Constraints on biological effects of weak extremely-low-frequency electromagnetic fields

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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 μT and varying fields weaker than the 4-μT 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.

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 an 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[1] 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 approximately equal to 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 the squeezing of electrolytes 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 thermal 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 50 μT (or 0.5 G), 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*—nonionizing 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 tissues:[2]

$$E_i \approx 3\epsilon_0 \omega \rho_t E_0 \ , \tag{1}$$

where $\omega = 2\pi\nu$ is the angular frequency and $\rho_t \approx 2\ \Omega$ m is the resistivity of the electrolyte saturating the tissue.[3] At 60 Hz, $E_i \approx 2\times 10^{-8} E_0$. Hence, for fields in the air of 300 V/m, we can expect field strengths in the conducting tissues of about 6×10^{-6} V/m. The cell membrane will have a specific resistance of the order of $\rho_{\text{mem}} \approx 10^5 \rightarrow 10^7$ Ω m and can then be considered as an insulator relative to the tissue electrolyte. In the valid approximation that the resistivity of the membrane material, $\rho_{\text{mem}} \gg \rho_t$, the resistivity of the tissue, the field in the membrane, E_{mem} of thickness d of a cell of radius r will be about

$$E_{\text{mem}} \approx 1.5 E_i \frac{r}{d} \ . \tag{2}$$

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

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 are subjected to are quite negligible.[2]

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.

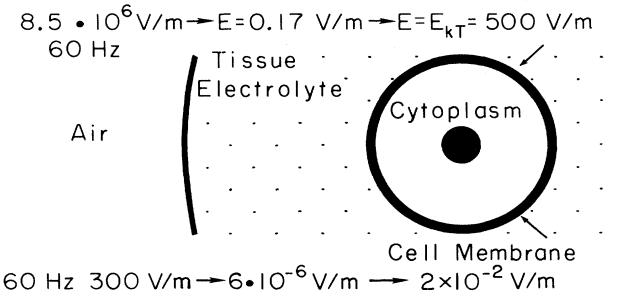

FIG. 1. Electric fields in tissues, cell membranes, and cell cytoplasm, induced by ELF external fields in the air outside of the tissue. The fields labeled above describe an externally induced field in the cell membrane that is equal to the Johnson noise, from dc to 100 Hz, measured from the cytoplasm inside 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.

B. Thermal electrical noise

A most important fundamental constraint on effects of very electric weak fields is the requirement that they not be masked by the noise fields generated by thermal fluctuations in charge densities. The magnitude of these Johnson-Nyquist noise fields generated in an element of matter can be expressed precisely in terms of the mean-square voltage $\overline{V_{kT}^2}$ over a frequency interval $\Delta\nu$ induced across the element:

$$\overline{V_{kT}^2} = 4RkT\Delta\nu \ , \tag{3}$$

where R is the resistance of the sample between the points where the voltage is measured.

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 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

$$\overline{V_{kT}^2} = 4RkT\Delta\nu = 4\frac{\rho}{d}kT\Delta\nu, \quad E_{kT} = \frac{\overline{V}_{kT}}{d} . \tag{4}$$

Using the above relations and taking $\rho = 2\Omega$ 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 approximately 5×10^7 than fields in air to tissue. With special receptors known as the ampullae of Lorenzini, which act as low-pass filters and extend over lengths near a meter, the response of sharks to quite small fields—as fields as small as 0.5 μV/m have been detected—does not violate thermal noise limits.[4]

D. Noise fields in cell membranes

A popular "explanation" of purported biological effects of external low-level ELF electromagnetic fields is that these effects are derived 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 inside the cell and the electrolyte outside 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 $\frac{3}{2}kT \approx 37$ 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

$$\overline{V_{kT}^2} = 4RkT/\Delta\nu \quad \text{where } R_{\text{mem}} = \frac{\rho d}{4\pi r^2} , \tag{5}$$

where the resistivity of the membrane material is taken as $\rho_{\text{mem}} = 10^6$ Ω m. With these values $R_{\text{mem}} = 4\times10^6$ Ω. Taking an ELF frequency band of 100 Hz, $V_{kT} \approx 2.6\times10^{-6}$ V and $E_{kT} = V_{kT}/d \approx 500$ V/m. (Since the resistivity of the membrane material is uncertain within a factor of 10, the field strengths calculated here are uncertain by a factor of 3.) This thermal noise voltage 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 $\approx 5\times10^{-5}$ than the normal potential difference of 0.05 V across the cell wall.[5] But the noise voltage across the membrane—and the noise field in the membrane—is about 25 000 times[6] 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 $d \approx 50$ Å 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 which is 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 Å on a side is held between the plates. The time average of the fluctuating noise voltage V_{kT} is again

$$\overline{V_{kT}^2} = 4RkT\Delta\nu \quad \text{where now } R = \frac{\rho_{\text{mem}}}{d} \approx 2\times10^{14}\ \Omega . \tag{6}$$

