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THE WHITE HOUSE
WASHINGTON

July 17, 1990

MEMORANDUM FOR THE HONORABLE WILLIAM K. REILLY

FROM: D. ALLAN BROMLEY *DLB*
SUBJECT: BIOLOGICAL EFFECTS OF WEAK ELECTROMAGNETIC
FIELDS

I have been peripherally involved with discussions of the possible biological effects of non-ionizing electromagnetic radiation for many years. In my case, the questions were first posed when the Navy in its Sanguine Project proposed to install a very large loop antenna in the sub-soil in Michigan and Wisconsin. The intent was to drive this antenna with low frequency high power signals which would be detectable throughout the earth's oceans, whereas, of course, high frequency signals are rapidly attenuated in the water medium. Although studies at the time generally suggested that expressed fears about biological effects resulting from these low frequency fields were unfounded, a general body of scare literature was generated and remained with little notice until it was taken up by those arguing against the installation of utility power lines in various parts of the country. A number of Soviet investigators also reported a variety of biological effects all on the edge of detectability that they attributed to non-ionizing electromagnetic radiation, and indeed to non-thermal phenomena in addition.

In response to Congressional interest in this question, the Office of Technology Assessment published a report entitled Biological Effects of Power Frequency Electronic and Magnetic Fields--Background Paper OAT-BP-E-53 in May of last year. I know also that the Electric Power Research Institute (EPRI) is interested in this area because so many of their utility members have run into difficulties in their attempts to install new power lines or to respond to fears from those living in the vicinity of existing lines.

More recently, I gather that a group in EPA has generated a new document that was reviewed by a committee that met on June 28 in Morrisville, North Carolina.

It has been suggested to me that there is the possibility that EPA plans to issue some conclusion in August of this year suggesting that very weak electromagnetic fields of the new kind encountered in our homes and factories maybe, or perhaps, even are carcinogenic.

While recognizing that biological systems are frequently complex beyond all imagining, it is still possible to apply some basic physics to this entire question and to set some limits on what is physically possible and what is not. Because an erroneous statement linking low frequency electromagnetic fields with carcinogenicity could have enormous consequences in stimulating unnecessary fears and worries on the part of our citizenry quite apart from having major economic consequences, it seems to me important to ask what rather elementary physics can say about the entire question.

For the past several years, two of my Yale colleagues, Robert and Eleanor Adair--Sterling Professor of Physics and Senior Staff Research Affiliate of the John B. Pearce Laboratory, respectively at Yale University, have been examining this field and I am enclosing herewith three recent preprints that they have produced that I think you might find of interest.

Bob Adair, in addition to his activities as one of the country's leading high energy particle physics experimentalist, served for extended periods as secretary and then chairman of the Physics Section of the National Academy of Sciences, has been the editor of Physical Review Letters, associate director of the Brookhaven National Laboratory--as well as the author of The Physics of Baseball. Eleanor is a distinguished experimental physiologist.

Eleanor's enclosed paper provides something of a overview of some of the public response whereas, Bob's papers address the questions of what limitations simple physics can place on the biological effects; he concludes that any such effects in the cellular level must be found outside of the scope of conventional physics.

I recognize fully that given the degree of concern that has surfaced in this area, EPA has the responsibility to lay it to rest one way or the other.

Inasmuch as the field has been characterized by measurements with relatively weak control, marginally detectible signals, and extraordinarily peculiar effect dependence on applied dose, it may well be that what is required here is a series of very carefully conceived, carefully controlled, experimental measurements. Based on the physics arguments in Adair's paper, I would be extremely surprised were any effects to emerge from such experiments and I hate to see good money utilized on pseudo science when there is so much good science that could use it.

I promised to get you the names of some "reliable" people in this area and will get such a list to you in a few days.

In the meantime, I hope that some of this is helpful.

Enclosure

THE NURTURING OF ELECTROPHOBIA

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Electrophobia, the irrational fear of electromagnetic fields, is rampant in America. It is fueled by exposés such as Paul Brodeur's "Currents of Death", available at your local bookseller, and extensive analyses of a mediocre scientific database such as that found in a background paper, available from the Congressional Office of Technology Assessment (OTA). The latter counsels a strategy of "prudent avoidance" of such fields with the implicit assumption that they may be hazardous to human health. Power distribution lines, computer terminals (but not television sets), and even bedside electric clocks are labelled villains in this electromagnetic assault upon the cells of our bodies.

Who can fail to listen when the EPA concludes that time-varying magnetic fields from ordinary household current may be carcinogenic, especially to our children? Who can deny the summons when Womans Day provides a reply coupon to Commissioner William Reilly requesting support for much more research on the biological effects of extremely-low-frequency (ELF) fields? How many VDT users will turn a deaf ear when the "eminent scientist" Paul Brodeur insists that the radiation from VDT monitors may be killing them?

Some votes have already been cast. Rep. Peter Kostmeier (D-PA), asserting that electromagnetic fields from power lines have passed the "duck test", has hailed the EPA conclusion of carcinogenicity. And some impoverished researchers have rejoiced at the prospect of renewed or increased funding for their efforts. Electrophobia is flourishing! If no voices are raised in challenge, the cost to the American taxpayer in meaningless research, product redesign, and electric power distribution retrofit (excluding billions in litigation costs) may soar into the trillions of dollars in the next decade; meanwhile, attention and funds will be diverted from other, proven hazards.

At the outset, it is important to keep a sense of perspective about the electromagnetic fields touted as hazardous by media activists parading as scientific experts. Because weak external ELF electric fields are weakly coupled to cells shielded by conductive electrolyte, the electric fields induced in cells are many orders of magnitude smaller than the intrinsic noise fields generated by thermal fluctuations in the cells themselves. Further, as Tenforde aptly stated in the CRC Handbook of Biological Effects of Electromagnetic Fields (p.211), "A straightforward calculation based on Faraday's law indicates that the motion of a human bending forward at the waist within the geomagnetic field will induce instantaneous internal currents comparable to those produced by exposure to an external 60-Hz sinusoidal field with an intensity of approximately 0.1 to 0.2 μ T. This magnetic field intensity is comparable to the ambient power-frequency fields in many residences and occupational settings." (italics mine)

What is the scientific basis for the furor lately created by the media? Investigation of the interactions of ELF electric and magnetic fields with biological systems has been underway for more than 20 years, both in the laboratory and in field (epidemiological) studies. Until only the last year or so, the quality of reports published in the archival literature has been abysmal, despite being labelled "outstanding" by the authors of the OTA report. Even today, honest researchers admit to limitations, deficiencies and biases in their data, reflecting the incredible complexity of the questions under investigation. Further, the most highly respected and honored scientists in the field (the likes of Schwan, Guy, Foster, Pickard, and Michaelson) insist that there is no convincing scientific evidence of biological interactions with such fields (apart from magnetotaxis, magnetophosphenes, and electrical shock) on a nonthermal basis. I count myself in their camp.

In 1986, an advisory committee of the NRC/NAS on nonthermal effects of nonionizing radiation concluded that this "abundance of empirical data...stands without unifying structure apart from their presumed adversity." A damaging indictment, indeed! Only last year, another NRC/NAS advisory committee failed to issue a report because of insufficient scientific progress on the topic. A major 1986 criticism still stands today -- that "...a preponderance of these reports have yet to be explained or replicated, and the claims cannot be

confirmed or refuted". A poignant illustration of this criticism concerns experimental attempts to describe the washout of imbibed calcium ions from chick brain tissue exposed to modulated ELF and radio frequency fields. Although the original studies of Bawin and Adey reported reduced calcium efflux, subsequent studies by Blackman reported enhanced calcium efflux with both power and frequency "windows". Several meticulously-controlled studies by other investigators yielded negative results. More recently, Blackman has offered yet another type of window, a "temperature window", to explain observations of increases, decreases, or no change in efflux. More and more, the calcium efflux phenomenon resembles N-Rays, ESP, or cold fusion, all examples of what Irving Langmuir characterized as "pathological science" many years ago.

In truth, no study, whether laboratory research or epidemiological survey, has demonstrated a causal link between low-level ELF fields and human cancer, the major theme echoed and re-echoed by the media experts. NONE! Nearly all epidemiological research published to date (whether relating VDTs to birth defects or power lines to cancer) suffers from recall bias, lack of appropriate case controls, inadequate or no measurements of ELF fields, and a myriad of uncontrolled and unevaluated confounding variables (including, among others, assorted environmental aerosols and allergens, traffic levels, diet, genetic predisposition, daily activity, and personal hygiene). Although some ongoing epidemiological surveys are far from complete, preliminary data are already loudly publicized in the media.

Suggestions of possible interaction mechanisms abound but only a few have generated hypotheses for testing in the laboratory. All of those that are well-defined violate basic physical, chemical, and biological principles (such as cyclotron resonance); some are farfetched (such as involving ornithine decarboxylase activity as a marker for cancer promotion) and so ill-defined that they are not even wrong; some are utter nonsense (such as the soliton model); and of course none can account for the often-reported lack of dose-response relationships and the necessity to invoke "windows" of frequency, intensity and temperature. To hard-nosed scientists, toiling at the bench to distill scientific truth by the sifting and winnowing process, the current grab-bag of contradictory or unreplicated evidence and miscellaneous theory falls far short of credibility.

There are many who demand that standards for exposure to ELF electric and magnetic fields be set as soon as possible. Others demand emission guidelines for appliances, VDTs, power-line rights-of-way, or the building industry. Since no hard scientific evidence exists of a health hazard from exposure to these fields, on what basis shall such guidelines be set? Early this year, the International Radiation Protection Association (IRPA) set high interim guidelines for human exposure to 50-60 Hz electric and magnetic fields that were formulated on the current scientific database. But no extant standards-setting body in the world agrees that exposure guidelines at any level should be based on speculation. I for one refuse to permit Paul Brodeur and Dan Rather to undertake this task.

Still others (of slightly more conservative bent) counsel a strategy of "prudent avoidance" of offending ELF sources whenever possible until results of a greatly-expanded research effort come in. Such a strategy is predicated on a belief in biological effects that may adversely affect human health. These proponents are convinced that the new research will be far better than the old and should prove causality, pinpoint the causative agent, delineate the interaction mechanism or, at least, demonstrate risk ratios much higher than found heretofore. Back in 1986, the NRC/NAS report begged for the establishment, through selective replication, that low level ELF electromagnetic fields do indeed significantly affect biological tissues by nonclassical mechanisms. Further, this report endorsed William Pickard's criteria for the selection of a suitable effect for replication and the design of the experiment. To date, all attempts at replication, albeit few in number, have met with abject failure. As a result, the rantings of the media activists and the counselors of palliative strategy are "full of sound and fury, signifying nothing".

Constraints on the Biological Effects of Weak ELF Fields

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Abstract

Concerns have been raised over the possibility that extremely-low-frequency (ELF) electromagnetic fields are carcinogenic and leukegenic. An examination of the physical interaction of such fields with the body shows that such interactions are too weak to have a significant effect on human biology at the cell level.

Because of the high electrical conductivity of tissues, the coupling of external electric fields in air to tissue in the body is such that the effects of the internal fields on cells is smaller than thermal noise. Static magnetic fields smaller than the earth's field of $50 \mu T$ and varying fields weaker than the $4 \mu T$ 60 Hz fields that are equivalent in effect to that from walking in the earth's field, cannot be expected to generate significant biological effects. Moreover the interactions of such weak fields at the cell level are also small compared to thermal noise. These conclusions would be modified by 60 Hz cell resonances. But such resonances are shown to be incompatible with cell characteristics and the requirement from equipartition that the mean resonance energy must be kT .

Hence, any biological effects of weak ELF fields on the cellular level must be found outside of the scope of conventional physics in much the same way as parapsychology or cold fusion.

I Introduction

Very weak extremely-low-frequency (ELF) electromagnetic fields from common electric appliances and lighting, from local home and workplace distribution wiring, and from the major national electric grids, are a ubiquitous part of modern civilization. Since the magnitudes of these "leakage" fields are very small, and seemingly small compared to natural fields in the body,

it has been commonly assumed that the fields could not affect any biological activity significantly and, hence, could not constitute a health hazard.

However concerns have been raised over the possibility that the biological effects of the fields have not been properly understood and that the fields may in fact generate changes on the cell level that might have carcinogenic and leukegenic consequences. Such effects have been largely associated with the breaking of molecular bonds of macromolecules such as those responsible for the genetic information. Since the extremely low frequency (60 Hz in North America and largely 50 Hz elsewhere) of the ELF fields means that the characteristic quantum energies are $\approx 10^{-14}$ eV, it has generally been accepted that such fields cannot disrupt these molecules and hence cannot induce carcinogenic or leukegenic effects.

However, it may be that less catastrophic effects of ELF fields on cells in the body may induce actions which we do not yet understand that alter the biology of the structures significantly. If such interactions of the ELF fields at the cell level are to result in any significant biological effects, those interactions must be significantly greater than the ordinary thermal interactions of the molecules with their environment. But we show that any effects on the cell level of fields in the body generated by weak external ELF fields will be masked by thermal noise effects and, hence, such fields cannot be expected to have *any* significant effect on the biological activities of the cells.

In any material the charge density fluctuates thermally according to thermodynamic imperatives generating fluctuating electric fields. Although there are other sources of biological noise, such as noise generated by muscle excitation and activity, electrokinetic noise from squeezing of electrolyte through tissues, and the $1/f$ noise from cell membrane activity, that contribute fields as great as 0.1 V/m at frequencies less than 100 Hz, we emphasize the generally smaller noise inasmuch as the magnitude of that noise stems from fundamental thermodynamic bases and must constitute an irrefutable constraint on biology.

For similar reasons, we emphasize effects on the cell level. Over larger regions, the impact of weak ELF external fields is limited more by biological and physiological considerations than by the competition with Johnson-Nyquist noise and is hence outside of the chosen scope of this paper. Since the bulk of the experimental results that have been interpreted as an indication of effects of such fields concern mechanisms on the cell level such as changes in ion transport through cell membrane walls and increases in genetic transcription errors, the analyses of mechanisms that might operate at the level of the cell are of primary importance. Any possible carcinogenic

effects of weak ELF radiation would also most likely operate at the cellular level.

In the quantitative features of this discussion of the effects of low frequency, low intensity, electromagnetic fields on biological materials, we will consider especially 60 Hz oscillations, and define *weak* fields as electric field strengths that do not exceed 300 V/m in air and magnetic field strengths no greater than 0.5 gauss (or 50 μT), the strength of the earth's field – the mean electric field at the earth's surface is about 100 V/m. The fields will, in general, be near-fields, and not radiative. Indeed, for the most part, we will not be talking about *radiation* – non-ionizing or otherwise.

II External Fields and Noise Fields

A Coupling of Tissue and Air for Electric Fields

For environmental concerns, the immediate measure of possible hazard is that field in the air about the tissues. Since the tissues are conducting, a constant external electric field will induce almost no field at all in the tissues though an alternating external electric field will induce small fields. At low frequencies, ν , the fields E_i in the tissues will be very much smaller than the fields E_0 in the air external to the tissues¹.

$$E_i \approx 3\epsilon_0\omega\rho_t E_0 \quad (1)$$

where $\omega = 2\pi\nu$ is the angular frequency and $\rho_t \approx 2 \Omega\cdot m$ is the resistivity of the electrolyte saturating the tissue². At 60 Hz, $E_i \approx 2 \cdot 10^{-8} E_0$. Hence, for fields in the air of 300 V/m, we can expect field strengths in the conducting tissues of about $6 \cdot 10^{-6}$ V/m. The cell membrane will have a specific resistance of the order of $\rho_{mem} \approx 10^5 \rightarrow 10^7$ ohms and can then be considered as an insulator relative to the tissue electrolyte. In the valid approximation that the resistivity of the membrane material, $\rho_{mem} \gg \rho_t$, the resistivity of the tissue, the field in the membrane, E_{mem} of thickness d of a cell of radius r will be about

$$E_{mem} \approx 1.5 E_i \frac{r}{d} \quad (2)$$

Hence, taking a typical cell radius of $10 \mu m$ and a membrane thickness of $50 \text{ \AA}$, for a field in the tissue electrolyte $E_i = 6 \cdot 10^{-6}$ V/m, induced by an external field of 300 V/m, we can expect a field $E_{mem} \approx 3000 \cdot E_i \approx 2 \cdot 10^{-2}$ V/m in the insulating membrane.

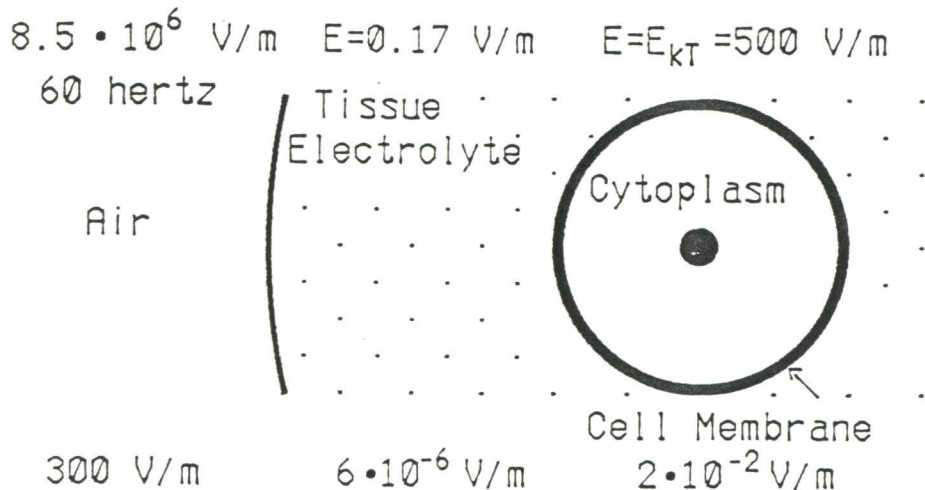


Figure 1: Electric fields in tissues, cell membranes, and cell cytoplasm, induced by ELF external fields in the air outside of the tissue. The fields labeled above describe an externally induced field in the cell membrane that is equal to the Johnson noise, from DC to 100 Hz, measured from the cytoplasm interior to the cell to the electrolyte outside of the cell across the cell membrane. The very large air field so postulated is larger than the dielectric breakdown strength for air of about 10^6 V/m and is then unobtainable in practice. The lower numbers describe the fields induced in the tissue and membrane by an external field of 300 V/m.

The internal elements of the cell, such as the nucleus and the genetic material, are shielded by the resistive cell membrane and the fields they see are quite negligible¹.

The fields in different areas of air, tissue, and cell, are shown in Fig. 1 normalized to a field in the air of 300 V/m. Too often, discussion of the effects of weak fields is complicated by misunderstandings concerning the region in which the field is defined. Since we are addressing environmental concerns, the fields labeled "external" in this report are *always* fields in the air about the tissues.

B Thermal Electrical Noise

Since the most important fundamental constraint on effects of very weak fields, is the requirement that they not be masked by thermal noise, we present a heuristic explanation of the Johnson-Nyquist noise designed to suggest the salient features of that noise. We proceed by describing thermal noise at a frequency ν in a sample of material by analyzing an imaginary experiment. The sample is inserted as a resistive load R in an LC oscillator circuit where the circuit elements are chosen such that

$$2\pi\nu = \omega = \frac{1}{\sqrt{LC}} \quad (3)$$

From the equipartition theorem the mean energy of the oscillator is $W = kT$ where T is the ambient temperature. But as the circuit oscillates it will lose energy as a consequence of the resistance of the sample. The rate of energy loss or loss power P will be

$$P = 4 kT \Delta\nu \quad (4)$$

where $\Delta\nu = 4R/L$ is the effective resonance width.

The effect of this action will be to transfer energy from the oscillator, which is then cooled below the ambient temperature, to the resistive sample, which is then heated above the ambient temperature. But this is in violation of the *second law*. Hence, if the system is to remain at thermal equilibrium (and we are to avoid violating the *second law*), the sample must generate electrical energy at a rate P at the frequency ν that will be fed back to the oscillator. Hence, the noise power generated thermally by the sample must be equal to P . That power is independent of the magnitude of the resistance of the sample and must hold for any frequency ν even as we could tune the oscillator to different frequencies.

If we write $P = V_{kT}^2/R$ where V_{kT} is the noise voltage across the resistance R , we find the usual formula for that voltage V_{kT} generated by Johnson noise over a frequency interval $\Delta\nu$,

$$\overline{V_{kT}^2} = 4R kT \Delta\nu \quad (5)$$

Although this noise voltage must follow from thermal fluctuations in the charge density in the sample material, the result – characteristic of thermodynamic results – is independent of detail; in particular of the detailed character of the charge carriers which may be conduction electrons, ions, or bound charges sensibly displaced by thermal buffeting.

Often the noise fields will be of more interest than the noise voltages – which are, however, better defined. Taking the sample as a cube with a side d for convenience, $R = \rho/d$, where ρ is the characteristic resistivity of the material, $E_{kT}^2 \propto 1/d^3$. As a consequence of averaging over fluctuations, the electric field noise limit varies inversely as the square root of the volume considered. Although, E_{kT}^2 was evaluated for a cube, the value depends only on the volume of the sample. The noise does not vary with volume as one might expect for random electric field fluctuations since the field fluctuations – taken to originate in charge density fluctuations – are correlated through the conservation of charge and Gauss's theorem.

Since the thermal noise is larger for small volumes – where the statistical fluctuations of electron densities are proportionally larger – than for larger volumes, to make the most useful assessment of the effects of thermal noise it is desirable to choose the smallest volume commensurate with the biological action. This increase in effective noise field strength as the sample size is reduced, extends to the molecular level. The characteristic molecular field strengths required to substantially change the momenta of molecules in a typical thermal collision, for example, are of the order of $kT/er \approx 10^8$ V/m, where $r \approx 1$ Å, is the interaction length relevant in the collision. Hence, very large electric field fluctuations can be expected as a consequence of “collisions” with surrounding molecules.

C Noise Fields in Tissues

We estimate the thermal noise generated in a quantity of tissue by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where a cube of tissue of length d on a side is held between the plates. The voltage across such a capacitor will be a *useful* measure of the local electric field at low frequencies. To estimate the thermal electric field noise, we consider the system as an equivalent parallel circuit of the membrane resistance R and the capacitance C between the plates. The time average noise voltage V_{kT} can then be expressed as,

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu = 4\frac{\rho}{d}kT\Delta\nu \text{ and } E_{kT} = \frac{\overline{V_{kT}}}{d} \quad (6)$$

Using the above relations, and taking $\rho = 2 \Omega \cdot m$ for tissue and a frequency span $\Delta\nu = 100$ Hz – i.e. from DC to 100 Hz – we find that the noise field generated in the electrolyte in a cubical volume the size of a cell,

20 μm on a side, is about 0.02 V/m, which is about 3000 times larger than the field induced by a 300 V/m external field.

Though the field is large, the thermal noise *potential difference* over 20 μm is but 3 μV . In general, thermal noise voltages between different regions of tissue will be very much less than 1 μV .

Experiments have shown that some fish – especially sharks – do respond to very weak electric fields. These are fields in the water surrounding the fish and are, therefore, strongly coupled to the watery tissue of the fish. In salt water, the fields are more strongly coupled by a factor of $\approx 5 \cdot 10^7$ than fields in air to tissue. With special receptors, the ampullae of Lorenzini, which act as low pass filters, that extend over lengths near a meter, the response of sharks to quite small fields – as fields as small as 0.5 $\mu\text{V}/\text{m}$ have been detected – does not violate thermal noise limits³.

D Noise Fields in Cell Membranes

A popular “explanation” of purported biological effects of external low-level ELF electromagnetic fields, is that these effects derive from the effects of the electric fields on the complex properties of the cell membranes. The fields are presumed to modify such membrane activities as the opening and closing of ion-conducting channels and the catalytic activity of membrane-associated enzymes. Of course if externally imposed fields are to have any important effect, those fields at the cell activity sites must not be swamped by the thermal Johnson noise fields.

Certain processes such as the passage of ions through the cell membrane walls may be likely defined by thermodynamic criteria and hence depend upon the potential difference – which is typically of the order of 50 mV – between the cytoplasm interior to the cell and the electrolyte outside of the cell. For such mechanisms the noise voltage across the membrane from the relatively highly conducting interior cytoplasm to the conducting electrolyte might be more significant than any local noise level. (The natural potential difference across the membrane will be of the order of 50 mV to be compared with the noise voltage across the membrane of $\approx 10^{-6}$ V and the thermal kinetic energy of an ion of $3/2 kT \approx 37$ meV.) The time average noise level from cytoplasm to electrolyte, across the whole membrane of thickness $d \approx 50$ Å, of a spherical cell of radius $r = 10^{-5}$ m will be;

$$\overline{V_{kT}^2} = 4R kT / \Delta\nu \text{ where } R_{mem} = \frac{\rho d}{4\pi r^2} \quad (7)$$

where the resistivity of the membrane material is taken as $\rho_{mem} = 10^6 \Omega m$. With these values, $R_{mem} = 4 \cdot 10^6 \Omega$. Taking an ELF frequency band of 100 Hz, $V_{kT} \approx 2.6 \cdot 10^{-6} V$ and $E_{kT} = V_{kT}/d \approx 500 V/m$. This thermal noise voltage. (Since the resistivity of the membrane material is uncertain within a factor of ten, the field strengths calculated here are uncertain by a factor of 3.) is probably much smaller than the $1/f$ noise, possibly associated with the flow of ions through cell membrane orifices, and smaller by a factor of $\approx 5 \cdot 10^{-5}$ than the normal potential difference of 0.05 V across the cell wall⁴. But the noise voltage across the membrane – and the noise field in the membrane – is about 25,000 times⁵ the voltage and field induced by the canonical external field of 300 V/m.

