissues to be uniform media of known dielectric properties. In principle it should be possible to extend the same dosimetric techniques to the cellular and molecular levels, in practice, it is very difficult to model with accuracy complex biological tissues including cells and their associated bioelectric fields. The theoretical considerations are not trivial even for random non biological systems (13). The answer may well rest with the development of experimental microdosimetric field measurement techniques (2,14) or indeed with a dual approach of experimental and computational methods.

The estimation of induced current density is important in the frequency range where direct action of the field on cells is anticipated. A different approach to microdosimetry should be adopted at higher frequencies where energy absorption is the prime consideration. For example, dielectric studies can yield relevant information on the polarisation of cells and molecules and help predict the distribution of energy absorptions at the molecular level (4,15). Experimental techniques include the use of molecular probes to provide spatial and temporal estimation of temperature and specific energy absorption at the cellular and subcellular levels (16). Progress rests with a multidiciplinary approach including experimental and theoretical investigations.

IMPLICATIONS FOR STANDARDS

Standards should, ideally, be based on rigorous scientific evidence that a physical agent is capable of causing harm under identifiable conditions. Standards, by their very nature, introduce controls and are bound to have an economic impact. However, when the science is clear cut, all other considerations are forsaken in favour of scientific data of health hazards and their corresponding thresholds. The scientific base underpinning em exposure standards is well established with respect to acute effects, but the issue is clouded by uncertainties provided by the growing database of low levels effects. It is important that such studies be continued and that their health implications, if any, be determined before their incorporation into standards. Equally important is to resist using the prevailing uncertainties as an excuse to adopt policies of 'prudent avoidance' and the like. Prudent avoidance measures may be, and indeed mostly are, harmless in their own right, their incorporation into guidance documents is however tantamount to the rejection of science as basis for protection.

CONCLUSIONS

The importance of microdosimetry has been highlighted to help elucidate the mechanisms of interaction responsible for low level effects. At low frequencies, the emphasis is on estimating the current at the cellular, at microwave frequencies energy absorption should be understood at the molecular level. The argument points to the importance and the relevance of extending dosimetric studies to include thermal modelling for both human and animal exposures. Because the biological effects are related to the temperature rise, thermal modelling would enable better extrapolation to human from animal experiment and also help our understanding of the mechanisms involved in the interaction.

REFERENCES

1. C.H. Durney, H. Massoudi, and M.F. Iskander, , Radiofrequency radiation dosimetry handbook, Brooks Air Force Base- USAFSAM-TR-85-73 , (1986)
2. K.J.Mcleod, Bioelectromagnetics, Supplement 1:1-10, 161-178 (1992)
3. C. N. Rafferty, R.D.Phillips and A.W. Guy, Bioelectromagnetics,Supplement 1 :1-10, 1-8 (1992)
4. J.B. Bateman, C. Gabriel and E.H. Grant, J. Chem. Soc. Faraday Trans. 2 86: 3577-3583 (1990)
5. J.H. Bernhart, Radiat. Environ. Biophys. 27, 1-27 (1988)
6. R. D. Saunders, C.I. Kowalczuk and Z. j. Siekiewcz, NRPB-R240 (1991)
7. P. Polson and L.N. Heynick, Radiofrequency Radiation Standards, B. J. Klauenberg, M. Grandolfo and D. N. Erwin (Editors), NATO ASI Series, Plenum Press 337- 388 (1993).
8. R. K. Adair, Physical ReviewA: 43 (2), 1039-1048 (1991)
9. H. A. Kues, L.W. Hirst, G. A. Lutty S. A. D'Anna and G. R. Dunkelberger, Bioelectromagnetics 6:2, 177-188 (1985)
10. H. A. Kues, J. C. Monohan, S. A. D'Anna D.S.Mcleod, G. A. Lutty and S. Koslov, Bioelectromagnetics 13:5, 379-393 (1992))
11. H. Lai and N.P. Singh, Bioelectromagnetics 16:3, 207-210 (1995)
12. C.-K. Chou, A.W.Guy, L.L.Kunz, R.B.Johmson, J.J.Croeley and J.H.Krupp, Bioelectromagnetics 13 (6) 469-496 (1992)
13. Z. Chen and P. Sheng, Physical ReviewB: 43 (7), 5735-5746 (1991)
14. L. M. Loew, Bioelectromagnetics,Supplement 1:1-10, 179-189 (1992)
15. C. Gabriel, State of Science Colloquium, University La Sapienza of Rome (1995)
16. J. L. Kiel, J. G. Bruno and W. D. Hurt, Radiofrequency Radiation Standards, B. J. Klauenberg, M. Grandolfo and D. N. Erwin (Editors), NATO ASI Series, Plenum Press 43-50 (1993).