If we use the mean resistivity of the membrane material of $\rho = 10^6$ Ω 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 $E_{kT} \approx \overline{V_{kT}}/d \approx 3.7 \times 10^6$ V/m, which is about 2×10^8 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 $E_i = 6 \times 10^{-6}$ V/m in tissue, and $E_m = 2 \times 10^{-2}$ V/m in membranes 50-Å thick with 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; this 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. The proportion of P that 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 $\mathbf{P} = \epsilon_0 (K-1)\,\mathbf{E}$ where K is the dielectric constant and $K - 1 \approx 80$ as for water and the volume $\mathcal{V}$ is that of a cell 10 μm in diameter. Then the interaction energy W will be about

$$W \approx (\mathbf{E}\cdot\mathbf{P})\mathcal{V} \approx 80 E_i^2 \epsilon_0 \mathcal{V} \approx 2.5 \times 10^{-14} kT \ . \tag{7}$$

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 $W \approx E_{\text{mem}} e r \approx 3 \times 10^{-8} kT$.

F. Magnetic fields

1. Static magnetic fields

A kind of restricted anthropic principle places immediate limits on the biological effects of static magnetic fields. 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

$$\mu = g \frac{e}{2m} \hbar \ , \tag{8}$$

where the value of g depends upon the specific structure but is usually near 1, 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 $B_e = 50$ μT, 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 approximately equal to 10^7 than for paramagnetic materials. Consequently, the earth's 50-μT field does affect those (rare) cells that contain ferromagnetic matter.

About 15 years ago, Blakemore[7] 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-μm long of grains of magnetite Fe_3O_4. A simple calculation[7] 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 a 50-μT 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 in-

teractions 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 rejoin.[9]

However, if the local external magnetic field acting on 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 be more likely to rejoin. Since this suppression requires magnetic fields that are typically two orders of magnitude greater than the 50-μT limit we have adopted, we need not consider the possibility of such effects.

2. *Changing magnetic fields*

Since life evolved in the presence of static magnetic fields of the order 1 G or 100 μT, 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,

$$\oint_S \mathbf{E}\cdot d\mathbf{s} = \frac{d\left[\int_A \mathbf{B}\cdot d\mathbf{a}\right]}{dt} \propto \frac{dB}{dt} , \tag{9}$$

where A is an area through which the field $\mathbf{B}$ 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 acting over the body, as

$$\bar{E}_B = \frac{B\omega r}{2} \approx 10^{-3}\ \text{V/m} . \tag{10}$$

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 Sec. II B for the electrolyte occupying a volume the size of a cell. This is the noise, over a bandwidth $\delta\nu = 100$ 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 200 times the magnetically induced field of 0.001 V/m multiplied by the factor of $1.5r/d$ from Eq. (2). 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 μm on a side, which will be about 1 V/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 approximately 7×10^{-5} V/m induced thus by walking will be about equal to the maximum field generated by a 4-μT (40 mG) 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 μT (700 mG) while a passenger in a jet plane will see electric fields similar to the maximum from a 7×10^{-4}-T (7-G) 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 induced the same electric fields in the cell as a 4-μT 60-Hz oscillating magnetic field. But 4 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 Sec. III that ELF resonances at the cell level are not possible.

3. *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 sawtooth 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 μT linearly over a period of approximately 50 μs and then returns to zero in a time less than 1 μs; and then repeats at a repetition rate of approximately 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:

$$E(t)=\frac{r}{2}\frac{dB(t)}{dt} , \tag{11}$$

and we write

$$\int E(t)dt = E_m \delta t = \frac{r}{2}\int \frac{dB}{dt}dt = \frac{r}{2}\delta B = B_0 \frac{r}{2} , \tag{12}$$

where E_m is the mean induced electric field and δt is the time over which the magnetic field changes by an amount δB. Hence, the impulse added to an element holding a charge q by the electric-field pulse will be

$$dp = E_m q \delta t = q\frac{r}{2}B_0 , \tag{13}$$

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

$$p_{kT} \approx \sqrt{mkT} , \tag{14}$$

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 a calcium ion, or may add to vibrational or rotational motion of a 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 the field $B_0=50$ μT is $dp \approx 4\times10^{-25}$ N s. But this is much smaller than the thermal momentum $p_{kT} \approx 1.7\times10^{-23}$ N s for a calcium ion and very much smaller than the thermal momentum $dp \approx 10^{-21}$ N s for a macromolecule with a mass of 40 000 amu, where the pulse couples through the dipole moment to incite vibration or rotation.

For a protein molecule held in the cell membrane, the effective field may be increased by a factor of the order of 1000 [Eq. (2)] through polarization of the membrane for pulses longer than 1 μs. (This polarization also acts to shield the interior of the cell from the electric field.) With this increment, $dp \approx p_{kt}$. But the molecule undergoes this characteristic impulse p_{kT} of the order of 10^4 times in a microsecond generating a mean impulse about 100 times dp. For shorter pulses the mean thermal impulse, proportional to the square root of the pulse duration, is reduced but the membrane passes the pulse through its capacitance and is not so strongly polarized. 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 bandwidth 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 initiates the biological effects, the relative noise interference is reduced. Certain biological actions act as bandpass 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 s, it is plausible that perturbations that change sign often in that time would have little overall effect. There are biological relaxation effects that admit transfer functions that peak at low frequencies—very much as a bandpass filter—but these peaks are quite broad.