It has been argued that the externally induced fields in the cell membrane may affect such biological activities as the catalytic actions by membrane-associated enzymes. If such induced fields are to affect the processes, those fields must be greater than the fields due to thermal fluctuations.

Since these kinds of biological activities would appear to be local, determined not by average fields over the whole cell membrane, but by conditions in a small sector of the membrane with a volume no larger than d^3 , where $d \approx 50 \text{ \AA}$ is the membrane thickness, it would seem that it would be the *local* thermal electric field fluctuations in such small regions that should be compared to the induced fields. Since the volume in question is quite small, and the effective noise fields over small volumes are greater than for larger volumes, we might expect that the local electric field noise would be much greater than that averaged over the whole membrane. The electrical properties of such a small sector are not necessarily simple but we can *estimate* that thermal noise generated in a small quantity of membrane material proceeding as before by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where an isolated cube of membrane material 50 $\text{\AA}$ on a side is held between the plates. The time average of the fluctuating noise voltage V_{kT} is again

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu \text{ where now } R = \frac{\rho_{mem}}{d} \approx 2 \cdot 10^{14} \Omega \quad (8)$$

If we use the mean resistivity of the membrane material of $\rho = 10^6 \Omega \cdot m$, for the small sector, which is simplistic, and taking, again, only frequencies less than 100 Hz, the mean noise voltage across this small, isolated, sample will be ≈ 0.02 and the thermal noise electric field over this frequency is then $E_{kT} \approx \overline{V_{kT}}/d \approx 3.7 \cdot 10^6 V/m$ which is about $2 \cdot 10^8$ times that from a 300 V/m external field.

E Electric Field Effects

Although the small values of the ratios of induced to noise electric fields must largely exclude any possibility that those induced fields can induce biological activity in cells, one can reach much the same conclusions by considering interactions in more detail. To be definite, we consider fields of $E_i = 6 \cdot 10^{-6}$ V/m in tissue, and $E_m = 2 \cdot 10^{-2}$ V/m in membranes 50 Å thick of cells of radius $r = 10^{-5}$ m, induced by external fields of 300 V/m and we compare the energies transferred to the elements to kT .

For membrane or tissue, the energy transferred by the field to an ion – or any singly charged element – in tissue or membrane will not be much larger than $E_i e r \approx 10^{-9} kT$, where e is the electronic charge. Which is to say neither the kinetic energy nor the direction of motion of a charged element can be sensibly affected by such small fields.

An imposed external field will tend to align electric dipoles so that, even in the face of thermal agitation, there will be a statistical excess of dipoles aligned with the field. That proportion P which are aligned can be estimated as $P \approx W/kT$ where W is the alignment energy. We can make a useful estimate of a *maximum* magnitude of such an interaction energy by considering the interaction of the field, E_i , in the tissue with a whole cell neglecting, for the purpose of the maximal estimate, the macroscopic shielding provided by the cell membrane. The electric dipole moment per unit volume of cytoplasm will be $P = \epsilon_0(K-1) \cdot E$ where K is the dielectric constant and $K-1 \approx 80$ as for water and the volume V is that of a cell 10 μm in diameter. Then the interaction energy W will be about

$$W \approx (E \cdot P) V \approx 80 E_i^2 \epsilon_0 V \approx 2.5 \cdot 10^{-14} kT \quad (9)$$

We can also consider the alignment of macromolecules that display permanent electric dipoles. Taking a characteristic magnitude of such a dipole moment as er where, $r = 200$ Å, the alignment energy of the molecule in the membrane will be $W \approx E_{mem} er \approx 3 \cdot 10^{-8} kT$.

F Magnetic Fields

Static Magnetic Fields

A kind of restricted anthropic principle places immediate limits on the biological effects of static magnetic fields. We live! And we live – and have lived through evolutionary history – in the earth's magnetic field of about 50 μT . Hence, the biological effects of static magnetic fields that are less

than the earth's field must not seriously affect our health. Nevertheless, we examine the effects of static fields in more detail.

Since magnetic fields exert no force on stationary charges and act on moving charges only in a direction normal to their motion, static magnetic fields do not add – or subtract – energy from single charges. The magnetic forces do change the direction of motion of charges but that effect is extremely small compared to effects of thermal fluctuations. However, charged particles in orbit generate magnetic dipole moments that interact directly with magnetic fields. Molecules, atoms, and nuclei possess magnetic dipole moments μ of the order of magnitude of

$$\mu = g \frac{e}{2m} \hbar \quad (10)$$

where the value of g depends upon the specific structure but is usually near one, and for atoms and molecules, $m = m_e$ is the mass of the electron and for nuclei m is the nuclear mass. The alignment energies for a field B are then $B\mu$ and for $B_e = 50 \mu T$, the earth's field, these energies are of the magnitude of $10^{-7} kT$ for atoms and molecules and typically less than $10^{-10} kT$ for nuclei. Hence, the net alignment – and the net magnetization of biological material induced by such weak fields is quite small (though significant effects have been observed for very large fields $B \gg 1 T$.) Such alignments will result in a net (paramagnetic) magnetic moment in a volume of material which in turn will interact with the field defining an energy. For a volume of the whole cell, this energy will only be of the magnitude of kT – about 14 orders of magnitude less than the thermal energy of the cell. Arguments similar to those applied to paramagnetic materials apply to the smaller diamagnetic moments.

For most (paramagnetic and diamagnetic) materials, the molecules or atoms do not act collectively. But for ferromagnetic materials, all of the atomic dipoles in a domain line up and the magnetic susceptibilities are greater by factors $\approx 10^7$ than for paramagnetic materials. Consequently, the earth's $50 \mu T$ field does affect those (rare) cells that contain ferromagnetic matter.

About 15 years ago, Richard Blakemore⁶ found anaerobic bacteria (single celled, of course) that, fearing fresh air, fled preferentially downwards guided along the lines of the earth's field by a compass of ferromagnetic material, in particular a chain about $2 \mu m$ long of grains of magnetite Fe_3O_4 . A simple calculation⁷ shows that the alignment energy in the earth's field B_e is $\mu B_e \approx 10 kT$ where μ is the magnetic moment of the bacterial lodestone.

This is enough to ensure efficient alignment of the cell in the earth's field so that the creature swims in the right direction. Hence, with the aid of ferromagnetic materials, a cell can – barely – sense $50 \mu T$ field. But Fe_3O_4 is found in few other cells. And without the crafting of such compasses, we cannot expect the effects of magnetic fields on cells to compete with thermal fluctuations.

We note that under rather special circumstances, moderate magnetic fields – of the order of $10^{-2} - 10^{-3} T$ may affect chemistry. A covalent binding of a molecule may break such that each piece retains one member of the singlet state electron pair that cemented the binding. Then as a consequence of different hyperfine magnetic interactions between the valence electron and nuclei in the two fragments, the two electrons may precess at different rates and the phase between their amplitudes which defines the initial singlet state will transform to a triplet state reducing the possibility that the two fragments will rejoin⁸.

However, if the local external magnetic field acting on the the ions is stronger than the effect of the nuclear fields, the precessions that lead to the singlet-triple interchange will be suppressed and the ions will more likely rejoin. Since this suppression requires magnetic fields that are typically two orders of magnitude greater than the $50 \mu T$ limit we have adopted, we need not consider the possibility of such effects.

Changing Magnetic Fields

Since life evolved in the presence of static magnetic fields of the order of a gauss or $100 \mu T$, the absence of biological effects of static fields should not be surprising. But changing magnetic fields generate electric fields. These magnetically induced electric fields are more pervasive than the electric fields induced by external electric fields since neither the electric shielding of the cell by the conducting electrolyte, nor the shielding of the cell nucleus and the cell genetic material by the conducting cell membrane, operates. The induced electric fields in biological material are nearly independent of the conductivity of that material and its surroundings.

But can weak 60 Hz oscillating magnetic fields produce electric fields of consequence – that is electric fields greater than those generated by thermal noise? Using the integral form of Faraday's law

$$\oint_S \mathbf{E} \cdot d\mathbf{s} = \frac{d(\int_A \mathbf{B} \cdot d\mathbf{a})}{dt} \propto \frac{dB}{dt} \quad (11)$$

where A is an area through which the field B passes and S is a path bounding the area. If we take a typical effective human body area as that of a circle with a radius of $r = 10$ cm, we estimate the mean amplitude of the electric field induced by a 60 Hz oscillating magnetic field of amplitude $B = 50 \mu T$ field acting over the body, as

$$\bar{E}_B = \frac{B\omega r}{2} \approx 10^{-3} \text{ V/m} \quad (12)$$

Then how will this induced field compare with low frequency thermal noise fields acting on cells? For a conservative comparison, we consider the noise field of $E_{kT} \approx 0.02$ V/m calculated in Section 2.2 for the electrolyte occupying a volume the size of a cell. This is the noise, over a band width $\delta\nu = 100$ Hz, generated by a volume the size of a cell taken conveniently as a cube $d \approx 20 \mu m$ on a side. Hence, the noise fields in cell-sized regions of the electrolyte are greater than the electric fields induced by the changing magnetic field by a factor greater than about 20.

But any biological events of interest must take place in elements of the cell, not in the electrolyte. Since the mean noise field is proportional to the square root of the resistance of the material, and inversely proportional to the square root of the volume of interest, the electric field noise in those smaller cell elements, characterized by larger specific resistances, will be much greater though the field induced by the changing magnetic field will not be very different. For example, the mean ELF noise field across the membrane, between the electrolyte and the cytoplasm, was found to be of the order of 500 V/m; about $5 \cdot 10^5$ times the magnetically induced field. The effective electric noise fields in the small internal elements of the cell, such as the nucleus and the genetic material, can be expected to be no smaller than that of a volume of cytoplasm the size of that element. Typically, that noise will be of the magnitude of the noise generated in a cube of cytoplasm $1 \mu m$ on a side, which will be about 1 eV/m, about 1000 times greater than the magnetically induced field. Hence, low frequency, low intensity, magnetic fields cannot be expected to induce biological activity through interactions with individual cells.

Even as electric fields, albeit small, are generated in human tissues by weak ELF magnetic fields, electric fields of similar strengths are produced in the course of our motion through the earth's field. A field E will be generated throughout the body by moving through the earth's field B_e at a velocity v ; $E = B_e v$. The electric field of $\approx 7 \cdot 10^{-5}$ V/m induced thus by walking will be about equal to the maximum field generated by a $4 \mu T$

(40 milligauss) 60 Hz magnetic field. Indeed, this electric field induced by walking will be greater at the sites of DNA, RNA, and the cell nucleus than that produced by any external ELF electric field. Riding in a car on the highway increases the equivalent level to about $70 \mu T$ (700 milligauss) while a passenger in a jet plane will see electric fields similar to the maximum from a $7 \cdot 10^{-4} T$ (7 gauss) 60 Hz magnetic field (here we neglect shielding effects in car and plane which will reduce the magnetic fields somewhat).

We can feed these simple results into our version of the anthropic principle to conclude that weak changing magnetic fields – like the changes from 60 Hz sine waves – are most unlikely to induce biologically deleterious effects. The magnetic field that a cell passes through from the walking of its host through the earth's field in the United States induces the same electric fields in the cell as a $4 \mu T$ 60 Hz oscillating magnetic field. But four μT is far larger than the fields from power lines, local and home wiring, and home appliances.

One might argue that there may be some special significance in the oscillatory character of the 60 Hz field; perhaps there are sympathetic resonant responses. But we show in Section 3, that ELF resonances at the cell level are not possible.

Rapid Changes in the Magnetic Field

Though the effects of pulsed fields are nominally outside of the discussions of weak ELF (sine wave) fields considered here, the saw tooth magnetic waves associated with the fly-back transformers in television sets and video display terminals have raised concerns similar to those associated with ELF fields. As an example, we consider a sawtooth wave where the magnetic field increases from zero to $50 \mu T$ linearly over a period of $\approx 50 \mu s$ and then returns to zero in a time $< 1 \mu s$; and then repeats at a repetition rate of ≈ 20 kHz. The constraints on the effects of such fields are similar to those established for ELF fields.

We consider the effects of pulses on biological elements from the electric field pulse generated by the changing magnetic field. The magnitude of that field, $E(t)$, can be estimated using the same approximations as for sine-wave fields;

$$E(t) = \frac{r}{2} \frac{dB(t)}{dt} \quad (13)$$

and we write

$$\int E(t) dt = E_{mem} \delta t = \frac{r}{2} \int \frac{dB}{dt} dt = \frac{r}{2} \delta B = B_0 \frac{r}{2} \quad (14)$$

Hence, the impulse added to an element holding a charge q by the electric field pulse will be,

$$dp = E_{mem} q \delta t = q \frac{r}{2} B_0 \quad (15)$$

where B_0 is the change in the magnetic field. The impulse depends only on the change in magnetic field and is independent of the rate of change.

The mean component of momentum in the direction of the pulsed field from thermal agitation of the element on which the field acts will be

$$p_{kT} \approx \sqrt{m kT} \quad (16)$$

where m is the effective mass of the element. If the pulse is to affect biological processes significantly, it must produce momentum changes in cell elements greater than that received at high frequency from thermal buffeting; that condition is $dp > p_{kT}$.

The momentum dp may accrue to the translational momentum of a free cell element, such as calcium ion, or may add to vibrational or rotational motion of more complex element such as a macromolecule.

For a charge $q = e$ and a value of $r = 0.1 m$, the momentum transfer for a change in field $B_0 = 50 \mu T$ is $dp \approx 4 \cdot 10^{-25}$ Ns. But this is much smaller than the thermal momentum $p_{kT} \approx 1.7 \cdot 10^{-23}$ Ns for a calcium ion and very much smaller than the thermal momentum $dp \approx 10^{-21}$ Ns for a macromolecule with a mass of 40,000 AMU where the pulse couples through the dipole moment to incite vibration or rotation. Consequently weak magnetic pulses can have no biological effect no matter the rise time.

III Resonances

A Bandwidths

In the description of thermal noise which is commonly used, the square of the mean noise voltage is proportional to the frequency band width over which the noise is measured – or relevant. Hence, if the acceptance of the biological system is such that only a narrow band of frequencies initiate the biological effects, the relative noise interference is reduced. Certain biological actions act as band-pass filters. In particular, those biological activities that have

long intrinsic time constants can act as simple, plausible, low pass filters. If an activity requires a time of 0.01 seconds, it is plausible that perturbations that change sign often in that time would have little over-all effect. There are biological relaxation effects that admit transfer functions that peak at low frequencies – very much as a band pass filter – but these peaks are quite broad.

However, since we have effectively assumed a low band-pass acceptance in using a frequency band of but 100 Hz in our discussions, if we are to find striking gains in signal-to-noise ratios in ELF actions, we must look farther to resonant mechanisms that act as narrow band-pass filters. However, the existence of such low-frequency, narrow band or high Q , resonances at the cellular level can be shown to be inconsistent with the properties of cells in biological media. We examine the properties of resonances.

The effective width of the pass-band depends not only on the characteristics of the biological system, but of the signal. A signal – e.g. an ELF wave – that lasts a time t must have an intrinsic frequency spread $\delta\nu \approx 1/t$. Hence if the band width $\delta\nu$, approximately equal to ν/Q for resonances, is very narrow, $\delta\nu \ll \nu$, the effective band width will be determined by the characteristics of the signal rather than of the system. In that case, the effective frequency acceptance will be inversely proportional to $1/t$ and the effective signal-to-noise will be proportional to $\sqrt{t}$. Or if the signal is integrated (or *averaged*) over a long time t_{max} , the signal-to-noise will be much improved. But only if the effective system width is small compared to $1/t_{max}$. Weaver and Astumian⁹ suggest averaging times t_{max} of the order of 1000 seconds (or about 20 minutes!). Such a long averaging time could only be relevant if the intrinsic band width of the system were as small as 1/1000 Hz; if the signal were tuned that accurately; and if the time constant of the biological system were longer than 20 minutes. At 60 Hz – assuming a resonant biological process with a $Q \geq 60,000$, exquisitely tuned to 60 ± 0.001 Hz – the signal to noise voltage from a 20 minute exposure would be improved by a factor of $\sqrt{1000} \approx 30$ over a one second exposure and a factor of about 250 over that from a single pulse.

Even with the factor of 250, which assumes an integration time of about 20 minutes and a resonance width of 0.001 Hz, (centered, *accidentally*, at exactly 60 Hz) the field in the membrane of about 0.018 V/m, induced by an 60 Hz external signal field of 300 V/m, would be one-hundred times smaller than the noise field over a frequency span of about $\delta\nu \approx 0.001$ Hz of about $500/250 = 2$ V/m.

B Coupling and Damping

Moreover, if a resonance is to store energy, the damping of the resonance must be sufficiently small that it will make at least one cycle without interruption. If the resonance is to be in the ELF range, that cycle will take a very long time in terms of characteristic molecular collision or interaction times. Consequently, the resonance state must have a very small probability of being interrupted if it is to be significant.

We can estimate the characteristic interaction time or energy exchange time for the smallest elements in a solid as roughly $a/v \approx 10^{-11}$ sec, where a is a mean spacing of molecules and v is a velocity of a bombarding molecule of mass m where $1/2 mv^2 \approx kT$. Then if the resonance is not to be deexcited by an interaction acting as a collision of the second kind in $1/60$ of a second, the probability of that deexcitation in an interaction must be of the order of 10^{-9} . So small a deexcitation probability is difficult to reconcile with the large excitation probability required if the resonance is to be excited by a weak, long-wavelength, electric field. If the cell element is as large as the cell membrane or the cell itself, and if the Q is large so as to allow the coherent contributions of many ELF cycles, the constraints are more severe.

At the long ELF wave-lengths, the electric field E must couple to a resonance through a dipole interaction. The estimates we made in Section 2.5 of the strength of the coupling of an electric field to the cell or elements of the cell, showed that for a characteristic set of interactions, the coupling was of the order of $10^{-9} kT$. Hence, the interaction energy would appear to be insufficient to generate oscillations that might produce biological effects even if the Q of the resonance is sufficiently high so that the energies of many cycles can be added coherently. (At $10^{-9} kT$ per cycle, the system would have to accumulate energy for six months from a 60 Hz oscillation to reach an energy kT .)

We can also consider the damping of resonances - or any other motion of cell elements - in terms of the viscous resistance to that motion. To estimate the magnitude of damping, we consider a model of the motion of a spherical body of radius a through cytoplasm or electrolyte where the viscosity $\eta \approx 7 \cdot 10^{-4} \text{ kg cm}^{-1} \text{ s}^{-1}$ is taken as that of water. For convenience we consider that the body is coupled to the field through a charge q . Then the drift velocity v_E under a field E will be

$$v_E = \frac{Eq}{6\pi\eta a} \quad (17)$$

It is useful to compare the distance $L_E = v_E \delta t$ the body will move in a

time δt with the mean distance L_{kT} the body will move in that time from thermal agitation or Brownian motion;

$$L_{kT} = \sqrt{\frac{2kT}{6\pi\eta a}} \delta t \quad (18)$$

Using these relations, a time $\delta t = 1/\omega_{60} = 1/(2\pi \cdot 60)$ relevant for 60 Hz oscillations, and a (large) canonical field strength $E = 1$ V/m, we find for $a = 3 \cdot 10^{-10}$ m and $q = 2e$ (e.g. a calcium ion), $L_E = 1.1 \cdot 10^{-10}$ m while $L_{kT} = 2.4 \cdot 10^{-6}$ m. For a large element (e.g. a very large macromolecule with a large dipole moment) where $a = 1$ μ m and $q = e$, $L_E \approx 5.5 \cdot 10^{-11}$ m while $L_{kT} = 4 \cdot 10^{-8}$ m. In either case, the amplitude L is strongly limited by viscosity and the motion induced by the field E is swamped by the Brownian motion.

Although the numerical values were derived from the model of a spherical body moving through water, the magnitudes are relevant for vibrational or rotational motion.

Hence, the narrow-banding, signal-integration, afforded by possible cellular resonances would not seem to work well enough to account for biological activity of weak ELF fields at the cell level. But there are further problems: we find that the size of cells is incommensurate with simple ELF resonances.

C Resonance Amplitudes

A resonant system stores energy (allowing the integration of perturbing signals) which is transferred from one form to another at the resonant frequency. For mechanical systems, the energy oscillates between potential and kinetic storage; in the case of LC electrical resonances, the energy oscillates between storage in electric and magnetic fields. Moreover, from the equipartition theorem, the resonance at thermal equilibrium must store an energy equal to kT .

The characteristic angular frequency $\omega = 2\pi\nu$, and stored energy W of a resonant system are

$$\omega = \sqrt{\frac{K}{M}} \text{ and } W = \frac{1}{2} M \omega^2 A^2 \quad (19)$$

where A is the amplitude of excursion of a characteristic mass M and K is a spring constant. From the equipartition theorem, $W = kT$. For ELF frequencies, such as 60 Hz, $\omega \approx 377$ s⁻¹ is small and MA^2 must be large;

too large to fit within the mass and amplitude constraints of a cell. *There can be no ELF cellular resonances.*

We illuminate this categorical statement with explicit examples:

- As an extreme, we consider the physiologically unlikely oscillation of a whole cell with a mass of $\approx 5 \cdot 10^{-13}$ kg, and a radius of about $5 \mu m$. If the energy of oscillation of the whole cell is equal to kT , the amplitude A of oscillation will be $0.34 \mu m$ or about 7% of the radius of the cell.
- However, the oscillation of smaller parts of the cell may be less unlikely. Without concern for the mechanical details of such an oscillation, we consider a 60 Hz resonance of the cell membrane, with a mass of about $2 \cdot 10^{-15}$ kg – or any other equally massive sector of the cell. With the smaller mass, the amplitude must be $\approx 5 \mu m$ and equal to the radius of the cell.
- And there has been interest in ion resonances, especially of Ca_{10} with a mass of $6.6 \cdot 10^{-26}$ kg. The amplitude at 60 Hz corresponding to such a mass is about 1 meter.

Element	Mass	Amp (60 Hz)	Amp (16 Hz)
Whole Cell	$5 \cdot 10^{-13}$ kg	$0.34 \mu m$	$1.35 \mu m$
Cell Membrane	$2 \cdot 10^{-15}$ kg	$5 \mu m$	$20 \mu m$
Calcium Ion	$6.6 \cdot 10^{-26}$ kg	1 meter	4 meters

Table 1: Masses and corresponding amplitudes for systems oscillating with an energy of kT at resonant frequencies of 60 Hz and 16 Hz.

Such results are tabulated here for 60 Hz and 16 Hz oscillations

D Specific Resonances

Since there are some data that are claimed to constitute evidence for the biological activity of weak ELF fields that suggest that the fields act only over narrow “windows” of frequency, for completeness, we discuss detailed characteristics of a set of specific resonances.

Mechanical Resonances

It is interesting to look at a specific oscillation in detail to gain some appreciation for the strength of the prohibition against mechanical oscillations. To maximize M , we choose a hypothetical oscillation of a whole cell where a spherical cell of quiescent radius $r = 5 \mu m$ vibrates in a quadrupole mode

changing from a prolate to an oblate spheroid in the course of a cycle. We take the density of the cell cytoplasm as 1 gm/cm^3 and set the energy of the vibration at $kT \approx 4.3 \cdot 10^{-21} \text{ J}$. With these constraints, we calculated the amplitude of the 60 Hz oscillation, measured in the direction of the axis, as about $1 \mu\text{m}$. This is a substantial oscillation – the radius in the direction of the axis changes by about 20%.

In the course of the oscillation, the kinetic energy of motion of the cell material must be stored in an energy associated with the distortion. Assuming that the cytoplasm is effectively an incompressible liquid, this potential energy storage must be found in the energy required to stretch the membrane inasmuch as the surface area of the cell increases by about 1.5% as the cell changes from a spherical to an ellipsoidal shape. Setting this energy to kT , we find that the surface energy of the membrane is required to be about 10^{-9} J/m^2 , a value about 10^8 smaller than the surface energy of water. Conversely, the natural oscillation frequency of a water droplet of the size of the cell would be about 640,000 Hz.

In summary, if the kinetic energy of the cell vibrating at 60 Hz is to be as large as kT , the whole cell must take part in an oscillation. And then the effective forces described by the spring constant K must be unrealistically small if the frequency is to be kept so low. For smaller cell elements with less mass, the spring constant must be even smaller if the element is to oscillate at ELF frequencies.

Electrical Resonances

But could the “observed” resonances be electrical, rather than mechanical, where the energy is transformed cyclically from storage in a magnetic field to storage in an electric field. We consider that we can describe some element of the cell by an equivalent LC circuit with a resonant frequency;

$$\nu = \frac{\omega}{2\pi} \text{ where } \omega = \sqrt{\frac{1}{LC}} \quad (20)$$

Such a circuit will be incited thermally such that the mean total energy of kT will oscillate between storage in magnetic and electric fields. We note that if the frequency is to be low, the product LC must be large. The capacitance is limited by the size of the cell. The largest capacitance that would seem to be evident is the capacitance between the inner and outer surface of the cell membrane. Taking the thickness of the membrane as $50 \text{ \AA}$

and the dielectric constant as 2.5, $C_{mem} \approx 6 \cdot 10^{-12}$ F. Then, for a resonant frequency of $\nu = 60$ Hz, the inductance must be $\approx 10^6$ henrys!

It is difficult to design an ideal paradigmatic cell inductance. However, we note that in the absence of ferromagnetic materials in cells and in the absence of a natural source of many current turns, we should expect that the characteristic cell inductance should be of a magnitude such that $L = \mu_0 r \approx 10^{-11}$ H; too small by 17 orders of magnitude! (There are mechanical processes that lead to current phase lags in biological material of an inductive nature that follow from the inertial mass of the ions that carry currents or to the viscous resistance to the ion motion but neither of these mechanisms leads to the substantial energy storage requisite for a resonance.) Truly, Nature may be much more clever than we think, but not by a factor of 10^{17} . There can be no 60 Hz LC cell resonances.

Cyclotron Resonances

Bawin and Adey interpreted the results of an experiment¹⁰ as indicating that the passage of calcium ions through chick-brain cell walls was reduced when the cells were subject to weak 16 Hz electromagnetic fields. Then, Liboff and McLeod¹¹ noted that under a magnetic field, $B = 50 \mu T$, the size of the earth's field, that the cyclotron resonance frequency ν ,

$$2\pi\nu = \omega = \frac{qB}{m} \quad (21)$$

for a calcium ion of mass $m = 40$ atomic mass units, carrying a charge $q = e$, was equal to 16 Hz. Hence, they suggested that the cyclotron resonance of the calcium ion might be responsible for the effect reported by Bawin and Adey.

Unlike the mechanical resonance, energy in the cyclotron resonance is wholly stored in the kinetic energy of the circulating ion. The energy is transferred from the kinetic energy of motion in one direction to the energy of motion in an orthogonal direction – all in the plane of the orbit but the energy-amplitude relations stated in the last section, still hold. Hence, quite generally, the orbit of such a resonance must be larger than the size of the cell by five orders of magnitude.

Nevertheless, Liboff and McLeod proposed a specific cyclotron resonance of the calcium ion where the energy of the ion was expected to be about 3.5 eV. But such an ion travels in an orbit with a diameter of 80 meters!

But, of course, the ion could be traveling much slower, slow enough to travel around a 5μ radius orbit that might be fitted into a cell. But the

resultant ion energy is then only about $5 \cdot 10^{-14}$ eV and very, very much less than the mean thermal energy of $kT = 1/40$ eV. Indeed, a estimate suggests that the Brownian effect would typically move the ion randomly $5 \mu m$ in any 1/100 of a second that the ion is to travel that distance about its circuit. Hence, the thermal Brownian-like motion overwhelms any orbital motion.

Nuclear Magnetic Resonances

The interaction of an ambient magnetic field such as the earth's field B_e with the magnetic moment μ of a nucleus (with non-zero spin) generates a torque on the spinning nucleus that induces the nucleus to precess about the direction of the field. Even as the rOTating magnetic moment generates an oscillating magnetic field normal to the ambient field, a weak external field normal to the ambient field that oscillates with the precession frequency will generate a precession of the nuclear polarization. The frequency ν of precession is $\nu = B_e \mu / \pi$. For the earth's field this precession frequency for protons will be about 2000 Hz; for nitrogen about 20 Hz. Moreover, the nucleus of an atom is so weakly coupled to the orbital electrons – and then the material environment – that relaxation times can be of the order of 30 seconds and more. So we have a resonance condition at ELF frequencies with a high Q . Can such resonances have significant biological effects?

No! It seems most unlikely that there can be any biological effect of such resonances. The proportion of the nuclei that will be aligned will be about equal to $B_e \mu / kT \approx 10^{-10}$; a proportion very much smaller than the statistical fluctuations in the alignment of nuclei in the cell. Moreover, as reflected in the large Q , that energy is coupled to the environment of the nucleus very, very, weakly. It is this weak coupling of the nucleus to the atomic structure – and hence to the chemical and biological environment – that makes nuclear magnetic resonance imaging (MRI) such a safe and non-invasive medical procedure though the patient is bathed in magnetic fields of $\approx 4T$, about 100,000 times the earth's field.

IV Summary

A The Experimental Record

Though the theoretical considerations that represent extrapolations and interpolations of tested observations must serve as a reliable guide to our understanding of Nature, such analyses cannot supplant a well-established

contrary observation. Hence we must defer to observations that are *established* through the scientific process of review and replication. But are there there any such well-established observations that demonstrate effects of weak ELF fields on the biology of cells?

There are very many (of the order of one hundred!) reports of experiments that purport to demonstrate that weak ELF fields affect cells. An OTA report¹² places the experiments in four categories: modulation of ion flows; interference with DNA synthesis and RNA transcription; interaction with the response of normal cells to various agents and biochemicals such as hormones, neurotransmitters, and growth factors; and interaction with the biokinetics of cancer cells. There is no near-consensus among those who work in the field to the effect that *any* of the reports of effects in any of these areas is valid; none have been satisfactorily replicated, many of the more substantial results have been contradicted. The problems with the research are stated succinctly (by non-scientist true-believers in the effects) in the OTA "background paper", which characterizes the experiments by noting that "... findings at the cell level display considerable complexity including resonant responses of 'windows' in frequency and field strength, complex time dependencies, and dependence on the ambient DC magnetic field created by the earth. ... ELF fields appear to be an agent to which there is no known analog." The unwitting indictment is severe.

It is, perhaps, the intensity windows that are reported that makes it most difficult to accept the experimental results. It is an almost firm rule of the behavior of systems that, above an action threshold, the response to a perturbing signal increases at least linearly with the incremental signal. This linear increase will generally be terminated only when the signal is so large that it can no longer be considered a perturbation. Since it is very difficult to consider that the small signals in question are sufficiently large to have any effect at all, the view that they can be so large as to dampen out a response is even more troubling¹³. Moreover, the windows seem almost maliciously defined (by man or by Nature) to thwart simple verification of the effects. If such windows did not exist, the verification of the effects of small fields would be simple as the experiment could be conducted with much larger fields to elicit a much larger and more easily detected response.

B Conclusions

In summary, it does not appear to be possible for weak external ELF electromagnetic fields to affect biological processes significantly at the cell level.

ELF electric fields are so completely shielded by the conductivity of the body tissues that the interaction of external fields with a strength less than 300 V/m with cells is far weaker than fundamental thermal noise.

ELF magnetic fields may act through static interactions with magnetic dipole moments of biological material or through the induced electric fields generated by changes in the magnetic fields. Since the static effects of ELF fields of $50 \mu T$ are no greater than the earth's field, it is difficult to believe that the intensity is harmful. Since the maximum induced electric field in the body induced by 60 Hz $4 \mu T$ magnetic fields is no greater than the electric field induced by walking through the earth's field, it is difficult to believe that such changing ELF magnetic fields are harmful. Also, both the static and kinetic effects of ELF fields as great as $50 \mu T$ at the cell level are, again, smaller than that from thermal noise. The impulses from weak $< 50 \mu T$ fast-rise-time ELF magnetic fields – such as from a 20 kHz sawtooth wave form – are also shown to be small compared to thermal effects.

The experimental record lacks coherence and credibility. After 20 years of experimentation, no significant effect of weak ELF fields at the cell level has been firmly established.

In summary: there are very good reasons to believe that weak ELF fields can have no significant biological effect at the cell level – and no strong reason to believe otherwise.

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2. This relation holds specifically for an isolated sphere of tissue but is an adequate approximation for other geometries such as that of the human

body. However, appreciably higher internal fields can result in the body under special conditions. In particular, fields as much as 500 times greater can be induced in the ankles of a man standing on a ground plane subject to a vertical field; M. W. Miller, p. 139, *CRC Handbook*, *ibid*.

3. W. F. Pickard; *IEEE Trans. Biomed. Engr.* **35**, 243 (1988).

4. These results are in accord with a more extensive discussion by Frank S. Barnes; *CRC Handbook* *ibid*, page 121.

5. Cellular effects have been reported by K.J. McLeod, R.C. Lee, and H.P. Ehrlich, *Science* **236**, 1465 (1987) are noted at field strengths in tissues as small as $5 \cdot 10^{-3}$ volts per meter. But these fields correspond to fields generated by external fields in air of $\approx 2.5 \cdot 10^5$ V/m. These fields of 0.005 V/m in the tissue lead to potential differences of about $7.5 \cdot 10^{-8}$ V across the membrane of the cells we consider and that is about 33 times smaller than the noise potential $2.5 \cdot 10^{-6}$ V we calculate. However, since the signal to noise varies as the square of the cell radius and the large bovine fibroblast cells that were studied are effectively about three times the size of our canonical cell, we gain a factor of nine. There is an uncertainty of an order of magnitude in the effective resistivity of membrane material. If we assume that the true resistivity is four times less than our canonical value of $10^6 \Omega\text{-m}$, we gain another factor of 2. Furthermore, it seems that there is a low frequency cut-off at about 10 Hz and if we take that as the band width rather than 100 Hz we gain another factor of 3 giving us an overall signal to noise ratio greater than one and we do not categorically reject the possibility that the purported effects are real.

6. R. P. Blakemore, *Science*, **190**, 377 (1975)

7. R. B. Frankel in the *CRC Handbook of the Biological Effects of Electromagnetic Fields*, p.169, C. Polk and E. Postow, Eds. (CRC Press, Boca Raton, FL 1986)

8. P. W. Atkins, *Chem. Br.*, **12**, 214 (1976). The subject is reviewed by R. B. Frankel⁷.

9. J.C. Weaver and R.D. Astumian, *Science* **247**, 459 (1990)

10. S. M. Bawin and W. R. Adey, *Proc. Nat. Acad. Sci.*, **73**, 1999 (1976)

11. A.R. Liboff and B. R. McLeod; *Bioelectromagnetics* **9**, 39 (1988), and earlier papers.

12. I. Nair, M. G. Morgan, and H. K. Florig; U. S. Congress, Office of Technological Assessment for the Office of Technological Assessment, *Biological*

Effects of Power Frequency Electric and Magnetic Fields - Background Paper, OTA-BP-E-53 (Washington, D. C: U. S. Government Printing Office, May 1989)

13. Intensity windows are not impossible; C.H. Durney, C.K. Rushforth, and A.A. Anderson; *Bioelectromagnetics* 9, 315 (1988), have constructed an ingenious system of cyclotron - and betatron - ion dynamics that would seem to display both intensity and frequency windows but they emphasize that their model cannot describe biological effects.

Biological Effects on the Cellular Level of Electric Field Pulses

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Abstract

Analyses of the electric and magnetic fields in the human body generated upon exposure to external pulsed electric fields are used to consider possible biological effects at the cellular level. For peak external field strengths as high as 100 kV/m, the effects of the consequent internal electric fields on sensitive cell elements such as the macromolecules that carry genetic information, are shown to be small compared to the normal thermal agitation of the elements. Hence, the pulsed fields cannot significantly affect the biological functions that depend upon these elements.

Keywords: Pulsed fields, Electric fields, Cells, Carcinogenic

Introduction

A. W. Guy (Guy 1988) recently conducted an extensive analysis of the electric fields and currents in a human body produced upon exposure to external electromagnetic pulsed (EMP) electric fields. He showed that the energies deposited in the body by a specific moderately intense pulse in a worse-case-situation are nowhere in excess of standards (ANSI 1982) set to limit the energy deposition and accompanying temperature rises in the body.

However concerns have been raised over the possibility that the fields may cause changes on the cellular level – not adequately addressed by the standards – that might have carcinogenic and leukegenic consequences. Such consequences have been considered to follow from interactions of the fields with the cell elements – such as the macromolecules which carry genetic information – that significantly alter the character of those molecules. Since the highest frequency components of pulses generated with nanosecond rise

times will be of the order of 10^9 Hz, corresponding to quantum energies of 10^{-7} eV, it has generally been accepted that such fields cannot disrupt these molecules and hence cannot induce carcinogenic or leukegenic effects.

However, it may be that less catastrophic effects of EMP fields on these important molecular structures may alter the biology of the structures significantly. If such interactions of the EMP fields on the macromolecules are to result in significant biological effects, those interactions must be greater than the ordinary thermal interactions of the molecules with their environment. But we show that any effects on the cellular level of fields in the body generated by external pulsed fields will be masked by thermal noise effects and, hence, such fields cannot be expected to have *any* significant effect on the biological activities of the cells.

Electromagnetic fields interact with matter only through the electric charge carried by matter. For short electric field pulses acting over a time δt , interacting with cell elements carrying a charge q , it is convenient to describe that interaction in terms of the impulse dp transferred to the element,

$$dp = q \int E(t) dt \approx q \langle E_i \rangle \delta t \quad (1)$$

where $E(t)$ is the time variation of the pulsed field, δt is an effective pulse length, and $\langle E_i \rangle$ is an effective mean field strength at the element. The time δt should be taken as the intrinsic width of the pulse or to the thermal relaxation time τ of the cell element if that be smaller.

The mean component of momentum of the cell element from thermal agitation in the direction of the imposed field will be,

$$p_{kT} \approx \sqrt{m kT} \quad (2)$$

where m is the effective mass of the cell element, k is Boltzmann's constant, and T is the temperature of the body. If the pulse is to have any significant biological effect, the impulse transferred to cell elements by the pulse must be greater than that received at a high frequency from thermal buffeting; that condition is $dp > p_{kT}$.

The impulse dp may add to the translational momentum of a free element such as a calcium ion, or add to the momentum corresponding to a vibrational degree of freedom of a macromolecule or other cell element, or to the rotational momentum of a macromolecule or other cell element. For vibration or rotation, the effective mass m would be less than the mass of the whole element.

The Internal Electric Field Pulse Shape

Although Guy studied the effects of a specific pulse, his results are applicable more generally. In particular, he analysed the effects of a pulsed field on a man standing on a ground plane where the electric field was directed in an up-down direction. That configuration was chosen as that which would result in a maximum internal electric field strength from a fast rise time external pulse. For analytic convenience, the external field amplitude was taken to have the form

$$E_0(t) = E_m(e^{-\alpha t} - e^{-\beta t}) \quad (3)$$

where $E_m = 105 \text{ kV/m}$, $\alpha = 4 \cdot 10^6 \text{ s}^{-1}$ and $\beta = 4.76 \cdot 10^8 \text{ s}^{-1}$. This pulse has a rise time of $\approx 10^{-8} \text{ s}$, a decay time of $\approx 2.5 \cdot 10^{-7} \text{ s}$, and rises to a maximum value of 100 kV/m .

Such an external pulse generates an internal up-down pulse, $E_i(t)$, in the body which reaches a maximum in the ankles. The body is effectively resonant for important frequency components where the wave length is about 2.5 times the body length. Then the current and electric field strength in this configuration is constrained by the body dimensions to a maximum at the small cross section afforded by the ankles.

The variation of the internal field with time at the ankles deduced by Guy from his calculations and measurements, is shown in Fig. 1 along with the early segment of the external pulse. For this maximum induced internal field in the body,

$$\int E_i(t) dt \approx \langle E_i \rangle \delta t \approx 1.5 \cdot 10^{-3} \text{ V s/m} \quad (4)$$

where it is often convenient to describe the pulse in terms of the mean amplitude $\langle E_i \rangle = 150 \text{ kV/m}$ over the time $\delta t = 10^{-8} \text{ s}$.

Note that the rise time of the internal and external pulse is similar but the internal pulse falls off very quickly. This abrupt fall off follows from the suppression of the low frequency components of the external pulse; the conductivity of the body, effective at frequencies below about 1 MHz , effectively shields the body. At higher frequencies, the reactance of the body falls off admitting such fields (Foster and Schwan 1986). The graph of Fig. 2 shows the frequency spectrum of the two pulses from a Fourier transform. The low frequency parts of the external pulse are strongly suppressed – hence the much reduced width of the internal pulse measured at the ankles. The magnification of the external pulse at high frequencies – by about a factor

of two at the ankles – follows from the resonance of the body as an antenna which peaks at about $6.5 \cdot 10^7$ Hz, and from the geometry of the body. The up-down internal field elsewhere in the body will generally be smaller than the external electric field intensity at all times and over all frequencies.

For the most part, the value of the time-integral of the internal pulse is roughly equal to the time-integral of the external pulse taken over the first 10 nanoseconds. Since the low frequency components of the external pulse are suppressed, an extension of the external pulse over a long decay time does not contribute to the internal pulse; since the high frequency components are not suppressed, and since the impulse is proportional to the time-integral of the pulse, a rise time of less than 10 nanoseconds does not much change the impulse from the internal pulse.

In short, the maximum internal up-down electric field time-integral in the body, for *any* 100 kV/m external pulse, will not be much greater than the value of $1.5 \cdot 10^{-3}$ kV s/m pulse field determined in this case. For a given external pulse shape, the internal time-integral will be proportional to the amplitude of the external pulse.

The Internal Electric Field Induced by the External Magnetic Field

If the origin of the up-down electric field pulse is at a distance from the subject greater than roughly 10 meters, the field at the subject will be a radiative far-field and the electric field will be accompanied by a well-defined magnetic field $B_0(t)$. The field will be parallel to the ground, normal to the direction of emission, and will have a magnitude;

$$B_0(t) = \frac{E_0(t)}{c} \quad (5)$$

For a 100 kV/m electric pulse, the maximum magnetic field will be about $3.3 \cdot 10^{-4}$ T (3.3 gauss). If near-field conditions obtain, the relation between the magnetic and electric fields will be different. Often a source is designed to produce a near-field that is predominantly electrical. In that case, the ratio of magnetic field to electric field will be reduced below that for the far-field.

The changing magnetic field will induce an electric field in the body. The line-integral of the electric field about any closed path S in the body will be proportional to the change in magnetic flux through the area A enclosed by

the path;

$$\oint_S \mathbf{E} \cdot d\mathbf{s} = \frac{d \int_A \mathbf{B} \cdot d\mathbf{a}}{dt} \quad (6)$$

We can use this relation to estimate a mean induced electric field strength $E_B(t)$;

$$E_B(t) \approx \frac{D}{4c} \frac{dE_0(t)}{dt} \quad (7)$$

where D is a typical body dimension taken here as 0.5 meters. The direction of the induced field in an erect subject will be largely up-down and will then add to, and subtract from, the field from the electric pulse. That field, induced by the rise of the magnetic field, will have a duration time equal to the rise time of the pulse – or about 10^{-8} seconds for the canonical pulse under consideration.

Now we can estimate the time-integral of the electric field induced in the course of the rise of the external magnetic field as,

$$\int E_B(t) dt = \frac{D}{4c} E_{max} = 4.2 \cdot 10^{-5} \text{ Vs/m} \quad (8)$$

where E_{max} is the peak value of the external electric field.

Since this impulse integral is only about 1/35 as great as great as the similar time-integral induced by the external electric field pulse, we do not consider the induced field specifically.

Relaxation Times

The energy equipartition that leaves each degree of freedom of each cell element with a mean energy of kT follows from a high frequency of interactions between elements that moderate any deviation from the mean energy in a short time. That *relaxation* time τ for an element of matter can be estimated as,

$$\tau \approx G \frac{C\rho}{K} L^2 \quad (9)$$

where C is the thermal capacity of the material, ρ is the density, K is the thermal conductivity, L is a characteristic length of the sample, and G is a geometric factor of the order of one. For a sphere of radius $r = L$, $G = 1/4$. We take the value of $C\rho/K \approx 7 \cdot 10^6 \text{ s/m}^2$ as for water which will err on the high side for most cell matter. Then for a whole cell of radius $r = 10 \mu\text{m}$, $\tau \approx 2 \cdot 10^{-4} \text{ s}$; for the cell membrane, $\tau \approx 2 \cdot 10^{-10} \text{ s}$ (the nuclear membrane will have a similar relaxation time); for a macromolecule with a mass of

10,000 atomic mass units and a volume of 10^{-25} m^3 , $\tau \approx 4 \cdot 10^{-11} \text{ s}$; and for a calcium ion, $\tau \approx 3 \cdot 10^{-13} \text{ s}$, which is about equal to the collision mean-free-path for the ion divided by the ion thermal velocity.

The Impulse to Cell Elements

Using the results on the time-integral of the internal field and the relaxation time constants, we compare the momentum transferred dp with the mean thermal momenta p_{kT} for various cell elements:

- The momentum transfer to a doubly charged calcium ion will be $dp = \langle E_i \rangle \delta t 2e \approx 4.8 \cdot 10^{-22} \text{ N s}$ where $p_{kT} = \sqrt{m kT} \approx 1.7 \cdot 10^{-23} \text{ N s}$. Then $dp/p_{kt} \approx 28$. However, since $\tau \approx 3 \cdot 10^{-13} \text{ s}$ the effective impulse is very much reduced. The momentum gain to the ion will never be much greater than $dp' \approx (\tau/\delta t) dP \ll p_{kT}$. But the ion will drift in the direction of the field under the force of the field on the ion charge. We can estimate that drift velocity v from Stokes law;

$$v = \frac{\langle E_i \rangle q}{6\pi\eta a} \quad (10)$$

where a is the radius of the element holding a charge q and $\eta = 7 \cdot 10^{-4}$ is the viscosity of the medium taken here as the viscosity of water. For the calcium ion, we take $a \approx 3 \cdot 10^{-10} \text{ m}$ and $q = 2e$. Then, the drift distance is $v \cdot \delta t \approx 1.2 \cdot 10^{-10} \text{ m}$

But the thermal activity will also move the ion in a Brownian motion. The mean distance x that the ion will move from thermal agitation in the direction of the field will be;

$$x = \sqrt{\frac{2 kT}{6\pi\eta a}} \delta t \approx 4.7 \cdot 10^{-9} \text{ m} \quad (11)$$

Since the random Brownian motion is about 40 times greater than the drift caused by the pulsed field, that drift cannot be biologically important.

- We can estimate an effective momentum transfer to the macromolecule, with a mass of 10,000 AMU, (perhaps inducing a spring like motion, or a rotation of the molecule, through the coupling of the field with a permanent electric dipole moment) as, $dp = \langle E_i \rangle e \delta t \approx 2.4 \cdot 10^{-22} \text{ N s}$. For the molecule we estimate $p_{kT} \approx \sqrt{m kT} = 2.6 \cdot 10^{-22} \text{ N s}$. Then $dp/p_{kt} \approx 1$. However, $\tau/\delta t \approx 1/250$ and the impulse will be broken up by thermalization. Using the same methods of estimation as above, but taking the effective charge

$q = e$ and choosing a radius of $20 \cdot 10^{-10} m$, we find a drift of $\approx 10^{-11} m$ and a Brownian motion $x \approx 2 \cdot 10^{-9} m$.

Again, the thermal motion completely masks the motion of the macro-molecule induced by the field, hence, the effects of the pulsed field will not be significant.

- At a more gross level, the field may couple to the whole cell through the induced dipole moment of the cell. We estimate this momentum transfer as,

$$dp = \langle E_i \rangle q \delta\tau \text{ where } qr = PV \text{ and } P = \epsilon_0(K - 1)\langle E_i \rangle \quad (12)$$

where $K \approx 80$ is the dielectric constant and P the polarizability of the cell material (largely that of the cytoplasm), and $r = 10^{-5} \mu m$ is the radius and V is the volume of the cell. This momentum transfer, $dp \approx 6.7 \cdot 10^{-17} Ns$, is to be compared with $p_{kT} \approx \sqrt{mkT} \approx 1.35 \cdot 10^{-12} Ns$, where m is the mass of the cell. Then $dp/p_{kT} \approx 10^{-4}$ and, again, the effects of the field cannot be significant.

Induced Currents

Guy (Guy 1988) has also determined the current flow at the ankles where the current is a maximum. The maximum current density $j(t)$ was found to be about $500 a/m^2$ and that current varied with time approximately as the internal field (Fig. 1) which has an effective width of about 10 ns. Hence the charge transfer is calculated to be,

$$\Delta q = \int_0^\infty j(t) dt \approx 5 \cdot 10^{-6} C/m^2 \quad (13)$$

To put this into context, the charge transferred through the cross section πr^2 of a cell of radius $r = 10 \mu m$, will be $\approx 1.6 \cdot 10^{-15} C$. We then consider an extreme worse-case where such a net charge was transferred across the cell membrane into the cell interior and retained after the pulse. Then, taking the capacitance of the membrane as about 6 pF, the potential across the membrane would be changed by 0.25 mV, which is about 0.5% of the normal trans-membrane potential. Since this extreme number is only about 20 times the noise voltage over the relaxation time of the typical cell (Weaver and Astumian 1990) calculated to be about $2.8 \cdot 10^{-5} V$, we suggest that any more realistic model will realize potential shifts smaller than the thermal noise – if such charge transfers were to occur at all.

Summary

In summary, 100 kV/m pulses, with rise times less than or equal to 10 nanoseconds, acting on a (worse-case) man standing on a ground plane, will not affect cell elements such as macromolecules to a degree that is as great as thermal effects. Hence, such pulses cannot be expected to produce any biological effects at the cellular level.

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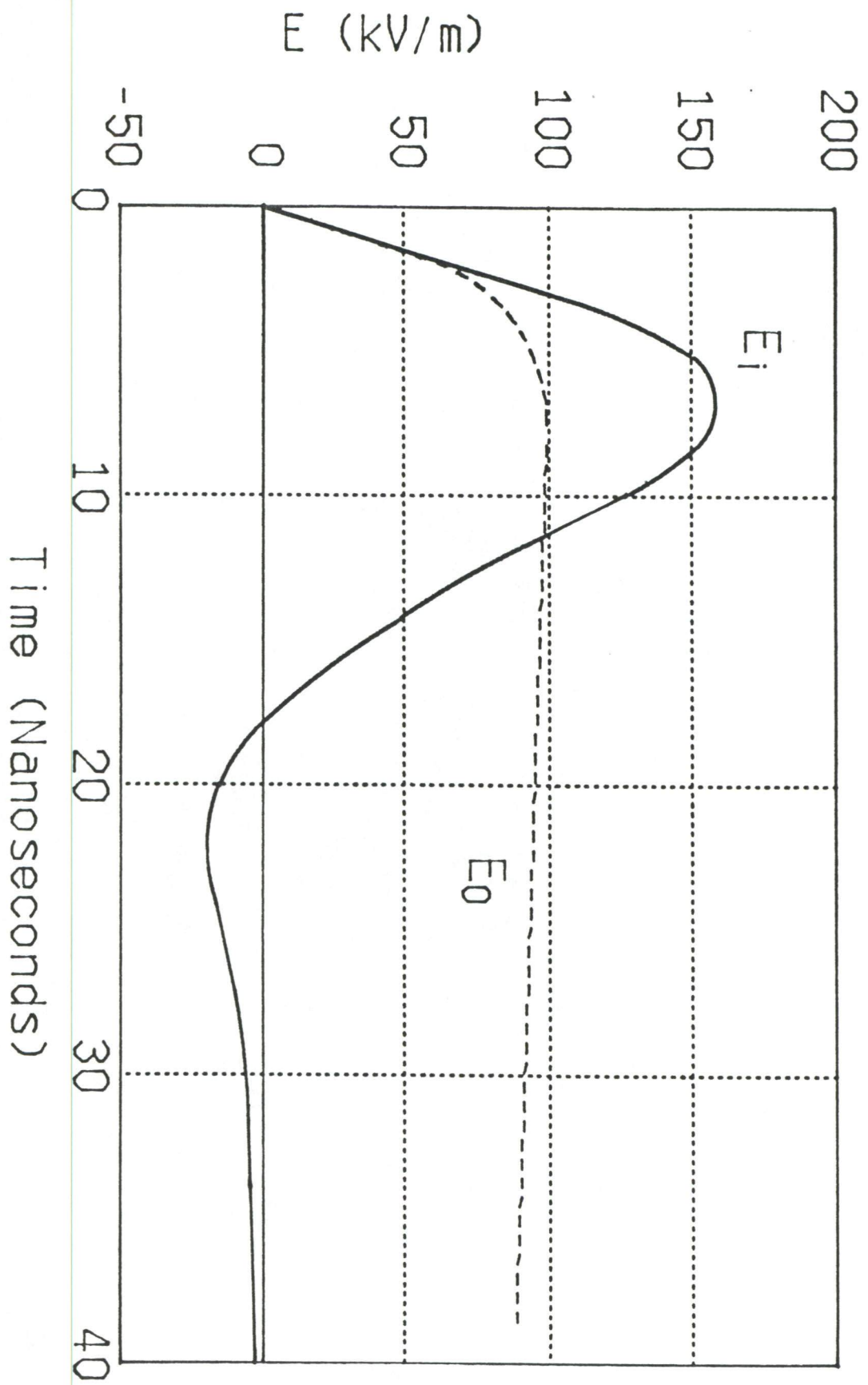
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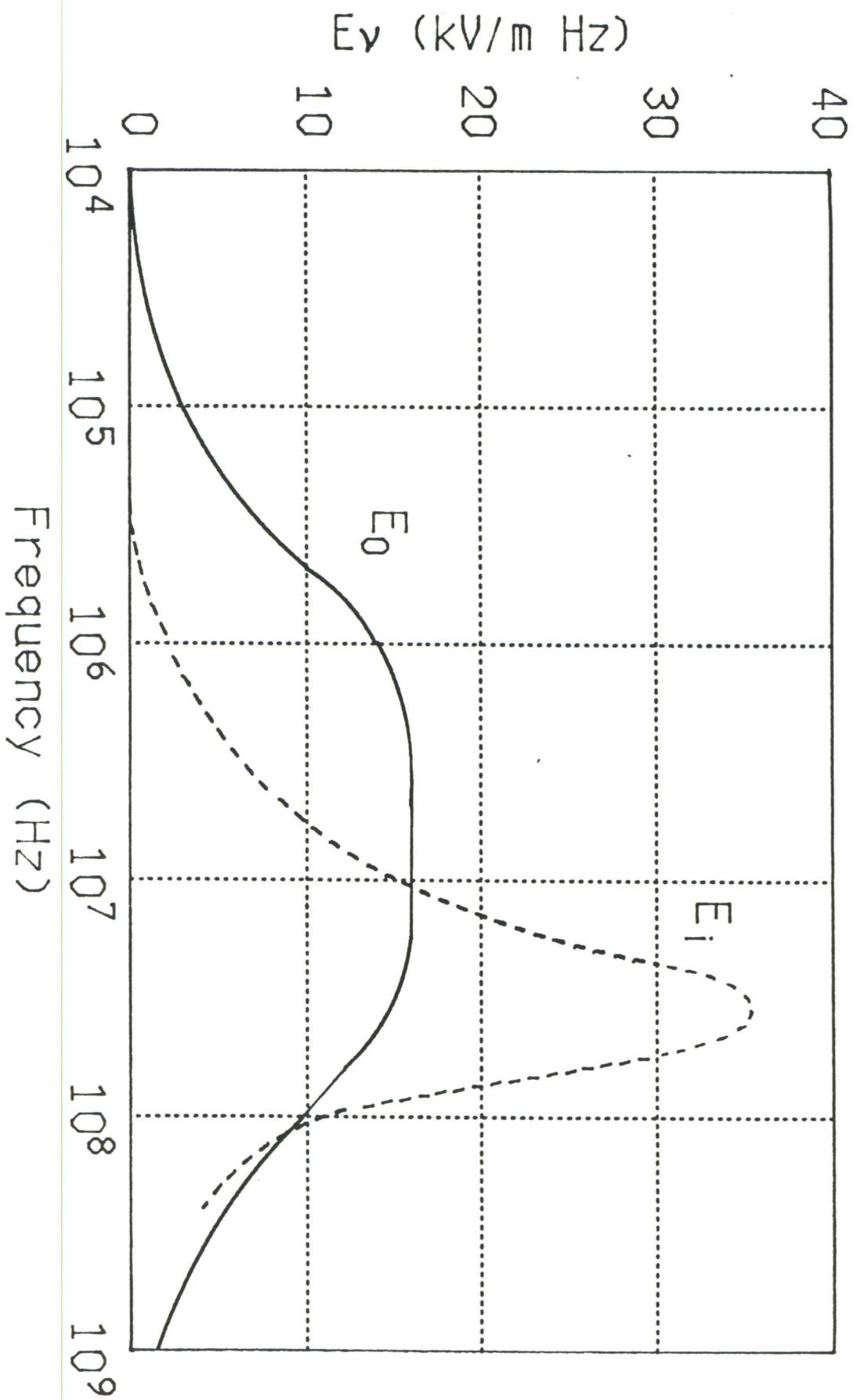
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Figure 1: The electric field in the ankle of a man exposed to a 100 kV/m EMP. The early segment of the external pulse is also shown.

Figure 2: The frequency spectrum of the external and internal pulses. The quantity $(dE/d\nu) \cdot \nu$ is plotted where ν is the frequency. In this representation, the area under the curves is proportional to the field integral.





THE WHITE HOUSE
WASHINGTON

August 2, 1990

MEMORANDUM FOR THE HONORABLE WILLIAM K. REILLY

FROM: D. ALLAN BROMLEY

Adair

SUBJECT: ELF STUDIES

As promised, I am sending you herewith a list of people whom I would recommend as persons whom you might consider as very knowledgeable ones in the area of alleged non-ionizing, non-thermal biological effects of low intensity, low frequency electromagnetic radiation. They cover a wide range of age, experience, background etc.

I also enclose, to keep your file of Adair papers up to date, a recent comment regarding alleged biological effects of static magnetic fields. Bob Adair is also someone whom you might want to keep in mind. He is very bright, uninhibited and someone who can be abrasive when he feels that the situation deserves it.

This is a very difficult area that I am sure you agree requires careful treatment if we are to serve the public well.

Enclosures

SOME GOOD PEOPLE FOR ELF STUDIES

A. W. (Bill) Guy (about 60)

Prof. of Electrical Engineering and Bioengineering
University of Washington, Seattle

Guy is very competent, very low key, highly respected in the field. Formerly President of the Bioelectromagnetic Society, second awardee of their D'Arsonval Medal. Expert on antenna theory, microwaves, etc. especially energy depositions of microwaves in humans. Guy was PI in an extensive study funded by the airforce (School of Aerospace Medicine, Brooks Air Force Base, San Antonio) of effects of microwaves on rats where rats were exposed for their lifetimes -- one and two years -- and about 150 biological endpoints were measured.

Kenneth Foster (about 35)

Associate Professor of Bioengineering, University of Pennsylvania.

Foster is a very bright, very sound, younger biophysicist specializing in the electrical properties of biological materials -- especially at the cellular level. (I believe that his Ph.D. is in physics.)

William Pickard (about 50)

Professor of Electrical Engineering at Washington, University, St. Louis

Pickard has made substantial contributions to our knowledge of the electrical properties of biological materials, experimental and theoretical. Bill is a Harvard Ph.D. in applied physics and is very bright and very sound. (Pickard and Foster wrote a Scientific American Article to the effect that there are no significant biological effects from low intensity microwaves.)

John deLorge (about 50)

Naval Aerospace Medical Research Laboratory, Pensacola, Florida

Psychologist, Radiation effects on primates.

Director of Programs, Alternate to Skip Kerschner on CIRRPC Committee

W. Gregory Lotz (about 38)

NAMRL, Pensacola, Florida

Endocrinologist who works with whole animals, primates, etc.

Conducted excellent ELF study on Rhesus Monkeys.

Intelligent and sensible, very able.

John Bergeron (about 55)

General Electric

Biophysicist, very good.

Herman Schwan (72)

Prof Emeritus Department of Biengineering
University of Rochester

Member National Academy of Engineering
Almost the father of the field in the US.

Sol M. Michaelson (about 65)
Prof. Dept. of Radiation Biology and Biophysics
University of Rochester
A grand old man of the field.

Mort Miller (about 40)
Prof. Radiation Biology and Biophysics, University of
Rochester
Biophysics with emphasis on biology. Very good.

E.L. Carstenson
Prof. Electrical Engineering, University of Rochester
Has written decent semi-popular book on effects of ambient
electromagnetic fields.

Eleanor Adair
Fellow John B. Pierce Foundation, New Haven
Ellie has some interesting capabilities concerning the
effects of magnetic fields on primates.

Allan Grodzinski
MIT
Was funded by Air Force (but they ran out of money). Good
man with excellent research facilities.

James Toler
Georgia Tech
Funded by Air Force to conduct major study of ELF fields on
rats.

Comments on Draft of the Report of NCRP Committee SC67 on the Biological Effects of Static Magnetic Fields

Robert K. Adair

July 18, 1990

The subject of the report is (1-1) "... the evaluation of the biologic effects of static magnetic fields and the potential health consequences of those effects." Recognizing the ubiquity of the earth's field of $\approx 50 \mu T$, the present electrophobias have not centered on static magnetic fields. Hence, the content and conclusions of the report do not now address the most sensitive areas of the interaction of electromagnetic fields with biological systems. Nevertheless, the subject is important in itself both in reference to the adequacy of present industrial practices and standards and as a part of the general question of the biological interaction of electromagnetic fields.

About 30% the report is devoted to a generally useful review of objective and non-controversial matters such as definitions, existing standards, sources of fields and their measurements, biological interaction mechanisms, and an important section on pacemakers and prosthetics. The rest of the report is directed towards analyses of biological data.

Although the committee is charged with "evaluation" (1-1), the report of the biological data is more nearly a compendium than a critical review. While the authors refer to the inadequacy of their data base, (9-15 to 9-24), and occasionally criticize reported results (e.g. 88-1 to 88-23), the overall review is not always critical. That may follow from the natural limitations of a small committee considering a very broad set of phenomena. It is noticeable that those areas that are close to work of committee members – such as the excellent work of the Berkeley group [Tenforde] – are discussed with a commendable depth not always evident elsewhere.

This sometimes lack of critical review leads to situations that can result in problems in a public document. While the authors often qualify their

reports of dubious experimental results – e.g. Baker ... purports to have demonstrated (114-12) – often they use statements that can be read by the layman as a considered acceptance of results that the committee probably does not accept uncritically – e.g. accelerated tomato ripening at 0.06 T, (64-5 to 64-13).

In at least one area, the committee appears to accept with enthusiasm results which are – at best – highly questionable (57-9 to 59-4; especially “The work by Blackman et al. and Smith et al. provide strong evidence of an interaction between magnetic fields and biological systems.” 55-10). Aside from internal inconsistencies, such as large variances in sham runs, similar work of Blackman has been contradicted by several more careful studies such as those by A.W. Guy and colleagues. Certainly the Blackman results have never been replicated nor has any rational experimental framework, such as a dose-response relation, emerged from a decade of studies. Since the results appear to violate thermodynamic criteria inasmuch as the signals seem to be very much below thermal noise, the results should be examined with special reserve.

The work of Smith et al is even more idiosyncratic and unreplicated and based on the ion cyclotron resonance theory of McLeod and Liboff which is ridiculous numerology, not science. If the ions have energies of kT, their orbital radii will be of the order of meters. If the radii are of the order of 25 Å, as suggested by the model, the ion energies must be of the order of 10^{-18} kT.

I would also prefer that the authors more strongly differentiate between strong fields ($B > 1$ T) where there are certainly biological effects, moderate fields $0.001 < B < 1$ T where there may be effects, and weak fields $B < 10^{-4}$ T where there is good reason to believe that there should be no effects.

I find the “Recommendations” (161-1 to 165-8) well-considered and sensible.

However the advice (165-10 to 165-20) regarding “additional funding” on Ca^{2+} ion transport is ill-advised since there are very good reasons to believe that such effects are impossible and the (two) experiments that purport to see such effects are extremely weak.

Indeed these two experiments (Smith and Blackman) exhibit serious general weakness common to *all* of the results that have been interpreted as indicating biological effects of weak fields. The results are always singular and exhibit no coherent structure. There is never a rational dose-response relation. Science is not stamp-collecting but the establishment of patterns and relationships. Without the internal discipline of a pattern, any error

in an experiment comparing exposures and shams shows up as a biological effect. Hence, incompetence is rewarded. The committee would be well advised to suggest that most further funding of purported effects on the mT or μT level be directed to efforts to validate - or invalidate - previous claims of effects.

THE WHITE HOUSE

WASHINGTON

July 19, 1990

MEMORANDUM FOR RONALD PETERSON

FROM: D. ALLAN BROMLEY 
SUBJECT: STATEMENT OF WILLIAM H. FARLAND

Enclosed herewith is a copy of a recent memo to Roger Porter on this topic. I am convinced that while EPA must indeed respond to public concern I do not believe that EPA should add to those concerns given the shabby quality of the current experimental evidence.

The indicated insert on pages 5 and 6 of this draft, i.e. the "preliminary conclusions", lend support to suggested cause and effect relationships concerning low frequency EM radiation and carcinogenesis that have no adequate scientific foundation.

I would strongly suggest that this section be modified to qualify these "preliminary conclusions" leaving the situation as an open one deserving of a high quality scientific examination under EPA auspices.

My memo to Porter makes clear my own prediction as to what this examination will reveal.

Enclosure

THE WHITE HOUSE

WASHINGTON

June 13, 1990

MEMORANDUM FOR ROGER B. PORTER

FROM: D. ALLAN BROMLEY 

SUBJECT: CANCER RISKS FROM ELECTROMAGNETIC RADIATION

As you note in your memorandum of April 29 to Governor Sununu there are now two recent reports dealing with the subject of potential carcinogenicity of electromagnetic fields at frequencies associated with electrical power generation and use—one from EPA and one from OTA.

Two of my old colleagues at Yale have been interested in this field for some time and have taken rather strong issue with the OTA report in particular. They are a husband and wife team, Eleanor and Robert Adair. Eleanor is associated with the Pierce Foundation in New Haven and is a physiologist while Bob is the Sterling Professor of Experimental Physics at Yale and for a number of years has been Chairman of the Physics Section of the National Academy of Sciences. In the recent past both have devoted substantial effort to understanding the literature in this field and Eleanor has been involved in some of the relevant experimental work. On the basis of these activities they have concluded that there is no acceptable evidence supporting the alleged linkage between carcinogenesis and exposure to the lower level fields typical at 60 Hertz.

Indeed, in a recent statement from the American Physical Society, it was pointed out that the recent literature demonstrated a most peculiar dose sensitivity where the alleged carcinogenesis appeared to increase as the field strength to which the subject was exposed decreased. Given that rather amazing data, the American Physical Society suggested that an obvious conclusion was that the public should be protected by being subjected to sufficiently intense fields so that the carcinogenesis affect (if real) would be suppressed!

I am enclosing herewith a copy of a paper entitled Are Biological Effects of Weak ELF Fields Possible? that Bob Adair produced for delivery at a recent meeting of the Electromagnetic Energy Policy Alliance (EPPA) recently here in Washington. He intends to publish it in the American Journal of Physics sometime in the near future.

I was particularly taken by Bob's evaluation of the ELF field effects within the framework of what Langmuir at General Electric long ago described as pathological science and for which he gave a set of identification rules (see pages 30-31).

Constraints on the Biological Effects of Weak ELF Fields

Robert K. Adair

Department of Physics, Yale University, New Haven, CT 06511

Abstract

Concerns have been raised over the possibility that extremely-low-frequency (ELF) electromagnetic fields are carcinogenic and leukegenic. An examination of the physical interaction of such fields with the body shows that such interactions are too weak to have a significant effect on human biology at the cell level.

Because of the high electrical conductivity of tissues, the coupling of external electric fields in air to tissue in the body is such that the effects of the internal fields on cells is smaller than thermal noise. Static magnetic fields smaller than the earth's field of $50 \mu T$ and varying fields weaker than the $4 \mu T$ 60 Hz fields that are equivalent in effect to that from walking in the earth's field, cannot be expected to generate significant biological effects. Moreover the interactions of such weak fields at the cell level are also small compared to thermal noise. These conclusions would be modified by 60 Hz cell resonances. But such resonances are shown to be incompatible with cell characteristics and the requirement from equipartition that the mean resonance energy must be kT .

Hence, any biological effects of weak ELF fields on the cellular level must be found outside of the scope of conventional physics in much the same way as parapsychology or cold fusion.

I Introduction

Very weak extremely-low-frequency (ELF) electromagnetic fields from common electric appliances and lighting, from local home and workplace distribution wiring, and from the major national electric grids, are a ubiquitous part of modern civilization. Since the magnitudes of these "leakage" fields are very small, and seemingly small compared to natural fields in the body,

it has been commonly assumed that the fields could not affect any biological activity significantly and, hence, could not constitute a health hazard.

However concerns have been raised over the possibility that the biological effects of the fields have not been properly understood and that the fields may in fact generate changes on the cell level that might have carcinogenic and leukogenic consequences. Such effects have been largely associated with the breaking of molecular bonds of macromolecules such as those responsible for the genetic information. Since the extremely low frequency (60 Hz in North America and largely 50 Hz elsewhere) of the ELF fields means that the characteristic quantum energies are $\approx 10^{-14}$ eV, it has generally been accepted that such fields cannot disrupt these molecules and hence cannot induce carcinogenic or leukogenic effects.

However, it may be that less catastrophic effects of ELF fields on cells in the body may induce actions which we do not yet understand that alter the biology of the structures significantly. If such interactions of the ELF fields at the cell level are to result in any significant biological effects, those interactions must be significantly greater than the ordinary thermal interactions of the molecules with their environment. But we show that any effects on the cell level of fields in the body generated by weak external ELF fields will be masked by thermal noise effects and, hence, such fields cannot be expected to have any significant effect on the biological activities of the cells.

In any material the charge density fluctuates thermally according to thermodynamic imperatives generating fluctuating electric fields. Although there are other sources of biological noise, such as noise generated by muscle excitation and activity, electrokinetic noise from squeezing of electrolyte through tissues, and the $1/f$ noise from cell membrane activity, that contribute fields as great as 0.1 V/m at frequencies less than 100 Hz, we emphasize the generally smaller noise inasmuch as the magnitude of that noise stems from fundamental thermodynamic bases and must constitute an irrefutable constraint on biology.

For similar reasons, we emphasize effects on the cell level. Over larger regions, the impact of weak ELF external fields is limited more by biological and physiological considerations than by the competition with Johnson-Nyquist noise and is hence outside of the chosen scope of this paper. Since the bulk of the experimental results that have been interpreted as an indication of effects of such fields concern mechanisms on the cell level such as changes in ion transport through cell membrane walls and increases in genetic transcription errors, the analyses of mechanisms that might operate at the level of the cell are of primary importance. Any possible carcinogenic

effects of weak ELF radiation would also most likely operate at the cellular level.

In the quantitative features of this discussion of the effects of low frequency, low intensity, electromagnetic fields on biological materials, we will consider especially 60 Hz oscillations, and define *weak* fields as electric field strengths that do not exceed 300 V/m in air and magnetic field strengths no greater than 0.5 gauss (or 50 μT), the strength of the earth's field – the mean electric field at the earth's surface is about 100 V/m. The fields will, in general, be near-fields, and not radiative. Indeed, for the most part, we will not be talking about *radiation* – non-ionizing or otherwise.

II External Fields and Noise Fields

A Coupling of Tissue and Air for Electric Fields

For environmental concerns, the immediate measure of possible hazard is that field in the air about the tissues. Since the tissues are conducting, a constant external electric field will induce almost no field at all in the tissues though an alternating external electric field will induce small fields. At low frequencies, ν , the fields E_i in the tissues will be very much smaller than the fields E_0 in the air external to the tissues¹.

$$E_i \approx 3\epsilon_0\omega\rho_t E_0 \quad (1)$$

where $\omega = 2\pi\nu$ is the angular frequency and $\rho_t \approx 2 \Omega\cdot m$ is the resistivity of the electrolyte saturating the tissue². At 60 Hz, $E_i \approx 2 \cdot 10^{-8} E_0$. Hence, for fields in the air of 300 V/m, we can expect field strengths in the conducting tissues of about $6 \cdot 10^{-6}$ V/m. The cell membrane will have a specific resistance of the order of $\rho_{mem} \approx 10^5 \rightarrow 10^7$ ohms and can then be considered as an insulator relative to the tissue electrolyte. In the valid approximation that the resistivity of the membrane material, $\rho_{mem} \gg \rho_t$, the resistivity of the tissue, the field in the membrane, E_{mem} of thickness d of a cell of radius r will be about

$$E_{mem} \approx 1.5 E_i \frac{r}{d} \quad (2)$$

Hence, taking a typical cell radius of 10 μm and a membrane thickness of 50 $\text{\AA}$, for a field in the tissue electrolyte $E_i = 6 \cdot 10^{-6}$ V/m, induced by an external field of 300 V/m, we can expect a field $E_{mem} \approx 3000 \cdot E_i \approx 2 \cdot 10^{-2}$ V/m in the insulating membrane.

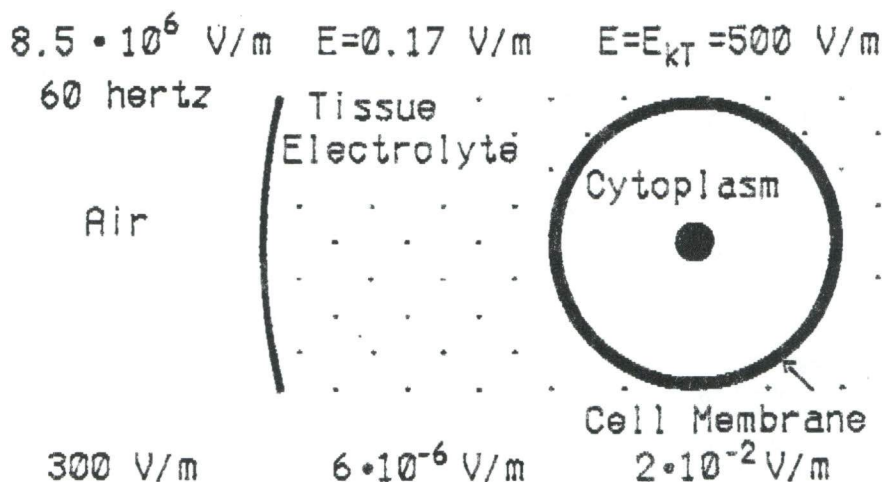


Figure 1: Electric fields in tissues, cell membranes, and cell cytoplasm, induced by ELF external fields in the air outside of the tissue. The fields labeled above describe an externally induced field in the cell membrane that is equal to the Johnson noise, from DC to 100 Hz, measured from the cytoplasm interior to the cell to the electrolyte outside of the cell across the cell membrane. The very large air field so postulated is larger than the dielectric breakdown strength for air of about 10^6 V/m and is then unobtainable in practice. The lower numbers describe the fields induced in the tissue and membrane by an external field of 300 V/m.

The internal elements of the cell, such as the nucleus and the genetic material, are shielded by the resistive cell membrane and the fields they see are quite negligible¹.

The fields in different areas of air, tissue, and cell, are shown in Fig. 1 normalized to a field in the air of 300 V/m. Too often, discussion of the effects of weak fields is complicated by misunderstandings concerning the region in which the field is defined. Since we are addressing environmental concerns, the fields labeled "external" in this report are *always* fields in the air about the tissues.

B Thermal Electrical Noise

Since the most important fundamental constraint on effects of very weak fields, is the requirement that they not be masked by thermal noise, we present a heuristic explanation of the Johnson-Nyquist noise designed to suggest the salient features of that noise. We proceed by describing thermal noise at a frequency ν in a sample of material by analyzing an imaginary experiment. The sample is inserted as a resistive load R in an LC oscillator circuit where the circuit elements are chosen such that

$$2\pi\nu = \omega = \frac{1}{\sqrt{LC}} \quad (3)$$

From the equipartition theorem the mean energy of the oscillator is $W = kT$ where T is the ambient temperature. But as the circuit oscillates it will lose energy as a consequence of the resistance of the sample. The rate of energy loss or loss power P will be

$$P = 4kT\Delta\nu \quad (4)$$

where $\Delta\nu = 4R/L$ is the effective resonance width.

The effect of this action will be to transfer energy from the oscillator, which is then cooled below the ambient temperature, to the resistive sample, which is then heated above the ambient temperature. But this is in violation of the *second law*. Hence, if the system is to remain at thermal equilibrium (and we are to avoid violating the *second law*), the sample must generate electrical energy at a rate P at the frequency ν that will be fed back to the oscillator. Hence, the noise power generated thermally by the sample must be equal to P . That power is independent of the magnitude of the resistance of the sample and must hold for any frequency ν even as we could tune the oscillator to different frequencies.

If we write $P = V_{kT}^2/R$ where V_{kT} is the noise voltage across the resistance R , we find the usual formula for that voltage V_{kT} generated by Johnson noise over a frequency interval $\Delta\nu$,

$$\overline{V_{kT}^2} = 4RkT\Delta\nu \quad (5)$$

Although this noise voltage must follow from thermal fluctuations in the charge density in the sample material, the result - characteristic of thermodynamic results - is independent of detail; in particular of the detailed character of the charge carriers which may be conduction electrons, ions, or bound charges sensibly displaced by thermal buffeting.

Often the noise fields will be of more interest than the noise voltages – which are, however, better defined. Taking the sample as a cube with a side d for convenience, $R = \rho/d$, where ρ is the characteristic resistivity of the material, $E_{kT}^2 \propto 1/d^3$. As a consequence of averaging over fluctuations, the electric field noise limit varies inversely as the square root of the volume considered. Although, E_{kT}^2 was evaluated for a cube, the value depends only on the volume of the sample. The noise does not vary with volume as one might expect for random electric field fluctuations since the field fluctuations – taken to originate in charge density fluctuations – are correlated through the conservation of charge and Gauss's theorem.

Since the thermal noise is larger for small volumes – where the statistical fluctuations of electron densities are proportionally larger – than for larger volumes, to make the most useful assessment of the effects of thermal noise it is desirable to choose the smallest volume commensurate with the biological action. This increase in effective noise field strength as the sample size is reduced, extends to the molecular level. The characteristic molecular field strengths required to substantially change the momenta of molecules in a typical thermal collision, for example, are of the order of $kT/er \approx 10^8$ V/m, where $r \approx 1$ Å, is the interaction length relevant in the collision. Hence, very large electric field fluctuations can be expected as a consequence of "collisions" with surrounding molecules.

C Noise Fields in Tissues

We estimate the thermal noise generated in a quantity of tissue by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where a cube of tissue of length d on a side is held between the plates. The voltage across such a capacitor will be a *useful* measure of the local electric field at low frequencies. To estimate the thermal electric field noise, we consider the system as an equivalent parallel circuit of the membrane resistance R and the capacitance C between the plates. The time average noise voltage V_{kT} can then be expressed as,

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu = 4\frac{\rho}{d}kT\Delta\nu \text{ and } E_{kT} = \frac{\overline{V_{kT}}}{d} \quad (6)$$

Using the above relations, and taking $\rho = 2 \Omega \cdot m$ for tissue and a frequency span $\Delta\nu = 100$ Hz – i.e. from DC to 100 Hz – we find that the noise field generated in the electrolyte in a cubical volume the size of a cell,

20 μm on a side, is about 0.02 V/m, which is about 3000 times larger than the field induced by a 300 V/m external field.

Though the field is large, the thermal noise *potential difference* over 20 μm is but 3 μV . In general, thermal noise voltages between different regions of tissue will be very much less than 1 μV .

Experiments have shown that some fish - especially sharks - do respond to very weak electric fields. These are fields in the water surrounding the fish and are, therefore, strongly coupled to the watery tissue of the fish. In salt water, the fields are more strongly coupled by a factor of $\approx 5 \cdot 10^7$ than fields in air to tissue. With special receptors, the ampullae of Lorenzini, which act as low pass filters, that extend over lengths near a meter, the response of sharks to quite small fields - as fields as small as 0.5 $\mu\text{V}/\text{m}$ have been detected - does not violate thermal noise limits³.

D Noise Fields in Cell Membranes

A popular "explanation" of purported biological effects of external low-level ELF electromagnetic fields, is that these effects derive from the effects of the electric fields on the complex properties of the cell membranes. The fields are presumed to modify such membrane activities as the opening and closing of ion-conducting channels and the catalytic activity of membrane-associated enzymes. Of course if externally imposed fields are to have any important effect, those fields at the cell activity sites must not be swamped by the thermal Johnson noise fields.

Certain processes such as the passage of ions through the cell membrane walls may be likely defined by thermodynamic criteria and hence depend upon the potential difference - which is typically of the order of 50 mV - between the cytoplasm interior to the cell and the electrolyte outside of the cell. For such mechanisms the noise voltage across the membrane from the relatively highly conducting interior cytoplasm to the conducting electrolyte might be more significant than any local noise level. (The natural potential difference across the membrane will be of the order of 50 mV to be compared with the noise voltage across the membrane of $\approx 10^{-6}$ V and the thermal kinetic energy of an ion of $3/2 kT \approx 37$ meV.) The time average noise level from cytoplasm to electrolyte, across the whole membrane of thickness $d \approx 50$ Å, of a spherical cell of radius $r = 10^{-5}$ m will be;

$$\overline{V_{kT}^2} = 4RkT / \Delta\nu \text{ where } R_{mem} = \frac{\rho d}{4\pi r^2} \quad (7)$$

where the resistivity of the membrane material is taken as $\rho_{mem} = 10^6 \Omega m$. With these values, $R_{mem} = 4 \cdot 10^6 \Omega$. Taking an ELF frequency band of 100 Hz, $V_{kT} \approx 2.6 \cdot 10^{-6} V$ and $E_{kT} = V_{kT}/d \approx 500 V/m$. This thermal noise voltage. (Since the resistivity of the membrane material is uncertain within a factor of ten, the field strengths calculated here are uncertain by a factor of 3.) is probably much smaller than the $1/f$ noise, possibly associated with the flow of ions through cell membrane orifices, and smaller by a factor of $\approx 5 \cdot 10^{-5}$ than the normal potential difference of 0.05 V across the cell wall⁴. But the noise voltage across the membrane – and the noise field in the membrane – is about 25,000 times⁵ the voltage and field induced by the canonical external field of 300 V/m.

It has been argued that the externally induced fields in the cell membrane may affect such biological activities as the catalytic actions by membrane-associated enzymes. If such induced fields are to affect the processes, those fields must be greater than the fields due to thermal fluctuations.

Since these kinds of biological activities would appear to be local, determined not by average fields over the whole cell membrane, but by conditions in a small sector of the membrane with a volume no larger than d^3 , where $d \approx 50 \text{ \AA}$ is the membrane thickness, it would seem that it would be the local thermal electric field fluctuations in such small regions that should be compared to the induced fields. Since the volume in question is quite small, and the effective noise fields over small volumes are greater than for larger volumes, we might expect that the local electric field noise would be much greater than that averaged over the whole membrane. The electrical properties of such a small sector are not necessarily simple but we can estimate that thermal noise generated in a small quantity of membrane material proceeding as before by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where an isolated cube of membrane material 50 $\text{\AA}$ on a side is held between the plates. The time average of the fluctuating noise voltage V_{kT} is again

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu \text{ where now } R = \frac{\rho_{mem}}{d} \approx 2 \cdot 10^{14} \Omega \quad (8)$$

If we use the mean resistivity of the membrane material of $\rho = 10^6 \Omega \cdot m$, for the small sector, which is simplistic, and taking, again, only frequencies less than 100 Hz, the mean noise voltage across this small, isolated, sample will be ≈ 0.02 and the thermal noise electric field over this frequency is then $E_{kT} \approx \overline{V_{kT}}/d \approx 3.7 \cdot 10^6 V/m$ which is about $2 \cdot 10^8$ times that from a 300 V/m external field.

E Electric Field Effects

Although the small values of the ratios of induced to noise electric fields must largely exclude any possibility that those induced fields can induce biological activity in cells, one can reach much the same conclusions by considering interactions in more detail. To be definite, we consider fields of $E_i = 6 \cdot 10^{-6}$ V/m in tissue, and $E_m = 2 \cdot 10^{-2}$ V/m in membranes 50 Å thick of cells of radius $r = 10^{-5}$ m, induced by external fields of 300 V/m and we compare the energies transferred to the elements to kT .

For membrane or tissue, the energy transferred by the field to an ion – or any singly charged element – in tissue or membrane will not be much larger than $E_i e r \approx 10^{-9} kT$, where e is the electronic charge. Which is to say neither the kinetic energy nor the direction of motion of a charged element can be sensibly affected by such small fields.

An imposed external field will tend to align electric dipoles so that, even in the face of thermal agitation, there will be a statistical excess of dipoles aligned with the field. That proportion P which are aligned can be estimated as $P \approx W/kT$ where W is the alignment energy. We can make a useful estimate of a *maximum* magnitude of such an interaction energy by considering the interaction of the field, E_i , in the tissue with a whole cell neglecting, for the purpose of the maximal estimate, the macroscopic shielding provided by the cell membrane. The electric dipole moment per unit volume of cytoplasm will be $\mathbf{P} = \epsilon_0(K - 1) \cdot \mathbf{E}$ where K is the dielectric constant and $K - 1 \approx 80$ as for water and the volume V is that of a cell 10 μm in diameter. Then the interaction energy W will be about

$$W \approx (\mathbf{E} \cdot \mathbf{P}) V \approx 80 E_i^2 \epsilon_0 V \approx 2.5 \cdot 10^{-14} kT \quad (9)$$

We can also consider the alignment of macromolecules that display permanent electric dipoles. Taking a characteristic magnitude of such a dipole moment as er where, $r = 200$ Å, the alignment energy of the molecule in the membrane will be $W \approx E_m e r \approx 3 \cdot 10^{-8} kT$.

F Magnetic Fields

Static Magnetic Fields

A kind of restricted anthropic principle places immediate limits on the biological effects of static magnetic fields. We live! And we live – and have lived through evolutionary history – in the earth's magnetic field of about 50 μT . Hence, the biological effects of static magnetic fields that are less

than the earth's field must not seriously affect our health. Nevertheless, we examine the effects of static fields in more detail.

Since magnetic fields exert no force on stationary charges and act on moving charges only in a direction normal to their motion, static magnetic fields do not add - or subtract - energy from single charges. The magnetic forces do change the direction of motion of charges but that effect is extremely small compared to effects of thermal fluctuations. However, charged particles in orbit generate magnetic dipole moments that interact directly with magnetic fields. Molecules, atoms, and nuclei possess magnetic dipole moments μ of the order of magnitude of

$$\mu = g \frac{e}{2m} \hbar \quad (10)$$

where the value of g depends upon the specific structure but is usually near one, and for atoms and molecules, $m = m_e$ is the mass of the electron and for nuclei m is the nuclear mass. The alignment energies for a field B are then $B\mu$ and for $B_e = 50 \mu T$, the earth's field, these energies are of the magnitude of $10^{-7} kT$ for atoms and molecules and typically less than $10^{-10} kT$ for nuclei. Hence, the net alignment - and the net magnetization of biological material induced by such weak fields is quite small (though significant effects have been observed for very large fields $B \gg 1 T$.) Such alignments will result in a net (paramagnetic) magnetic moment in a volume of material which in turn will interact with the field defining an energy. For a volume of the whole cell, this energy will only be of the magnitude of kT - about 14 orders of magnitude less than the thermal energy of the cell. Arguments similar to those applied to paramagnetic materials apply to the smaller diamagnetic moments.

For most (paramagnetic and diamagnetic) materials, the molecules or atoms do not act collectively. But for ferromagnetic materials, all of the atomic dipoles in a domain line up and the magnetic susceptibilities are greater by factors $\approx 10^7$ than for paramagnetic materials. Consequently, the earth's $50 \mu T$ field does affect those (rare) cells that contain ferromagnetic matter.

About 15 years ago, Richard Blakemore⁶ found anaerobic bacteria (single celled, of course) that, fearing fresh air, fled preferentially downwards guided along the lines of the earth's field by a compass of ferromagnetic material, in particular a chain about $2 \mu m$ long of grains of magnetite Fe_3O_4 . A simple calculation⁷ shows that the alignment energy in the earth's field B_e is $\mu B_e \approx 10 kT$ where μ is the magnetic moment of the bacterial lodestone.

This is enough to ensure efficient alignment of the cell in the earth's field so that the creature swims in the right direction. Hence, with the aid of ferromagnetic materials, a cell can – barely – sense $50 \mu T$ field. But Fe_3O_4 is found in few other cells. And without the crafting of such compasses, we cannot expect the effects of magnetic fields on cells to compete with thermal fluctuations.

We note that under rather special circumstances, moderate magnetic fields – of the order of $10^{-2} - 10^{-3} T$ may affect chemistry. A covalent binding of a molecule may break such that each piece retains one member of the singlet state electron pair that cemented the binding. Then as a consequence of different hyperfine magnetic interactions between the valence electron and nuclei in the two fragments, the two electrons may precess at different rates and the phase between their amplitudes which defines the initial singlet state will transform to a triplet state reducing the possibility that the two fragments will rejoin⁶.

However, if the local external magnetic field acting on the the ions is stronger than the effect of the nuclear fields, the precessions that lead to the singlet-triple interchange will be suppressed and the ions will more likely rejoin. Since this suppression requires magnetic fields that are typically two orders of magnitude greater than the $50 \mu T$ limit we have adopted, we need not consider the possibility of such effects.

Changing Magnetic Fields

Since life evolved in the presence of static magnetic fields of the order of a gauss or $100 \mu T$, the absence of biological effects of static fields should not be surprising. But changing magnetic fields generate electric fields. These magnetically induced electric fields are more pervasive than the electric fields induced by external electric fields since neither the electric shielding of the cell by the conducting electrolyte, nor the shielding of the cell nucleus and the cell genetic material by the conducting cell membrane, operates. The induced electric fields in biological material are nearly independent of the conductivity of that material and its surroundings.

But can weak 60 Hz oscillating magnetic fields produce electric fields of consequence – that is electric fields greater than those generated by thermal noise? Using the integral form of Faraday's law

$$\oint_S \mathbf{E} \cdot d\mathbf{s} = \frac{d(\int_A \mathbf{B} \cdot d\mathbf{a})}{dt} \propto \frac{dB}{dt} \quad (11)$$

where A is an area through which the field B passes and S is a path bounding the area. If we take a typical effective human body area as that of a circle with a radius of $r = 10$ cm, we estimate the mean amplitude of the electric field induced by a 60 Hz oscillating magnetic field of amplitude $B = 50 \mu T$ field acting over the body, as

$$\bar{E}_B = \frac{B\omega r}{2} \approx 10^{-3} \text{ V/m} \quad (12)$$

Then how will this induced field compare with low frequency thermal noise fields acting on cells? For a conservative comparison, we consider the noise field of $E_{kT} \approx 0.02$ V/m calculated in Section 2.2 for the electrolyte occupying a volume the size of a cell. This is the noise, over a band width $\delta\nu = 100$ Hz, generated by a volume the size of a cell taken conveniently as a cube $d \approx 20 \mu m$ on a side. Hence, the noise fields in cell-sized regions of the electrolyte are greater than the electric fields induced by the changing magnetic field by a factor greater than about 20.

But any biological events of interest must take place in elements of the cell, not in the electrolyte. Since the mean noise field is proportional to the square root of the resistance of the material, and inversely proportional to the square root of the volume of interest, the electric field noise in those smaller cell elements, characterized by larger specific resistances, will be much greater though the field induced by the changing magnetic field will not be very different. For example, the mean ELF noise field across the membrane, between the electrolyte and the cytoplasm, was found to be of the order of 500 V/m; about $5 \cdot 10^5$ times the magnetically induced field. The effective electric noise fields in the small internal elements of the cell, such as the nucleus and the genetic material, can be expected to be no smaller than that of a volume of cytoplasm the size of that element. Typically, that noise will be of the magnitude of the noise generated in a cube of cytoplasm $1 \mu m$ on a side, which will be about 1 eV/m, about 1000 times greater than the magnetically induced field. Hence, low frequency, low intensity, magnetic fields cannot be expected to induce biological activity through interactions with individual cells.

Even as electric fields, albeit small, are generated in human tissues by weak ELF magnetic fields, electric fields of similar strengths are produced in the course of our motion through the earth's field. A field E will be generated throughout the body by moving through the earth's field B_e at a velocity v ; $E = B_e v$. The electric field of $\approx 7 \cdot 10^{-5}$ V/m induced thus by walking will be about equal to the maximum field generated by a $4 \mu T$

(40 milligauss) 60 Hz magnetic field. Indeed, this electric field induced by walking will be greater at the sites of DNA, RNA, and the cell nucleus than that produced by any external ELF electric field. Riding in a car on the highway increases the equivalent level to about $70 \mu T$ (700 milligauss) while a passenger in a jet plane will see electric fields similar to the maximum from a $7 \cdot 10^{-4} T$ (7 gauss) 60 Hz magnetic field (here we neglect shielding effects in car and plane which will reduce the magnetic fields somewhat).

We can feed these simple results into our version of the anthropic principle to conclude that weak changing magnetic fields – like the changes from 60 Hz sine waves – are most unlikely to induce biologically deleterious effects. The magnetic field that a cell passes through from the walking of its host through the earth's field in the United States induces the same electric fields in the cell as a $4 \mu T$ 60 Hz oscillating magnetic field. But four μT is far larger than the fields from power lines, local and home wiring, and home appliances.

One might argue that there may be some special significance in the oscillatory character of the 60 Hz field; perhaps there are sympathetic resonant responses. But we show in Section 3, that ELF resonances at the cell level are not possible.

Rapid Changes in the Magnetic Field

Though the effects of pulsed fields are nominally outside of the discussions of weak ELF (sine wave) fields considered here, the saw tooth magnetic waves associated with the fly-back transformers in television sets and video display terminals have raised concerns similar to those associated with ELF fields. As an example, we consider a sawtooth wave where the magnetic field increases from zero to $50 \mu T$ linearly over a period of $\approx 50 \mu s$ and then returns to zero in a time $< 1 \mu s$; and then repeats at a repetition rate of ≈ 20 kHz. The constraints on the effects of such fields are similar to those established for ELF fields.

We consider the effects of pulses on biological elements from the electric field pulse generated by the changing magnetic field. The magnitude of that field, $E(t)$, can be estimated using the same approximations as for sine-wave fields;

$$E(t) = \frac{r}{2} \frac{dB(t)}{dt} \quad (13)$$

and we write

$$\int E(t) dt = E_{mcm} \delta t = \frac{r}{2} \int \frac{dB}{dt} dt = \frac{r}{2} \delta B = B_0 \frac{r}{2} \quad (14)$$

Hence, the impulse added to an element holding a charge q by the electric field pulse will be,

$$dp = E_{mcm} q \delta t = q \frac{r}{2} B_0 \quad (15)$$

where B_0 is the change in the magnetic field. The impulse depends only on the change in magnetic field and is independent of the rate of change.

The mean component of momentum in the direction of the pulsed field from thermal agitation of the element on which the field acts will be

$$p_{kT} \approx \sqrt{m kT} \quad (16)$$

where m is the effective mass of the element. If the pulse is to affect biological processes significantly, it must produce momentum changes in cell elements greater than that received at high frequency from thermal buffeting; that condition is $dp > p_{kT}$.

The momentum dp may accrue to the translational momentum of a free cell element, such as calcium ion, or may add to vibrational or rotational motion of more complex element such as a macromolecule.

For a charge $q = e$ and a value of $r = 0.1 m$, the momentum transfer for a change in field $B_0 = 50 \mu T$ is $dp \approx 4 \cdot 10^{-25}$ Ns. But this is much smaller than the thermal momentum $p_{kT} \approx 1.7 \cdot 10^{-23}$ Ns for a calcium ion and very much smaller than the thermal momentum $dp \approx 10^{-21}$ Ns for a macromolecule with a mass of 40,000 AMU where the pulse couples through the dipole moment to incite vibration or rotation. Consequently weak magnetic pulses can have no biological effect no matter the rise time.

III Resonances

A Bandwidths

In the description of thermal noise which is commonly used, the square of the mean noise voltage is proportional to the frequency band width over which the noise is measured – or relevant. Hence, if the acceptance of the biological system is such that only a narrow band of frequencies initiate the biological effects, the relative noise interference is reduced. Certain biological actions act as band-pass filters. In particular, those biological activities that have

long intrinsic time constants can act as simple, plausible, low pass filters. If an activity requires a time of 0.01 seconds, it is plausible that perturbations that change sign often in that time would have little over-all effect. There are biological relaxation effects that admit transfer functions that peak at low frequencies - very much as a band pass filter - but these peaks are quite broad.

However, since we have effectively assumed a low band-pass acceptance in using a frequency band of but 100 Hz in our discussions, if we are to find striking gains in signal-to-noise ratios in ELF actions, we must look farther to resonant mechanisms that act as narrow band-pass filters. However, the existence of such low-frequency, narrow band or high Q, resonances at the cellular level can be shown to be inconsistent with the properties of cells in biological media. We examine the properties of resonances.

The effective width of the pass-band depends not only on the characteristics of the biological system, but of the signal. A signal - e.g. an ELF wave - that lasts a time t must have an intrinsic frequency spread $\delta\nu \approx 1/t$. Hence if the band width $\delta\nu$, approximately equal to ν/Q for resonances, is very narrow, $\delta\nu \ll \nu$, the effective band width will be determined by the characteristics of the signal rather than of the system. In that case, the effective frequency acceptance will be inversely proportional to $1/t$ and the effective signal-to-noise will be proportional to $\sqrt{t}$. Or if the signal is integrated (or averaged) over a long time t_{max} , the signal-to-noise will be much improved. But only if the effective system width is small compared to $1/t_{max}$. Weaver and Astumian⁹ suggest averaging times t_{max} of the order of 1000 seconds (or about 20 minutes!). Such a long averaging time could only be relevant if the intrinsic band width of the system were as small as 1/1000 Hz; if the signal were tuned that accurately; and if the time constant of the biological system were longer than 20 minutes. At 60 Hz - assuming a resonant biological process with a $Q \geq 60,000$, exquisitely tuned to 60 ± 0.001 Hz - the signal to noise voltage from a 20 minute exposure would be improved by a factor of $\sqrt{1000} \approx 30$ over a one second exposure and a factor of about 250 over that from a single pulse.

Even with the factor of 250, which assumes an integration time of about 20 minutes and a resonance width of 0.001 Hz, (centered, *accidentally*, at exactly 60 Hz) the field in the membrane of about 0.018 V/m, induced by an 60 Hz external signal field of 300 V/m, would be one-hundred times smaller than the noise field over a frequency span of about $\delta\nu \approx 0.001$ Hz of about $500/250 = 2$ V/m.

B Coupling and Damping

Moreover, if a resonance is to store energy, the damping of the resonance must be sufficiently small that it will make at least one cycle without interruption. If the resonance is to be in the ELF range, that cycle will take a very long time in terms of characteristic molecular collision or interaction times. Consequently, the resonance state must have a very small probability of being interrupted if it is to be significant.

We can estimate the characteristic interaction time or energy exchange time for the smallest elements in a solid as roughly $a/v \approx 10^{-11}$ sec, where a is a mean spacing of molecules and v is a velocity of a bombarding molecule of mass m where $1/2 mv^2 \approx kT$. Then if the resonance is not to be deexcited by an interaction acting as a collision of the second kind in $1/60$ of a second, the probability of that deexcitation in an interaction must be of the order of 10^{-9} . So small a deexcitation probability is difficult to reconcile with the large excitation probability required if the resonance is to be excited by a weak, long-wavelength, electric field. If the cell element is as large as the cell membrane or the cell itself, and if the Q is large so as to allow the coherent contributions of many ELF cycles, the constraints are more severe.

At the long ELF wave-lengths, the electric field E must couple to a resonance through a dipole interaction. The estimates we made in Section 2.5 of the strength of the coupling of an electric field to the cell or elements of the cell, showed that for a characteristic set of interactions, the coupling was of the order of $10^{-9} kT$. Hence, the interaction energy would appear to be insufficient to generate oscillations that might produce biological effects even if the Q of the resonance is sufficiently high so that the energies of many cycles can be added coherently. (At $10^{-9} kT$ per cycle, the system would have to accumulate energy for six months from a 60 Hz oscillation to reach an energy kT .)

We can also consider the damping of resonances - or any other motion of cell elements - in terms of the viscous resistance to that motion. To estimate the magnitude of damping, we consider a model of the motion of a spherical body of radius a through cytoplasm or electrolyte where the viscosity $\eta \approx 7 \cdot 10^{-4} \text{ kg cm}^{-1} \text{ s}^{-1}$ is taken as that of water. For convenience we consider that the body is coupled to the field through a charge q . Then the drift velocity v_E under a field E will be

$$V_E = \frac{Eq}{6\pi\eta a} \quad (17)$$

It is useful to compare the distance $L_E = v_E \delta t$ the body will move in a

time δt with the mean distance L_{kT} the body will move in that time from thermal agitation or Brownian motion;

$$L_{kT} = \sqrt{\frac{2kT}{6\pi\eta a}} \delta t \quad (18)$$

Using these relations, a time $\delta t = 1/\omega_{60} = 1/(2\pi \cdot 60)$ relevant for 60 Hz oscillations, and a (large) canonical field strength $E = 1$ V/m, we find for $a = 3 \cdot 10^{-10}$ m and $q = 2e$ (e.g. a calcium ion), $L_E = 1.1 \cdot 10^{-10}$ m while $L_{kT} = 2.4 \cdot 10^{-6}$ m. For a large element (e.g. a very large macromolecule with a large dipole moment) where $a = 1 \mu\text{m}$ and $q = e$, $L_E \approx 5.5 \cdot 10^{-11}$ m while $L_{kT} = 4 \cdot 10^{-8}$ m. In either case, the amplitude L is strongly limited by viscosity and the motion induced by the field E is swamped by the Brownian motion.

Although the numerical values were derived from the model of a spherical body moving through water, the magnitudes are relevant for vibrational or rotational motion.

Hence, the narrow-banding, signal-integration, afforded by possible cellular resonances would not seem to work well enough to account for biological activity of weak ELF fields at the cell level. But there are further problems: we find that the size of cells is incommensurate with simple ELF resonances.

C Resonance Amplitudes

A resonant system stores energy (allowing the integration of perturbing signals) which is transferred from one form to another at the resonant frequency. For mechanical systems, the energy oscillates between potential and kinetic storage; in the case of LC electrical resonances, the energy oscillates between storage in electric and magnetic fields. Moreover, from the equipartition theorem, the resonance at thermal equilibrium must store an energy equal to kT .

The characteristic angular frequency $\omega = 2\pi\nu$, and stored energy W of a resonant system are

$$\omega = \sqrt{\frac{K}{M}} \text{ and } W = \frac{1}{2} M \omega^2 A^2 \quad (19)$$

where A is the amplitude of excursion of a characteristic mass M and K is a spring constant. From the equipartition theorem, $W = kT$. For ELF frequencies, such as 60 Hz, $\omega \approx 377 \text{ s}^{-1}$ is small and MA^2 must be large;

too large to fit within the mass and amplitude constraints of a cell. *There can be no ELF cellular resonances.*

We illuminate this categorical statement with explicit examples:

- As an extreme, we consider the physiologically unlikely oscillation of a whole cell with a mass of $\approx 5 \cdot 10^{-13}$ kg, and a radius of about $5 \mu m$. If the energy of oscillation of the whole cell is equal to kT , the amplitude A of oscillation will be $0.34 \mu m$ or about 7% of the radius of the cell.
- However, the oscillation of smaller parts of the cell may be less unlikely. Without concern for the mechanical details of such an oscillation, we consider a 60 Hz resonance of the cell membrane, with a mass of about $2 \cdot 10^{-15}$ kg – or any other equally massive sector of the cell. With the smaller mass, the amplitude must be $\approx 5 \mu m$ and equal to the radius of the cell.
- And there has been interest in ion resonances, especially of Ca_{10} with a mass of $6.6 \cdot 10^{-26}$ kg. The amplitude at 60 Hz corresponding to such a mass is about 1 meter.

Element	Mass	Amp (60 Hz)	Amp (16 Hz)
Whole Cell	$5 \cdot 10^{-13}$ kg	$0.34 \mu m$	$1.35 \mu m$
Cell Membrane	$2 \cdot 10^{-15}$ kg	$5 \mu m$	$20 \mu m$
Calcium Ion	$6.6 \cdot 10^{-26}$ kg	1 meter	4 meters

Table 1: Masses and corresponding amplitudes for systems oscillating with an energy of kT at resonant frequencies of 60 Hz and 16 Hz.

Such results are tabulated here for 60 Hz and 16 Hz oscillations

D Specific Resonances

Since there are some data that are claimed to constitute evidence for the biological activity of weak ELF fields that suggest that the fields act only over narrow “windows” of frequency, for completeness, we discuss detailed characteristics of a set of specific resonances.

Mechanical Resonances

It is interesting to look at a specific oscillation in detail to gain some appreciation for the strength of the prohibition against mechanical oscillations. To maximize M , we choose a hypothetical oscillation of a whole cell where a spherical cell of quiescent radius $r = 5 \mu m$ vibrates in a quadrupole mode

changing from a prolate to an oblate spheroid in the course of a cycle. We take the density of the cell cytoplasm as 1 gm/cm^3 and set the energy of the vibration at $kT \approx 4.3 \cdot 10^{-21} \text{ J}$. With these constraints, we calculated the amplitude of the 60 Hz oscillation, measured in the direction of the axis, as about $1 \mu\text{m}$. This is a substantial oscillation - the radius in the direction of the axis changes by about 20%.

In the course of the oscillation, the kinetic energy of motion of the cell material must be stored in an energy associated with the distortion. Assuming that the cytoplasm is effectively an incompressible liquid, this potential energy storage must be found in the energy required to stretch the membrane inasmuch as the surface area of the cell increases by about 1.5% as the cell changes from a spherical to an ellipsoidal shape. Setting this energy to kT , we find that the surface energy of the membrane is required to be about 10^{-9} J/m^2 , a value about 10^6 smaller than the surface energy of water. Conversely, the natural oscillation frequency of a water droplet of the size of the cell would be about 640,000 Hz.

In summary, if the kinetic energy of the cell vibrating at 60 Hz is to be as large as kT , the whole cell must take part in an oscillation. And then the effective forces described by the spring constant K must be unrealistically small if the frequency is to be kept so low. For smaller cell elements with less mass, the spring constant must be even smaller if the element is to oscillate at ELF frequencies.

Electrical Resonances

But could the "observed" resonances be electrical, rather than mechanical, where the energy is transformed cyclically from storage in a magnetic field to storage in an electric field. We consider that we can describe some element of the cell by an equivalent LC circuit with a resonant frequency;

$$\nu = \frac{\omega}{2\pi} \text{ where } \omega = \sqrt{\frac{1}{LC}} \quad (20)$$

Such a circuit will be incited thermally such that the mean total energy of kT will oscillate between storage in magnetic and electric fields. We note that if the frequency is to be low, the product LC must be large. The capacitance is limited by the size of the cell. The largest capacitance that would seem to be evident is the capacitance between the inner and outer surface of the cell membrane. Taking the thickness of the membrane as $50 \text{ \AA}$

and the dielectric constant as 2.5, $C_{mem} \approx 6 \cdot 10^{-12}$ F. Then, for a resonant frequency of $\nu = 60$ Hz, the inductance must be $\approx 10^6$ henrys!

It is difficult to design an ideal paradigmatic cell inductance. However, we note that in the absence of ferromagnetic materials in cells and in the absence of a natural source of many current turns, we should expect that the characteristic cell inductance should be of a magnitude such that $L = \mu_0 r \approx 10^{-11}$ H; too small by 17 orders of magnitude! (There are mechanical processes that lead to current phase lags in biological material of an inductive nature that follow from the inertial mass of the ions that carry currents or to the viscous resistance to the ion motion but neither of these mechanisms leads to the substantial energy storage requisite for a resonance.) Truly, Nature may be much more clever than we think, but not by a factor of 10^{17} . There can be no 60 Hz LC cell resonances.

Cyclotron Resonances

Bawin and Adey interpreted the results of an experiment¹⁰ as indicating that the passage of calcium ions through chick-brain cell walls was reduced when the cells were subject to weak 16 Hz electromagnetic fields. Then, Liboff and McLeod¹¹ noted that under a magnetic field, $B = 50 \mu T$, the size of the earth's field, that the cyclotron resonance frequency ν ,

$$2\pi\nu = \omega = \frac{qB}{m} \quad (21)$$

for a calcium ion of mass $m = 40$ atomic mass units, carrying a charge $q = e$, was equal to 16 Hz. Hence, they suggested that the cyclotron resonance of the calcium ion might be responsible for the effect reported by Bawin and Adey.

Unlike the mechanical resonance, energy in the cyclotron resonance is wholly stored in the kinetic energy of the circulating ion. The energy is transferred from the kinetic energy of motion in one direction to the energy of motion in an orthogonal direction - all in the plane of the orbit but the energy-amplitude relations stated in the last section, still hold. Hence, quite generally, the orbit of such a resonance must be larger than the size of the cell by five orders of magnitude.

Nevertheless, Liboff and McLeod proposed a specific cyclotron resonance of the calcium ion where the energy of the ion was expected to be about 3.5 eV. But such an ion travels in an orbit with a diameter of 80 meters!

But, of course, the ion could be traveling much slower, slow enough to travel around a 5μ radius orbit that might be fitted into a cell. But the

resultant ion energy is then only about $5 \cdot 10^{-14}$ eV and very, very much less than the mean thermal energy of $kT = 1/40$ eV. Indeed, a estimate suggests that the Brownian effect would typically move the ion randomly $5 \mu m$ in any 1/100 of a second that the ion is to travel that distance about its circuit. Hence, the thermal Brownian-like motion overwhelms any orbital motion.

Nuclear Magnetic Resonances

The interaction of an ambient magnetic field such as the earth's field B_e with the magnetic moment μ of a nucleus (with non-zero spin) generates a torque on the spinning nucleus that induces the nucleus to precess about the direction of the field. Even as the rOTating magnetic moment generates an oscillating magnetic field normal to the ambient field, a weak external field normal to the ambient field that oscillates with the precession frequency will generate a precession of the nuclear polarization. The frequency ν of precession is $\nu = B_e \mu / \pi$. For the earth's field this precession frequency for protons will be about 2000 Hz; for nitrogen about 20 Hz. Moreover, the nucleus of an atom is so weakly coupled to the orbital electrons - and then the material environment - that relaxation times can be of the order of 30 seconds and more. So we have a resonance condition at ELF frequencies with a high Q . Can such resonances have significant biological effects?

No! It seems most unlikely that there can be any biological effect of such resonances. The proportion of the nuclei that will be aligned will be about equal to $B_e \mu / kT \approx 10^{-10}$; a proportion very much smaller than the statistical fluctuations in the alignment of nuclei in the cell. Moreover, as reflected in the large Q , that energy is coupled to the environment of the nucleus very, very, weakly. It is this weak coupling of the nucleus to the atomic structure - and hence to the chemical and biological environment - that makes nuclear magnetic resonance imaging (MRI) such a safe and non-invasive medical procedure though the patient is bathed in magnetic fields of $\approx 4T$, about 100,000 times the earth's field.

IV Summary

A The Experimental Record

Though the theoretical considerations that represent extrapolations and interpolations of tested observations must serve as a reliable guide to our understanding of Nature, such analyses cannot supplant a well-established

contrary observation. Hence we must defer to observations that are *established* through the scientific process of review and replication. But are there there any such well-established observations that demonstrate effects of weak ELF fields on the biology of cells?

There are very many (of the order of one hundred!) reports of experiments that purport to demonstrate that weak ELF fields affect cells. An OTA report¹² places the experiments in four categories: modulation of ion flows; interference with DNA synthesis and RNA transcription; interaction with the response of normal cells to various agents and biochemicals such as hormones, neurotransmitters, and growth factors; and interaction with the biokinetics of cancer cells. There is no near-consensus among those who work in the field to the effect that *any* of the reports of effects in any of these areas is valid; none have been satisfactorily replicated, many of the more substantial results have been contradicted. The problems with the research are stated succinctly (by non-scientist true-believers in the effects) in the OTA "background paper", which characterizes the experiments by noting that "... findings at the cell level display considerable complexity including resonant responses of 'windows' in frequency and field strength, complex time dependencies, and dependence on the ambient DC magnetic field created by the earth. ... ELF fields appear to be an agent to which there is no known analog." The unwitting indictment is severe.

It is, perhaps, the intensity windows that are reported that makes it most difficult to accept the experimental results. It is an almost firm rule of the behavior of systems that, above an action threshold, the response to a perturbing signal increases at least linearly with the incremental signal. This linear increase will generally be terminated only when the signal is so large that it can no longer be considered a perturbation. Since it is very difficult to consider that the small signals in question are sufficiently large to have any effect at all, the view that they can be so large as to dampen out a response is even more troubling¹³. Moreover, the windows seem almost maliciously defined (by man or by Nature) to thwart simple verification of the effects. If such windows did not exist, the verification of the effects of small fields would be simple as the experiment could be conducted with much larger fields to elicit a much larger and more easily detected response.

B Conclusions

In summary, it does not appear to be possible for weak external ELF electromagnetic fields to affect biological processes significantly at the cell level.

ELF electric fields are so completely shielded by the conductivity of the body tissues that the interaction of external fields with a strength less than 300 V/m with cells is far weaker than fundamental thermal noise.

ELF magnetic fields may act through static interactions with magnetic dipole moments of biological material or through the induced electric fields generated by changes in the magnetic fields. Since the static effects of ELF fields of 50 μT are no greater than the earth's field, it is difficult to believe that the intensity is harmful. Since the maximum induced electric field in the body induced by 60 Hz 4 μT magnetic fields is no greater than the electric field induced by walking through the earth's field, it is difficult to believe that such changing ELF magnetic fields are harmful. Also, both the static and kinetic effects of ELF fields as great as 50 μT at the cell level are, again, smaller than that from thermal noise. The impulses from weak < 50 μT fast-rise-time ELF magnetic fields – such as from a 20 kHz sawtooth wave form – are also shown to be small compared to thermal effects.

The experimental record lacks coherence and credibility. After 20 years of experimentation, no significant effect of weak ELF fields at the cell level has been firmly established.

In summary: there are very good reasons to believe that weak ELF fields can have no significant biological effect at the cell level – and no strong reason to believe otherwise.

Acknowledgements

In the course of preparation of the paper, I found essential encouragement and information in the course of many, many discussions with Eleanor R. Adair. I owe a great deal to the papers of Herman Schwan and Ken Foster and to their help and criticism. And I want to thank William Pickard, Robert Pound, Charles Bean, Jack Sandweiss, Dean Astumian, James Weaver, and Richard Setlow for the benefit of conversations and correspondence as well as too many others to name.

References

1. K.R. Foster and H.P. Schwan, in *CRC Handbook of Biological Effects of Electromagnetic Fields*, p. 27, C. Polk and E. Postow, Eds. (CRC Press, Boca Raton, FL, 1986)
2. This relation holds specifically for an isolated sphere of tissue but is an adequate approximation for other geometries such as that of the human

body. However, appreciably higher internal fields can result in the body under special conditions. In particular, fields as much as 500 times greater can be induced in the ankles of a man standing on a ground plane subject to a vertical field; M. W. Miller, p. 139, *CRC Handbook, ibid.*

3. W. F. Pickard; *IEEE Trans. Biomed. Engr.* **35**, 243 (1988).

4. These results are in accord with a more extensive discussion by Frank S. Barnes; *CRC Handbook ibid*, page 121.

5. Cellular effects have been reported by K.J. McLeod, R.C. Lee, and H.P. Ehrlich, *Science* **236**, 1465 (1987) are noted at field strengths in tissues as small as $5 \cdot 10^{-3}$ volts per meter. But these fields correspond to fields generated by external fields in air of $\approx 2.5 \cdot 10^5$ V/m. These fields of 0.005 V/m in the tissue lead to potential differences of about $7.5 \cdot 10^{-8}$ V across the membrane of the cells we consider and that is about 33 times smaller than the noise potential $2.5 \cdot 10^{-6}$ V we calculate. However, since the signal to noise varies as the square of the cell radius and the large bovine fibroblast cells that were studied are effectively about three times the size of our canonical cell, we gain a factor of nine. There is an uncertainty of an order of magnitude in the effective resistivity of membrane material. If we assume that the true resistivity is four times less than our canonical value of $10^6 \Omega\text{-m}$, we gain another factor of 2. Furthermore, it seems that there is a low frequency cut-off at about 10 Hz and if we take that as the band width rather than 100 Hz we gain another factor of 3 giving us an overall signal to noise ratio greater than one and we do not categorically reject the possibility that the purported effects are real.

6. R. P. Blakemore, *Science*, **190**, 377 (1975)

7. R. B. Frankel in the *CRC Handbook of the Biological Effects of Electromagnetic Fields*, p.169, C. Polk and E. Postow, Eds. (CRC Press, Boca Raton, FL 1986)

8. P. W. Atkins, *Chem. Br.*, **12**, 214 (1976). The subject is reviewed by R. B. Frankel⁷.

9. J.C. Weaver and R.D. Astumian, *Science* **247**, 459 (1990)

10. S. M. Bawin and W. R. Adey, *Proc. Nat. Acad. Sci.*, **73**, 1999 (1976)

11. A.R. Liboff and B. R. McLeod; *Bioelectromagnetics* **9**, 39 (1988), and earlier papers.

12. I. Nair, M. G. Morgan, and H. K. Florig; U. S. Congress, Office of Technological Assessment for the Office of Technological Assessment, *Biological*

Effects of Power Frequency Electric and Magnetic Fields - Background Paper, OTA-BP-E-53 (Washington, D. C: U. S. Government Printing Office, May 1989)

13. Intensity windows are not impossible; C.H. Durney, C.K. Rushforth, and A.A. Anderson; *Bioelectromagnetics* 9, 315 (1988), have constructed an ingenious system of cyclotron - and betatron - ion dynamics that would seem to display both intensity and frequency windows but they emphasize that their model cannot describe biological effects.

THE WHITE HOUSE

WASHINGTON

July 17, 1990

MEMORANDUM FOR THE HONORABLE WILLIAM K. REILLY

FROM:

D. ALLAN BROMLEY

Alan

SUBJECT:

BIOLOGICAL EFFECTS OF WEAK ELECTROMAGNETIC
FIELDS

I have been peripherally involved with discussions of the possible biological effects of non-ionizing electromagnetic radiation for many years. In my case, the questions were first posed when the Navy in its Sanguine Project proposed to install a very large loop antenna in the sub-soil in Michigan and Wisconsin. The intent was to drive this antenna with low frequency high power signals which would be detectable throughout the earth's oceans, whereas, of course, high frequency signals are rapidly attenuated in the water medium. Although studies at the time generally suggested that expressed fears about biological effects resulting from these low frequency fields were unfounded, a general body of scare literature was generated and remained with little notice until it was taken up by those arguing against the installation of utility power lines in various parts of the country. A number of Soviet investigators also reported a variety of biological effects all on the edge of detectability that they attributed to non-ionizing electromagnetic radiation, and indeed to non-thermal phenomena in addition.

In response to Congressional interest in this question, the Office of Technology Assessment published a report entitled Biological Effects of Power Frequency Electronic and Magnetic Fields--Background Paper OAT-BP-E-53 in May of last year. I know also that the Electric Power Research Institute (EPRI) is interested in this area because so many of their utility members have run into difficulties in their attempts to install new power lines or to respond to fears from those living in the vicinity of existing lines.

More recently, I gather that a group in EPA has generated a new document that was reviewed by a committee that met on June 28 in Morrisville, North Carolina.

It has been suggested to me that there is the possibility that EPA plans to issue some conclusion in August of this year suggesting that very weak electromagnetic fields of the new kind encountered in our homes and factories maybe, or perhaps, even are carcinogenic.

While recognizing that biological systems are frequently complex beyond all imagining, it is still possible to apply some basic physics to this entire question and to set some limits on what is physically possible and what is not. Because an erroneous statement linking low frequency electromagnetic fields with carcinogenicity could have enormous consequences in stimulating unnecessary fears and worries on the part of our citizenry quite apart from having major economic consequences, it seems to me important to ask what rather elementary physics can say about the entire question.

For the past several years, two of my Yale colleagues, Robert and Eleanor Adair--Sterling Professor of Physics and Senior Staff Research Affiliate of the John B. Pearce Laboratory, respectively at Yale University, have been examining this field and I am enclosing herewith three recent preprints that they have produced that I think you might find of interest.

Bob Adair, in addition to his activities as one of the country's leading high energy particle physics experimentalist, served for extended periods as secretary and then chairman of the Physics Section of the National Academy of Sciences, has been the editor of Physical Review Letters, associate director of the Brookhaven National Laboratory--as well as the author of The Physics of Baseball. Eleanor is a distinguished experimental physiologist.

Eleanor's enclosed paper provides something of a overview of some of the public response whereas, Bob's papers address the questions of what limitations simple physics can place on the biological effects; he concludes that any such effects in the cellular level must be found outside of the scope of conventional physics.

I recognize fully that given the degree of concern that has surfaced in this area, EPA has the responsibility to lay it to rest one way or the other.

Inasmuch as the field has been characterized by measurements with relatively weak control, marginally detectible signals, and extraordinarily peculiar effect dependence on applied dose, it may well be that what is required here is a series of very carefully conceived, carefully controlled, experimental measurements. Based on the physics arguments in Adair's paper, I would be extremely surprised were any effects to emerge from such experiments and I hate to see good money utilized on pseudo science when there is so much good science that could use it.

I promised to get you the names of some "reliable" people in this area and will get such a list to you in a few days.

In the meantime, I hope that some of this is helpful.

Enclosure

THE WHITE HOUSE

WASHINGTON

July 20, 1990

MEMORANDUM FOR ALVIN L. YOUNG, CHAIRMAN
CIRRPC

FROM:

D. ALLAN BROMLEY



SUBJECT:

LOW FREQUENCY ELECTROMAGNETIC FIELDS

There has, as you know, been growing public concern as to the possible harmful effects of exposure to low frequency (< 100Hz) electromagnetic radiation--fanned in some cases by press over-reaction to poorly controlled studies and experiments.

The attached memorandum from Robert Grady is self-explanatory and I am requesting that your Committee undertake the requested study on an accelerated basis.

In particular, I would ask you to focus not on the relatively well understood effects of ionizing radiation or on phenomena that involve thermal effects of electromagnetic radiation but rather on the reported possibility of non-ionizing, non-thermal phenomena that may result in possible carcinogenesis under exposure to low frequency, low intensity electromagnetic fields.

Please respond by COB Wednesday, July 25. If either OMB or OSTP can be of assistance, please let me or Bob Grady know.

Attachment

cc: Robert Grady

THE WHITE HOUSE

WASHINGTON

July 20, 1990

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Attachment

cc: Robert Grady

THE WHITE HOUSE

WASHINGTON

July 20, 1990

MEMORANDUM FOR ALVIN L. YOUNG

FROM: D. ALLAN BROMLEY

D. Allan

SUBJECT: ELF RADIATION

I do not wish to prejudice your study in any way but I thought that you might be interested in a copy of my recent memo to Roger Porter on this topic with its enclosure from my old colleague, Robert Adair, who has spent substantial time considering some of the questions involved.

Enclosure

THE WHITE HOUSE

WASHINGTON

May 11, 1990

Dear Bob:

It was good to see you at the Academy Garden Party and warmest thanks for your gracious note of congratulations.

I have now had an opportunity to read through your paper, "Are Biological Effects of Weak ELF Fields Possible?" and believe that it represents a major contribution to sanity in what promises to be the polywater field of the 1990s. I continue to find it astonishing that once a few papers, none of which deserve belief, get published in a particular area, a snowball effect develops a certain credibility based on the bulk of publications quite apart from any possible connection to the alleged content.

I very much appreciate the work that you and Ellie are doing in this field and have been making copies of your papers available in the appropriate quarters here.

Pat joins me in sending you and Ellie our very warmest best wishes,

Sincerely yours,



D. Allan Bromley
Assistant to the President
for
Science and Technology

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502-4 J.W. Gibbs Laboratory

April 9, 1990

Dr. D. Allan Bromley
The White House
Washington

Dear Allan;

Thank you so much for the marvelous picture of the President looking at my book. I'm getting it framed to put on the piano.

Bart Giamatti was right as usual, the book does seem to have hit a resonance somehow and has been well received. Thursday I had a TV crew from ESPN filming me in Gibbs and Friday a crew from ABC -- and I have decided to turn down David Letterman! Andy Warhol said that we are in an era where everyone will be famous for fifteen minutes. I guess this is my turn and I have found it fun but a little much -- so fifteen minutes is about right.

More seriously, the whole community is very appreciative of your work rationalizing decisions in science. For fun, for love, and as a consequence of my social conscience, (in that order, with "social conscience" running a very weak third). I have appointed myself as a major counter-propagandist on this low level ELF business. A problem serious scientists have, is that polemics outside of the scientific tradition are needed to get the attention of the press -- and others. As an outsider in biophysics, with no reputation in the field to lose, I am not harmed much by strong statements (perhaps not always completely responsible) that I might make that will attract attention. Of course this probably rules me out of consideration for a place on any committee, panel, etc. to consider such matters but there are many others much better qualified for that anyway.

I have been talking to people in the DOD (Air Force) about the virtues of a National Academy-NRC study on ELF that might help if things get out-of-hand.

I enclose a didactic (and polemical) paper I have written on the biological effects of low level ELF for a talk I am to give at an EEPa (Electromagnetic Energy Policy Alliance) meeting later this month in Washington. My last section is a Langmuir evaluation of the science. The paper you see will be given out at the meeting and to a small mailing list. But I have been encouraged by people I respect to publish the more scientific parts -- perhaps I will try the American Journal of Physics.

Sincerely



Robert K. Adair

Constraints on the Biological Effects of Weak ELF Fields

Robert K. Adair

Department of Physics, Yale University, New Haven, CT 06511

Abstract

Concerns have been raised over the possibility that extremely-low-frequency (ELF) electromagnetic fields are carcinogenic and leukogenic. An examination of the physical interaction of such fields with the body shows that such interactions are too weak to have a significant effect on human biology at the cell level.

Because of the high electrical conductivity of tissues, the coupling of external electric fields in air to tissue in the body is such that the effects of the internal fields on cells is smaller than thermal noise. Static magnetic fields smaller than the earth's field of $50 \mu T$ and varying fields weaker than the $4 \mu T$ 60 Hz fields that are equivalent in effect to that from walking in the earth's field, cannot be expected to generate significant biological effects. Moreover the interactions of such weak fields at the cell level are also small compared to thermal noise. These conclusions would be modified by 60 Hz cell resonances. But such resonances are shown to be incompatible with cell characteristics and the requirement from equipartition that the mean resonance energy must be kT .

Hence, any biological effects of weak ELF fields on the cellular level must be found outside of the scope of conventional physics in much the same way as parapsychology or cold fusion.

I Introduction

Very weak extremely-low-frequency (ELF) electromagnetic fields from common electric appliances and lighting, from local home and workplace distribution wiring, and from the major national electric grids, are a ubiquitous part of modern civilization. Since the magnitudes of these "leakage" fields are very small, and seemingly small compared to natural fields in the body,

it has been commonly assumed that the fields could not affect any biological activity significantly and, hence, could not constitute a health hazard.

However concerns have been raised over the possibility that the biological effects of the fields have not been properly understood and that the fields may in fact generate changes on the cell level that might have carcinogenic and leukogenic consequences. Such effects have been largely associated with the breaking of molecular bonds of macromolecules such as those responsible for the genetic information. Since the extremely low frequency (60 Hz in North America and largely 50 Hz elsewhere) of the ELF fields means that the characteristic quantum energies are $\approx 10^{-14}$ eV, it has generally been accepted that such fields cannot disrupt these molecules and hence cannot induce carcinogenic or leukogenic effects.

However, it may be that less catastrophic effects of ELF fields on cells in the body may induce actions which we do not yet understand that alter the biology of the structures significantly. If such interactions of the ELF fields at the cell level are to result in any significant biological effects, those interactions must be significantly greater than the ordinary thermal interactions of the molecules with their environment. But we show that any effects on the cell level of fields in the body generated by weak external ELF fields will be masked by thermal noise effects and, hence, such fields cannot be expected to have any significant effect on the biological activities of the cells.

In any material the charge density fluctuates thermally according to thermodynamic imperatives generating fluctuating electric fields. Although there are other sources of biological noise, such as noise generated by muscle excitation and activity, electrokinetic noise from squeezing of electrolyte through tissues, and the $1/f$ noise from cell membrane activity, that contribute fields as great as 0.1 V/m at frequencies less than 100 Hz, we emphasize the generally smaller noise inasmuch as the magnitude of that noise stems from fundamental thermodynamic bases and must constitute an irrefutable constraint on biology.

For similar reasons, we emphasize effects on the cell level. Over larger regions, the impact of weak ELF external fields is limited more by biological and physiological considerations than by the competition with Johnson-Nyquist noise and is hence outside of the chosen scope of this paper. Since the bulk of the experimental results that have been interpreted as an indication of effects of such fields concern mechanisms on the cell level such as changes in ion transport through cell membrane walls and increases in genetic transcription errors, the analyses of mechanisms that might operate at the level of the cell are of primary importance. Any possible carcinogenic

effects of weak ELF radiation would also most likely operate at the cellular level.

In the quantitative features of this discussion of the effects of low frequency, low intensity, electromagnetic fields on biological materials, we will consider especially 60 Hz oscillations, and define *weak* fields as electric field strengths that do not exceed 300 V/m in air and magnetic field strengths no greater than 0.5 gauss (or 50 μT), the strength of the earth's field – the mean electric field at the earth's surface is about 100 V/m. The fields will, in general, be near-fields, and not radiative. Indeed, for the most part, we will not be talking about *radiation* – non-ionizing or otherwise.

II External Fields and Noise Fields

A Coupling of Tissue and Air for Electric Fields

For environmental concerns, the immediate measure of possible hazard is that field in the air about the tissues. Since the tissues are conducting, a constant external electric field will induce almost no field at all in the tissues though an alternating external electric field will induce small fields. At low frequencies, ν , the fields E_i in the tissues will be very much smaller than the fields E_0 in the air external to the tissues¹.

$$E_i \approx 3\epsilon_0\omega\rho_t E_0 \quad (1)$$

where $\omega = 2\pi\nu$ is the angular frequency and $\rho_t \approx 2 \Omega\cdot m$ is the resistivity of the electrolyte saturating the tissue². At 60 Hz, $E_i \approx 2 \cdot 10^{-8} E_0$. Hence, for fields in the air of 300 V/m, we can expect field strengths in the conducting tissues of about $6 \cdot 10^{-6}$ V/m. The cell membrane will have a specific resistance of the order of $\rho_{mem} \approx 10^5 \rightarrow 10^7$ ohms and can then be considered as an insulator relative to the tissue electrolyte. In the valid approximation that the resistivity of the membrane material, $\rho_{mem} \gg \rho_t$, the resistivity of the tissue, the field in the membrane, E_{mem} of thickness d of a cell of radius r will be about

$$E_{mem} \approx 1.5 E_i \frac{r}{d} \quad (2)$$

Hence, taking a typical cell radius of 10 μm and a membrane thickness of 50 $\text{\AA}$, for a field in the tissue electrolyte $E_i = 6 \cdot 10^{-6}$ V/m, induced by an external field of 300 V/m, we can expect a field $E_{mem} \approx 3000 \cdot E_i \approx 2 \cdot 10^{-2}$ V/m in the insulating membrane.

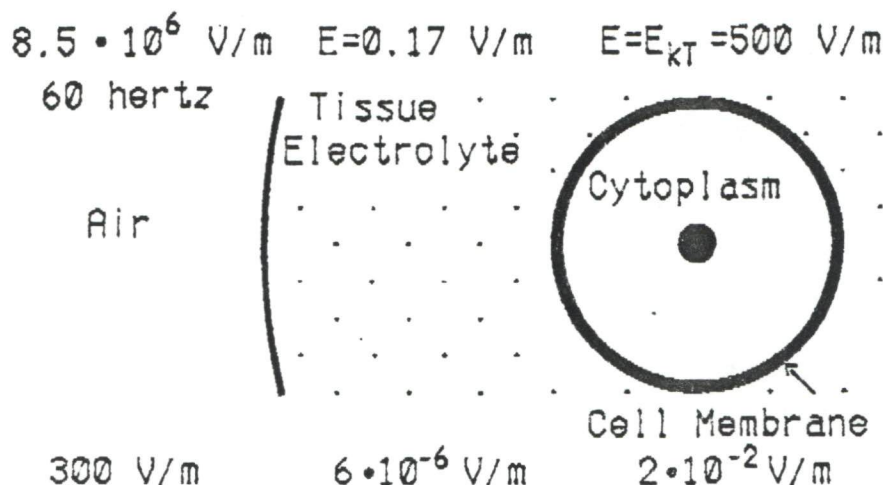


Figure 1: Electric fields in tissues, cell membranes, and cell cytoplasm, induced by ELF external fields in the air outside of the tissue. The fields labeled above describe an externally induced field in the cell membrane that is equal to the Johnson noise, from DC to 100 Hz, measured from the cytoplasm interior to the cell to the electrolyte outside of the cell across the cell membrane. The very large air field so postulated is larger than the dielectric breakdown strength for air of about 10^6 V/m and is then unobtainable in practice. The lower numbers describe the fields induced in the tissue and membrane by an external field of 300 V/m .

The internal elements of the cell, such as the nucleus and the genetic material, are shielded by the resistive cell membrane and the fields they see are quite negligible¹.

The fields in different areas of air, tissue, and cell, are shown in Fig. 1 normalized to a field in the air of 300 V/m . Too often, discussion of the effects of weak fields is complicated by misunderstandings concerning the region in which the field is defined. Since we are addressing environmental concerns, the fields labeled "external" in this report are *always* fields in the air about the tissues.

B Thermal Electrical Noise

Since the most important fundamental constraint on effects of very weak fields, is the requirement that they not be masked by thermal noise, we present a heuristic explanation of the Johnson-Nyquist noise designed to suggest the salient features of that noise. We proceed by describing thermal noise at a frequency ν in a sample of material by analyzing an imaginary experiment. The sample is inserted as a resistive load R in an LC oscillator circuit where the circuit elements are chosen such that

$$2\pi\nu = \omega = \frac{1}{\sqrt{LC}} \quad (3)$$

From the equipartition theorem the mean energy of the oscillator is $W = kT$ where T is the ambient temperature. But as the circuit oscillates it will lose energy as a consequence of the resistance of the sample. The rate of energy loss or loss power P will be

$$P = 4kT\Delta\nu \quad (4)$$

where $\Delta\nu = 4R/L$ is the effective resonance width.

The effect of this action will be to transfer energy from the oscillator, which is then cooled below the ambient temperature, to the resistive sample, which is then heated above the ambient temperature. But this is in violation of the *second law*. Hence, if the system is to remain at thermal equilibrium (and we are to avoid violating the *second law*), the sample must generate electrical energy at a rate P at the frequency ν that will be fed back to the oscillator. Hence, the noise power generated thermally by the sample must be equal to P . That power is independent of the magnitude of the resistance of the sample and must hold for any frequency ν even as we could tune the oscillator to different frequencies.

If we write $P = V_{kT}^2/R$ where V_{kT} is the noise voltage across the resistance R , we find the usual formula for that voltage V_{kT} generated by Johnson noise over a frequency interval $\Delta\nu$,

$$\overline{V_{kT}^2} = 4RkT\Delta\nu \quad (5)$$

Although this noise voltage must follow from thermal fluctuations in the charge density in the sample material, the result - characteristic of thermodynamic results - is independent of detail; in particular of the detailed character of the charge carriers which may be conduction electrons, ions, or bound charges sensibly displaced by thermal buffeting.

Often the noise fields will be of more interest than the noise voltages – which are, however, better defined. Taking the sample as a cube with a side d for convenience, $R = \rho/d$, where ρ is the characteristic resistivity of the material, $E_{kT}^2 \propto 1/d^3$. As a consequence of averaging over fluctuations, the electric field noise limit varies inversely as the square root of the volume considered. Although, E_{kT}^2 was evaluated for a cube, the value depends only on the volume of the sample. The noise does not vary with volume as one might expect for random electric field fluctuations since the field fluctuations – taken to originate in charge density fluctuations – are correlated through the conservation of charge and Gauss's theorem.

Since the thermal noise is larger for small volumes – where the statistical fluctuations of electron densities are proportionally larger – than for larger volumes, to make the most useful assessment of the effects of thermal noise it is desirable to choose the smallest volume commensurate with the biological action. This increase in effective noise field strength as the sample size is reduced, extends to the molecular level. The characteristic molecular field strengths required to substantially change the momenta of molecules in a typical thermal collision, for example, are of the order of $kT/er \approx 10^8$ V/m, where $r \approx 1$ Å, is the interaction length relevant in the collision. Hence, very large electric field fluctuations can be expected as a consequence of "collisions" with surrounding molecules.

C Noise Fields in Tissues

We estimate the thermal noise generated in a quantity of tissue by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where a cube of tissue of length d on a side is held between the plates. The voltage across such a capacitor will be a *useful* measure of the local electric field at low frequencies. To estimate the thermal electric field noise, we consider the system as an equivalent parallel circuit of the membrane resistance R and the capacitance C between the plates. The time average noise voltage V_{kT} can then be expressed as,

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu = 4\frac{\rho}{d}kT\Delta\nu \text{ and } E_{kT} = \frac{\overline{V_{kT}}}{d} \quad (6)$$

Using the above relations, and taking $\rho = 2 \Omega \cdot m$ for tissue and a frequency span $\Delta\nu = 100$ Hz – i.e. from DC to 100 Hz – we find that the noise field generated in the electrolyte in a cubical volume the size of a cell,

20 μm on a side, is about 0.02 V/m, which is about 3000 times larger than the field induced by a 300 V/m external field.

Though the field is large, the thermal noise *potential difference* over 20 μm is but 3 μV . In general, thermal noise voltages between different regions of tissue will be very much less than 1 μV .

Experiments have shown that some fish - especially sharks - do respond to very weak electric fields. These are fields in the water surrounding the fish and are, therefore, strongly coupled to the watery tissue of the fish. In salt water, the fields are more strongly coupled by a factor of $\approx 5 \cdot 10^7$ than fields in air to tissue. With special receptors, the ampullae of Lorenzini, which act as low pass filters, that extend over lengths near a meter, the response of sharks to quite small fields - as fields as small as 0.5 $\mu\text{V}/\text{m}$ have been detected - does not violate thermal noise limits³.

D Noise Fields in Cell Membranes

A popular "explanation" of purported biological effects of external low-level ELF electromagnetic fields, is that these effects derive from the effects of the electric fields on the complex properties of the cell membranes. The fields are presumed to modify such membrane activities as the opening and closing of ion-conducting channels and the catalytic activity of membrane-associated enzymes. Of course if externally imposed fields are to have any important effect, those fields at the cell activity sites must not be swamped by the thermal Johnson noise fields.

Certain processes such as the passage of ions through the cell membrane walls may be likely defined by thermodynamic criteria and hence depend upon the potential difference - which is typically of the order of 50 mV - between the cytoplasm interior to the cell and the electrolyte outside of the cell. For such mechanisms the noise voltage across the membrane from the relatively highly conducting interior cytoplasm to the conducting electrolyte might be more significant than any local noise level. (The natural potential difference across the membrane will be of the order of 50 mV to be compared with the noise voltage across the membrane of $\approx 10^{-6}$ V and the thermal kinetic energy of an ion of $3/2 kT \approx 37$ meV.) The time average noise level from cytoplasm to electrolyte, across the whole membrane of thickness $d \approx 50$ Å, of a spherical cell of radius $r = 10^{-5}$ m will be;

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu \text{ where } R_{mem} = \frac{\rho d}{4\pi r^2} \quad (7)$$

where the resistivity of the membrane material is taken as $\rho_{mem} = 10^6 \Omega m$. With these values, $R_{mem} = 4 \cdot 10^6 \Omega$. Taking an ELF frequency band of 100 Hz, $V_{kT} \approx 2.6 \cdot 10^{-6} V$ and $E_{kT} = V_{kT}/d \approx 500 V/m$. This thermal noise voltage. (Since the resistivity of the membrane material is uncertain within a factor of ten, the field strengths calculated here are uncertain by a factor of 3.) is probably much smaller than the $1/f$ noise, possibly associated with the flow of ions through cell membrane orifices, and smaller by a factor of $\approx 5 \cdot 10^{-5}$ than the normal potential difference of 0.05 V across the cell wall⁴. But the noise voltage across the membrane – and the noise field in the membrane – is about 25,000 times⁵ the voltage and field induced by the canonical external field of 300 V/m.

It has been argued that the externally induced fields in the cell membrane may affect such biological activities as the catalytic actions by membrane-associated enzymes. If such induced fields are to affect the processes, those fields must be greater than the fields due to thermal fluctuations.

Since these kinds of biological activities would appear to be local, determined not by average fields over the whole cell membrane, but by conditions in a small sector of the membrane with a volume no larger than d^3 , where $d \approx 50 \text{ \AA}$ is the membrane thickness, it would seem that it would be the local thermal electric field fluctuations in such small regions that should be compared to the induced fields. Since the volume in question is quite small, and the effective noise fields over small volumes are greater than for larger volumes, we might expect that the local electric field noise would be much greater than that averaged over the whole membrane. The electrical properties of such a small sector are not necessarily simple but we can estimate that thermal noise generated in a small quantity of membrane material proceeding as before by examining the results of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where an isolated cube of membrane material 50 $\text{\AA}$ on a side is held between the plates. The time average of the fluctuating noise voltage V_{kT} is again

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu \text{ where now } R = \frac{\rho_{mem}}{d} \approx 2 \cdot 10^{14} \Omega \quad (8)$$

If we use the mean resistivity of the membrane material of $\rho = 10^6 \Omega \cdot m$, for the small sector, which is simplistic, and taking, again, only frequencies less than 100 Hz, the mean noise voltage across this small, isolated, sample will be ≈ 0.02 and the thermal noise electric field over this frequency is then $E_{kT} \approx \overline{V_{kT}}/d \approx 3.7 \cdot 10^6 V/m$ which is about $2 \cdot 10^8$ times that from a 300 V/m external field.

E Electric Field Effects

Although the small values of the ratios of induced to noise electric fields must largely exclude any possibility that those induced fields can induce biological activity in cells, one can reach much the same conclusions by considering interactions in more detail. To be definite, we consider fields of $E_i = 6 \cdot 10^{-6}$ V/m in tissue, and $E_m = 2 \cdot 10^{-2}$ V/m in membranes 50 Å thick of cells of radius $r = 10^{-5}$ m, induced by external fields of 300 V/m and we compare the energies transferred to the elements to kT .

For membrane or tissue, the energy transferred by the field to an ion - or any singly charged element - in tissue or membrane will not be much larger than $E_i e r \approx 10^{-9} kT$, where e is the electronic charge. Which is to say neither the kinetic energy nor the direction of motion of a charged element can be sensibly affected by such small fields.

An imposed external field will tend to align electric dipoles so that, even in the face of thermal agitation, there will be a statistical excess of dipoles aligned with the field. That proportion P which are aligned can be estimated as $P \approx W/kT$ where W is the alignment energy. We can make a useful estimate of a *maximum* magnitude of such an interaction energy by considering the interaction of the field, E_i , in the tissue with a whole cell neglecting, for the purpose of the maximal estimate, the macroscopic shielding provided by the cell membrane. The electric dipole moment per unit volume of cytoplasm will be $\mathbf{P} = \epsilon_0(K-1) \cdot \mathbf{E}$ where K is the dielectric constant and $K-1 \approx 80$ as for water and the volume V is that of a cell $10 \mu\text{m}$ in diameter. Then the interaction energy W will be about

$$W \approx (\mathbf{E} \cdot \mathbf{P}) V \approx 80 E_i^2 \epsilon_0 V \approx 2.5 \cdot 10^{-14} kT \quad (9)$$

We can also consider the alignment of macromolecules that display permanent electric dipoles. Taking a characteristic magnitude of such a dipole moment as er where, $r = 200$ Å, the alignment energy of the molecule in the membrane will be $W \approx E_m e r \approx 3 \cdot 10^{-8} kT$.

F Magnetic Fields

Static Magnetic Fields

A kind of restricted anthropic principle places immediate limits on the biological effects of static magnetic fields. We live! And we live - and have lived through evolutionary history - in the earth's magnetic field of about $50 \mu T$. Hence, the biological effects of static magnetic fields that are less

than the earth's field must not seriously affect our health. Nevertheless, we examine the effects of static fields in more detail.

Since magnetic fields exert no force on stationary charges and act on moving charges only in a direction normal to their motion, static magnetic fields do not add - or subtract - energy from single charges. The magnetic forces do change the direction of motion of charges but that effect is extremely small compared to effects of thermal fluctuations. However, charged particles in orbit generate magnetic dipole moments that interact directly with magnetic fields. Molecules, atoms, and nuclei possess magnetic dipole moments μ of the order of magnitude of

$$\mu = g \frac{e}{2m} \hbar \quad (10)$$

where the value of g depends upon the specific structure but is usually near one, and for atoms and molecules, $m = m_e$ is the mass of the electron and for nuclei m is the nuclear mass. The alignment energies for a field B are then $B\mu$ and for $B_e = 50 \mu T$, the earth's field, these energies are of the magnitude of $10^{-7} kT$ for atoms and molecules and typically less than $10^{-10} kT$ for nuclei. Hence, the net alignment - and the net magnetization of biological material induced by such weak fields is quite small (though significant effects have been observed for very large fields $B \gg 1 T$.) Such alignments will result in a net (paramagnetic) magnetic moment in a volume of material which in turn will interact with the field defining an energy. For a volume of the whole cell, this energy will only be of the magnitude of kT - about 14 orders of magnitude less than the thermal energy of the cell. Arguments similar to those applied to paramagnetic materials apply to the smaller diamagnetic moments.

For most (paramagnetic and diamagnetic) materials, the molecules or atoms do not act collectively. But for ferromagnetic materials, all of the atomic dipoles in a domain line up and the magnetic susceptibilities are greater by factors $\approx 10^7$ than for paramagnetic materials. Consequently, the earth's $50 \mu T$ field does affect those (rare) cells that contain ferromagnetic matter.

About 15 years ago, Richard Blakemore⁶ found anaerobic bacteria (single celled, of course) that, fearing fresh air, fled preferentially downwards guided along the lines of the earth's field by a compass of ferromagnetic material, in particular a chain about $2 \mu m$ long of grains of magnetite Fe_3O_4 . A simple calculation⁷ shows that the alignment energy in the earth's field B_e is $\mu B_e \approx 10 kT$ where μ is the magnetic moment of the bacterial lodestone.

This is enough to ensure efficient alignment of the cell in the earth's field so that the creature swims in the right direction. Hence, with the aid of ferromagnetic materials, a cell can - barely - sense $50 \mu T$ field. But Fe_3O_4 is found in few other cells. And without the crafting of such compasses, we cannot expect the effects of magnetic fields on cells to compete with thermal fluctuations.

We note that under rather special circumstances, moderate magnetic fields - of the order of $10^{-2} - 10^{-3} T$ may affect chemistry. A covalent binding of a molecule may break such that each piece retains one member of the singlet state electron pair that cemented the binding. Then as a consequence of different hyperfine magnetic interactions between the valence electron and nuclei in the two fragments, the two electrons may precess at different rates and the phase between their amplitudes which defines the initial singlet state will transform to a triplet state reducing the possibility that the two fragments will rejoin⁸.

However, if the local external magnetic field acting on the the ions is stronger than the effect of the nuclear fields, the precessions that lead to the singlet-triple interchange will be suppressed and the ions will more likely rejoin. Since this suppression requires magnetic fields that are typically two orders of magnitude greater than the $50 \mu T$ limit we have adopted, we need not consider the possibility of such effects.

Changing Magnetic Fields

Since life evolved in the presence of static magnetic fields of the order of a gauss or $100 \mu T$, the absence of biological effects of static fields should not be surprising. But changing magnetic fields generate electric fields. These magnetically induced electric fields are more pervasive than the electric fields induced by external electric fields since neither the electric shielding of the cell by the conducting electrolyte, nor the shielding of the cell nucleus and the cell genetic material by the conducting cell membrane, operates. The induced electric fields in biological material are nearly independent of the conductivity of that material and its surroundings.

But can weak 60 Hz oscillating magnetic fields produce electric fields of consequence - that is electric fields greater than those generated by thermal noise? Using the integral form of Faraday's law

$$\oint_S \mathbf{E} \cdot d\mathbf{s} = \frac{d(\int_A \mathbf{B} \cdot d\mathbf{a})}{dt} \propto \frac{dB}{dt} \quad (11)$$

where A is an area through which the field B passes and S is a path bounding the area. If we take a typical effective human body area as that of a circle with a radius of $r = 10$ cm, we estimate the mean amplitude of the electric field induced by a 60 Hz oscillating magnetic field of amplitude $B = 50 \mu T$ field acting over the body, as

$$\bar{E}_B = \frac{B\omega r}{2} \approx 10^{-3} \text{ V/m} \quad (12)$$

Then how will this induced field compare with low frequency thermal noise fields acting on cells? For a conservative comparison, we consider the noise field of $E_{kT} \approx 0.02 \text{ V/m}$ calculated in Section 2.2 for the electrolyte occupying a volume the size of a cell. This is the noise, over a band width $\delta\nu = 100 \text{ Hz}$, generated by a volume the size of a cell taken conveniently as a cube $d \approx 20 \mu m$ on a side. Hence, the noise fields in cell-sized regions of the electrolyte are greater than the electric fields induced by the changing magnetic field by a factor greater than about 20.

But any biological events of interest must take place in elements of the cell, not in the electrolyte. Since the mean noise field is proportional to the square root of the resistance of the material, and inversely proportional to the square root of the volume of interest, the electric field noise in those smaller cell elements, characterized by larger specific resistances, will be much greater though the field induced by the changing magnetic field will not be very different. For example, the mean ELF noise field across the membrane, between the electrolyte and the cytoplasm, was found to be of the order of 500 V/m ; about $5 \cdot 10^5$ times the magnetically induced field. The effective electric noise fields in the small internal elements of the cell, such as the nucleus and the genetic material, can be expected to be no smaller than that of a volume of cytoplasm the size of that element. Typically, that noise will be of the magnitude of the noise generated in a cube of cytoplasm $1 \mu m$ on a side, which will be about 1 eV/m , about 1000 times greater than the magnetically induced field. Hence, low frequency, low intensity, magnetic fields cannot be expected to induce biological activity through interactions with individual cells.

Even as electric fields, albeit small, are generated in human tissues by weak ELF magnetic fields, electric fields of similar strengths are produced in the course of our motion through the earth's field. A field E will be generated throughout the body by moving through the earth's field B_e at a velocity v ; $E = B_e v$. The electric field of $\approx 7 \cdot 10^{-5} \text{ V/m}$ induced thus by walking will be about equal to the maximum field generated by a $4 \mu T$

(40 milligauss) 60 Hz magnetic field. Indeed, this electric field induced by walking will be greater at the sites of DNA, RNA, and the cell nucleus than that produced by any external ELF electric field. Riding in a car on the highway increases the equivalent level to about $70 \mu T$ (700 milligauss) while a passenger in a jet plane will see electric fields similar to the maximum from a $7 \cdot 10^{-4} T$ (7 gauss) 60 Hz magnetic field (here we neglect shielding effects in car and plane which will reduce the magnetic fields somewhat).

We can feed these simple results into our version of the anthropic principle to conclude that weak changing magnetic fields - like the changes from 60 Hz sine waves - are most unlikely to induce biologically deleterious effects. The magnetic field that a cell passes through from the walking of its host through the earth's field in the United States induces the same electric fields in the cell as a $4 \mu T$ 60 Hz oscillating magnetic field. But four μT is far larger than the fields from power lines, local and home wiring, and home appliances.

One might argue that there may be some special significance in the oscillatory character of the 60 Hz field; perhaps there are sympathetic resonant responses. But we show in Section 3, that ELF resonances at the cell level are not possible.

Rapid Changes in the Magnetic Field

Though the effects of pulsed fields are nominally outside of the discussions of weak ELF (sine wave) fields considered here, the saw tooth magnetic waves associated with the fly-back transformers in television sets and video display terminals have raised concerns similar to those associated with ELF fields. As an example, we consider a sawtooth wave where the magnetic field increases from zero to $50 \mu T$ linearly over a period of $\approx 50 \mu s$ and then returns to zero in a time $< 1 \mu s$; and then repeats at a repetition rate of ≈ 20 kHz. The constraints on the effects of such fields are similar to those established for ELF fields.

We consider the effects of pulses on biological elements from the electric field pulse generated by the changing magnetic field. The magnitude of that field, $E(t)$, can be estimated using the same approximations as for sine-wave fields;

$$E(t) = \frac{r}{2} \frac{dB(t)}{dt} \quad (13)$$

and we write

$$\int E(t) dt = E_{mcm} \delta t = \frac{r}{2} \int \frac{dB}{dt} dt = \frac{r}{2} \delta B = B_0 \frac{r}{2} \quad (14)$$

Hence, the impulse added to an element holding a charge q by the electric field pulse will be,

$$dp = E_{mcm} q \delta t = q \frac{r}{2} B_0 \quad (15)$$

where B_0 is the change in the magnetic field. The impulse depends only on the change in magnetic field and is independent of the rate of change.

The mean component of momentum in the direction of the pulsed field from thermal agitation of the element on which the field acts will be

$$p_{kT} \approx \sqrt{m kT} \quad (16)$$

where m is the effective mass of the element. If the pulse is to affect biological processes significantly, it must produce momentum changes in cell elements greater than that received at high frequency from thermal buffeting; that condition is $dp > p_{kT}$.

The momentum dp may accrue to the translational momentum of a free cell element, such as calcium ion, or may add to vibrational or rotational motion of more complex element such as a macromolecule.

For a charge $q = e$ and a value of $r = 0.1 m$, the momentum transfer for a change in field $B_0 = 50 \mu T$ is $dp \approx 4 \cdot 10^{-25}$ Ns. But this is much smaller than the thermal momentum $p_{kT} \approx 1.7 \cdot 10^{-23}$ Ns for a calcium ion and very much smaller than the thermal momentum $dp \approx 10^{-21}$ Ns for a macromolecule with a mass of 40,000 AMU where the pulse couples through the dipole moment to incite vibration or rotation. Consequently weak magnetic pulses can have no biological effect no matter the rise time.

III Resonances

A Bandwidths

In the description of thermal noise which is commonly used, the square of the mean noise voltage is proportional to the frequency band width over which the noise is measured - or relevant. Hence, if the acceptance of the biological system is such that only a narrow band of frequencies initiate the biological effects, the relative noise interference is reduced. Certain biological actions act as band-pass filters. In particular, those biological activities that have

long intrinsic time constants can act as simple, plausible, low pass filters. If an activity requires a time of 0.01 seconds, it is plausible that perturbations that change sign often in that time would have little over-all effect. There are biological relaxation effects that admit transfer functions that peak at low frequencies - very much as a band pass filter - but these peaks are quite broad.

However, since we have effectively assumed a low band-pass acceptance in using a frequency band of but 100 Hz in our discussions, if we are to find striking gains in signal-to-noise ratios in ELF actions, we must look farther to resonant mechanisms that act as narrow band-pass filters. However, the existence of such low-frequency, narrow band or high Q , resonances at the cellular level can be shown to be inconsistent with the properties of cells in biological media. We examine the properties of resonances.

The effective width of the pass-band depends not only on the characteristics of the biological system, but of the signal. A signal - e.g. an ELF wave - that lasts a time t must have an intrinsic frequency spread $\delta\nu \approx 1/t$. Hence if the band width $\delta\nu$, approximately equal to ν/Q for resonances, is very narrow, $\delta\nu \ll \nu$, the effective band width will be determined by the characteristics of the signal rather than of the system. In that case, the effective frequency acceptance will be inversely proportional to $1/t$ and the effective signal-to-noise will be proportional to $\sqrt{t}$. Or if the signal is integrated (or averaged) over a long time t_{max} , the signal-to-noise will be much improved. But only if the effective system width is small compared to $1/t_{max}$. Weaver and Astumian⁹ suggest averaging times t_{max} of the order of 1000 seconds (or about 20 minutes!). Such a long averaging time could only be relevant if the intrinsic band width of the system were as small as 1/1000 Hz; if the signal were tuned that accurately; and if the time constant of the biological system were longer than 20 minutes. At 60 Hz - assuming a resonant biological process with a $Q \geq 60,000$, exquisitely tuned to 60 ± 0.001 Hz - the signal to noise voltage from a 20 minute exposure would be improved by a factor of $\sqrt{1000} \approx 30$ over a one second exposure and a factor of about 250 over that from a single pulse.

Even with the factor of 250, which assumes an integration time of about 20 minutes and a resonance width of 0.001 Hz, (centered, *accidentally*, at exactly 60 Hz) the field in the membrane of about 0.018 V/m, induced by an 60 Hz external signal field of 300 V/m, would be one-hundred times smaller than the noise field over a frequency span of about $\delta\nu \approx 0.001$ Hz of about $500/250 = 2$ V/m.

B Coupling and Damping

Moreover, if a resonance is to store energy, the damping of the resonance must be sufficiently small that it will make at least one cycle without interruption. If the resonance is to be in the ELF range, that cycle will take a very long time in terms of characteristic molecular collision or interaction times. Consequently, the resonance state must have a very small probability of being interrupted if it is to be significant.

We can estimate the characteristic interaction time or energy exchange time for the smallest elements in a solid as roughly $a/v \approx 10^{-11}$ sec, where a is a mean spacing of molecules and v is a velocity of a bombarding molecule of mass m where $1/2 mv^2 \approx kT$. Then if the resonance is not to be deexcited by an interaction acting as a collision of the second kind in $1/60$ of a second, the probability of that deexcitation in an interaction must be of the order of 10^{-9} . So small a deexcitation probability is difficult to reconcile with the large excitation probability required if the resonance is to be excited by a weak, long-wavelength, electric field. If the cell element is as large as the cell membrane or the cell itself, and if the Q is large so as to allow the coherent contributions of many ELF cycles, the constraints are more severe.

At the long ELF wave-lengths, the electric field E must couple to a resonance through a dipole interaction. The estimates we made in Section 2.5 of the strength of the coupling of an electric field to the cell or elements of the cell, showed that for a characteristic set of interactions, the coupling was of the order of $10^{-9} kT$. Hence, the interaction energy would appear to be insufficient to generate oscillations that might produce biological effects even if the Q of the resonance is sufficiently high so that the energies of many cycles can be added coherently. (At $10^{-9} kT$ per cycle, the system would have to accumulate energy for six months from a 60 Hz oscillation to reach an energy kT .)

We can also consider the damping of resonances - or any other motion of cell elements - in terms of the viscous resistance to that motion. To estimate the magnitude of damping, we consider a model of the motion of a spherical body of radius a through cytoplasm or electrolyte where the viscosity $\eta \approx 7 \cdot 10^{-4} \text{ kg cm}^{-1} \text{ s}^{-1}$ is taken as that of water. For convenience we consider that the body is coupled to the field through a charge q . Then the drift velocity v_E under a field E will be

$$V_E = \frac{Eq}{6\pi\eta a} \quad (17)$$

It is useful to compare the distance $L_E = v_E \delta t$ the body will move in a

time δt with the mean distance L_{kT} the body will move in that time from thermal agitation or Brownian motion;

$$L_{kT} = \sqrt{\frac{2kT}{6\pi\eta a}} \delta t \quad (18)$$

Using these relations, a time $\delta t = 1/\omega_{60} = 1/(2\pi \cdot 60)$ relevant for 60 Hz oscillations, and a (large) canonical field strength $E = 1$ V/m, we find for $a = 3 \cdot 10^{-10}$ m and $q = 2e$ (e.g. a calcium ion), $L_E = 1.1 \cdot 10^{-10}$ m while $L_{kT} = 2.4 \cdot 10^{-6}$ m. For a large element (e.g. a very large macromolecule with a large dipole moment) where $a = 1 \mu\text{m}$ and $q = e$, $L_E \approx 5.5 \cdot 10^{-11}$ m while $L_{kT} = 4 \cdot 10^{-8}$ m. In either case, the amplitude L is strongly limited by viscosity and the motion induced by the field E is swamped by the Brownian motion.

Although the numerical values were derived from the model of a spherical body moving through water, the magnitudes are relevant for vibrational or rotational motion.

Hence, the narrow-banding, signal-integration, afforded by possible cellular resonances would not seem to work well enough to account for biological activity of weak ELF fields at the cell level. But there are further problems: we find that the size of cells is incommensurate with simple ELF resonances.

C Resonance Amplitudes

A resonant system stores energy (allowing the integration of perturbing signals) which is transferred from one form to another at the resonant frequency. For mechanical systems, the energy oscillates between potential and kinetic storage; in the case of LC electrical resonances, the energy oscillates between storage in electric and magnetic fields. Moreover, from the equipartition theorem, the resonance at thermal equilibrium must store an energy equal to kT .

The characteristic angular frequency $\omega = 2\pi\nu$, and stored energy W of a resonant system are

$$\omega = \sqrt{\frac{K}{M}} \text{ and } W = \frac{1}{2} M \omega^2 A^2 \quad (19)$$

where A is the amplitude of excursion of a characteristic mass M and K is a spring constant. From the equipartition theorem, $W = kT$. For ELF frequencies, such as 60 Hz, $\omega \approx 377 \text{ s}^{-1}$ is small and MA^2 must be large;

too large to fit within the mass and amplitude constraints of a cell. *There can be no ELF cellular resonances.*

We illuminate this categorical statement with explicit examples:

- As an extreme, we consider the physiologically unlikely oscillation of a whole cell with a mass of $\approx 5 \cdot 10^{-13}$ kg, and a radius of about $5 \mu m$. If the energy of oscillation of the whole cell is equal to kT , the amplitude A of oscillation will be $0.34 \mu m$ or about 7% of the radius of the cell.
- However, the oscillation of smaller parts of the cell may be less unlikely. Without concern for the mechanical details of such an oscillation, we consider a 60 Hz resonance of the cell membrane, with a mass of about $2 \cdot 10^{-15}$ kg – or any other equally massive sector of the cell. With the smaller mass, the amplitude must be $\approx 5 \mu m$ and equal to the radius of the cell.
- And there has been interest in ion resonances, especially of Ca_{10} with a mass of $6.6 \cdot 10^{-26}$ kg. The amplitude at 60 Hz corresponding to such a mass is about 1 meter.

Element	Mass	Amp (60 Hz)	Amp (16 Hz)
Whole Cell	$5 \cdot 10^{-13}$ kg	$0.34 \mu m$	$1.35 \mu m$
Cell Membrane	$2 \cdot 10^{-15}$ kg	$5 \mu m$	$20 \mu m$
Calcium Ion	$6.6 \cdot 10^{-26}$ kg	1 meter	4 meters

Table 1: Masses and corresponding amplitudes for systems oscillating with an energy of kT at resonant frequencies of 60 Hz and 16 Hz.

Such results are tabulated here for 60 Hz and 16 Hz oscillations

D Specific Resonances

Since there are some data that are claimed to constitute evidence for the biological activity of weak ELF fields that suggest that the fields act only over narrow "windows" of frequency, for completeness, we discuss detailed characteristics of a set of specific resonances.

Mechanical Resonances

It is interesting to look at a specific oscillation in detail to gain some appreciation for the strength of the prohibition against mechanical oscillations. To maximize M , we choose a hypothetical oscillation of a whole cell where a spherical cell of quiescent radius $r = 5 \mu m$ vibrates in a quadrupole mode

changing from a prolate to an oblate spheroid in the course of a cycle. We take the density of the cell cytoplasm as 1 gm/cm^3 and set the energy of the vibration at $kT \approx 4.3 \cdot 10^{-21} \text{ J}$. With these constraints, we calculated the amplitude of the 60 Hz oscillation, measured in the direction of the axis, as about $1 \mu\text{m}$. This is a substantial oscillation - the radius in the direction of the axis changes by about 20%.

In the course of the oscillation, the kinetic energy of motion of the cell material must be stored in an energy associated with the distortion. Assuming that the cytoplasm is effectively an incompressible liquid, this potential energy storage must be found in the energy required to stretch the membrane inasmuch as the surface area of the cell increases by about 1.5% as the cell changes from a spherical to an ellipsoidal shape. Setting this energy to kT , we find that the surface energy of the membrane is required to be about 10^{-9} J/m^2 , a value about 10^6 smaller than the surface energy of water. Conversely, the natural oscillation frequency of a water droplet of the size of the cell would be about 640,000 Hz.

In summary, if the kinetic energy of the cell vibrating at 60 Hz is to be as large as kT , the whole cell must take part in an oscillation. And then the effective forces described by the spring constant K must be unrealistically small if the frequency is to be kept so low. For smaller cell elements with less mass, the spring constant must be even smaller if the element is to oscillate at ELF frequencies.

Electrical Resonances

But could the "observed" resonances be electrical, rather than mechanical, where the energy is transformed cyclically from storage in a magnetic field to storage in an electric field. We consider that we can describe some element of the cell by an equivalent LC circuit with a resonant frequency;

$$\nu = \frac{\omega}{2\pi} \text{ where } \omega = \sqrt{\frac{1}{LC}} \quad (20)$$

Such a circuit will be incited thermally such that the mean total energy of kT will oscillate between storage in magnetic and electric fields. We note that if the frequency is to be low, the product LC must be large. The capacitance is limited by the size of the cell. The largest capacitance that would seem to be evident is the capacitance between the inner and outer surface of the cell membrane. Taking the thickness of the membrane as $50 \text{ \AA}$

and the dielectric constant as 2.5, $C_{mem} \approx 6 \cdot 10^{-12}$ F. Then, for a resonant frequency of $\nu = 60$ Hz, the inductance must be $\approx 10^6$ henrys!

It is difficult to design an ideal paradigmatic cell inductance. However, we note that in the absence of ferromagnetic materials in cells and in the absence of a natural source of many current turns, we should expect that the characteristic cell inductance should be of a magnitude such that $L = \mu_0 r \approx 10^{-11}$ H; too small by 17 orders of magnitude! (There are mechanical processes that lead to current phase lags in biological material of an inductive nature that follow from the inertial mass of the ions that carry currents or to the viscous resistance to the ion motion but neither of these mechanisms leads to the substantial energy storage requisite for a resonance.) Truly, Nature may be much more clever than we think, but not by a factor of 10^{17} . There can be no 60 Hz LC cell resonances.

Cyclotron Resonances

Bawin and Adey interpreted the results of an experiment¹⁰ as indicating that the passage of calcium ions through chick-brain cell walls was reduced when the cells were subject to weak 16 Hz electromagnetic fields. Then, Liboff and McLeod¹¹ noted that under a magnetic field, $B = 50 \mu T$, the size of the earth's field, that the cyclotron resonance frequency ν ,

$$2\pi\nu = \omega = \frac{qB}{m} \quad (21)$$

for a calcium ion of mass $m = 40$ atomic mass units, carrying a charge $q = e$, was equal to 16 Hz. Hence, they suggested that the cyclotron resonance of the calcium ion might be responsible for the effect reported by Bawin and Adey.

Unlike the mechanical resonance, energy in the cyclotron resonance is wholly stored in the kinetic energy of the circulating ion. The energy is transferred from the kinetic energy of motion in one direction to the energy of motion in an orthogonal direction - all in the plane of the orbit but the energy-amplitude relations stated in the last section, still hold. Hence, quite generally, the orbit of such a resonance must be larger than the size of the cell by five orders of magnitude.

Nevertheless, Liboff and McLeod proposed a specific cyclotron resonance of the calcium ion where the energy of the ion was expected to be about 3.5 eV. But such an ion travels in an orbit with a diameter of 80 meters!

But, of course, the ion could be traveling much slower, slow enough to travel around a 5μ radius orbit that might be fitted into a cell. But the

resultant ion energy is then only about $5 \cdot 10^{-14}$ eV and very, very much less than the mean thermal energy of $kT = 1/40$ eV. Indeed, a estimate suggests that the Brownian effect would typically move the ion randomly $5 \mu m$ in any 1/100 of a second that the ion is to travel that distance about its circuit. Hence, the thermal Brownian-like motion overwhelms any orbital motion.

Nuclear Magnetic Resonances

The interaction of an ambient magnetic field such as the earth's field B_e with the magnetic moment μ of a nucleus (with non-zero spin) generates a torque on the spinning nucleus that induces the nucleus to precess about the direction of the field. Even as the rOTating magnetic moment generates an oscillating magnetic field normal to the ambient field, a weak external field normal to the ambient field that oscillates with the precession frequency will generate a precession of the nuclear polarization. The frequency ν of precession is $\nu = B_e \mu / \pi$. For the earth's field this precession frequency for protons will be about 2000 Hz; for nitrogen about 20 Hz. Moreover, the nucleus of an atom is so weakly coupled to the orbital electrons - and then the material environment - that relaxation times can be of the order of 30 seconds and more. So we have a resonance condition at ELF frequencies with a high Q . Can such resonances have significant biological effects?

No! It seems most unlikely that there can be any biological effect of such resonances. The proportion of the nuclei that will be aligned will be about equal to $B_e \mu / kT \approx 10^{-10}$; a proportion very much smaller than the statistical fluctuations in the alignment of nuclei in the cell. Moreover, as reflected in the large Q , that energy is coupled to the environment of the nucleus very, very, weakly. It is this weak coupling of the nucleus to the atomic structure - and hence to the chemical and biological environment - that makes nuclear magnetic resonance imaging (MRI) such a safe and non-invasive medical procedure though the patient is bathed in magnetic fields of $\approx 4T$, about 100,000 times the earth's field.

IV Summary

A The Experimental Record

Though the theoretical considerations that represent extrapolations and interpolations of tested observations must serve as a reliable guide to our understanding of Nature, such analyses cannot supplant a well-established

contrary observation. Hence we must defer to observations that are *established* through the scientific process of review and replication. But are there there any such well-established observations that demonstrate effects of weak ELF fields on the biology of cells?

There are very many (of the order of one hundred!) reports of experiments that purport to demonstrate that weak ELF fields affect cells. An OTA report¹² places the experiments in four categories: modulation of ion flows; interference with DNA synthesis and RNA transcription; interaction with the response of normal cells to various agents and biochemicals such as hormones, neurotransmitters, and growth factors; and interaction with the biokinetics of cancer cells. There is no near-consensus among those who work in the field to the effect that *any* of the reports of effects in any of these areas is valid; none have been satisfactorily replicated, many of the more substantial results have been contradicted. The problems with the research are stated succinctly (by non-scientist true-believers in the effects) in the OTA "background paper", which characterizes the experiments by noting that "... findings at the cell level display considerable complexity including resonant responses of 'windows' in frequency and field strength, complex time dependencies, and dependence on the ambient DC magnetic field created by the earth. ... ELF fields appear to be an agent to which there is no known analog." The unwitting indictment is severe.

It is, perhaps, the intensity windows that are reported that makes it most difficult to accept the experimental results. It is an almost firm rule of the behavior of systems that, above an action threshold, the response to a perturbing signal increases at least linearly with the incremental signal. This linear increase will generally be terminated only when the signal is so large that it can no longer be considered a perturbation. Since it is very difficult to consider that the small signals in question are sufficiently large to have any effect at all, the view that they can be so large as to dampen out a response is even more troubling¹³. Moreover, the windows seem almost maliciously defined (by man or by Nature) to thwart simple verification of the effects. If such windows did not exist, the verification of the effects of small fields would be simple as the experiment could be conducted with much larger fields to elicit a much larger and more easily detected response.

B Conclusions

In summary, it does not appear to be possible for weak external ELF electromagnetic fields to affect biological processes significantly at the cell level.

ELF electric fields are so completely shielded by the conductivity of the body tissues that the interaction of external fields with a strength less than 300 V/m with cells is far weaker than fundamental thermal noise.

ELF magnetic fields may act through static interactions with magnetic dipole moments of biological material or through the induced electric fields generated by changes in the magnetic fields. Since the static effects of ELF fields of 50 μT are no greater than the earth's field, it is difficult to believe that the intensity is harmful. Since the maximum induced electric field in the body induced by 60 Hz 4 μT magnetic fields is no greater than the electric field induced by walking through the earth's field, it is difficult to believe that such changing ELF magnetic fields are harmful. Also, both the static and kinetic effects of ELF fields as great as 50 μT at the cell level are, again, smaller than that from thermal noise. The impulses from weak < 50 μT fast-rise-time ELF magnetic fields – such as from a 20 kHz sawtooth wave form – are also shown to be small compared to thermal effects.

The experimental record lacks coherence and credibility. After 20 years of experimentation, no significant effect of weak ELF fields at the cell level has been firmly established.

In summary: there are very good reasons to believe that weak ELF fields can have no significant biological effect at the cell level – and no strong reason to believe otherwise.

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