However, since we have effectively assumed a low bandpass acceptance in using a frequency band of only 100 Hz in our discussions, if we are to find striking gains in signal-to-noise ratios in ELF actions, we must look further to resonant mechanisms that act as narrow bandpass 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 passband 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 bandwidth $\delta\nu$, approximately equal to ν/Q for resonances, is very narrow, $\delta\nu \ll \nu$, the effective bandwidth 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 ratio will be proportional to $\sqrt{t}$. Or if the signal is integrated (or *averaged*) over a long time $t_{\max}$, the signal-to-noise ratio will be much improved, but only if the effective system width is small compared to $1/t_{\max}$. Weaver and Astumian[10] suggest averaging times $t_{\max}$ of the order of 1000 s (or about 20 min). Such a long averaging time could only be relevant if the intrinsic bandwidth 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 min. 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-min exposure would be improved by a factor of $\sqrt{1000} \approx 30$ over a 1-s 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 min and a resonance width of 0.001 Hz (centered, *accidently*, 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 100 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 $a/v \approx 10^{-11}$ s, where a is a mean spacing of molecules and v is a velocity of a bombarding molecule of mass m where $\frac{1}{2}mv^2 \approx kT$. Then if the resonance is not to be deexcited by an interaction acting as a collision of the second kind in $\frac{1}{60}$ 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 enough to allow the coherent contributions of many ELF cycles, the constraints are more severe.

At the long ELF wavelengths, the electric field E must couple to a resonance through a dipole interaction. The estimates we made in Sec. II E 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 of $1\ kT$.)

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 $\eta \approx 7\times10^{-4}$ kg cm^{-1} 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

$$v_E = \frac{Eq}{6\pi\eta a} . \tag{15}$$

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:

$$L_{kT} = \left[\frac{2kT}{6\pi\eta a}\delta t\right]^{1/2} . \tag{16}$$

Using these relations, a time $\delta t = 1/\omega_{60} = 1/(2\pi\times60)$ relevant for 60-Hz oscillations, and a (large) canonical field strength $E = 1$ V/m, we find for $a = 3\times10^{-10}$ m and $q = 2e$ (e.g., a calcium ion), $L_E = 1.1\times10^{-10}$ m while $L_{kT} = 2.4\times10^{-6}$ m. For a large element (e.g., a very large macromolecule with a large dipole moment) where $a = 1$ μm and $q = e$, $L_E \approx 5.5\times10^{-11}$ m while $L_{kT} = 4\times10^{-8}$ 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

$$\omega = \left[\frac{K}{M}\right]^{1/2} , \quad W = \tfrac{1}{2}M\omega^2A^2 , \tag{17}$$

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:

(i) As an extreme, we consider the physiologically unlikely oscillation of a whole cell with a mass of $\approx 5\times10^{-13}$ kg, and a radius of about 5 μm. If the energy of oscillation of the whole cell is equal to kT, the amplitude A of oscillation will be 0.34 μm or about 7% of the radius of the cell.

(ii) 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 2×10^{-15} kg, or any other equally massive sector of the cell. With the smaller mass, the amplitude must be approximately equal to 5 μm and equal to the radius of the cell.

(iii) And there has been interest in ion resonances, especially of ^{40}Ca with a mass of 6.6×10^{-26} kg. The ampli-

TABLE I. Masses and corresponding amplitudes for systems oscillating with an energy of kT at resonant frequencies of 60 and 16 Hz.

Element	Mass (kg)	Amplitude 60 Hz	16 Hz
Whole cell	5×10^{-13}	0.34 μm	1.35 μm
Cell membrane	2×10^{-15}	5 μm	20 μm
Calcium ion	6.6×10^{-26}	1 m	4 m

tude at 60 Hz corresponding to such a mass is about 1 m. Such results are presented in Table I for 60- and 16-Hz oscillations.

D. Specific resonances

Since there are some data that are claimed to constitute evidence of 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

1. 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 $r=5$ μm 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 g/cm^3 and set the energy of the vibration at $kT\approx4.3\times10^{-21}$ J. With these constraints, we calculated the amplitude of the 60-Hz oscillation, measured in the direction of the axis, as about 1 μm. 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.

2. 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:

$$\nu=\frac{\omega}{2\pi} \quad \text{where } \omega=\left[\frac{1}{LC}\right]^{1/2}. \tag{18}$$

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 Å and the dielectric constant as 2.5, $C_{\text{mem}}\approx6\times10^{-12}$ F. Then, for a resonant frequency of $\nu=60$ Hz, the inductance must be approximately equal to 10^6 H.

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 $L\approx\mu_0 r\approx10^{-11}$ 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.

3. Cyclotron resonances

Bawin and Adey interpreted the results of an experiment[11] 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 McLeod[12] noted that under a magnetic field $B=50$ μT, the size of the earth's field, the cyclotron resonance frequency ν

$$2\pi\nu=\omega=\frac{qB}{m} \tag{19}$$

for a calcium ion of mass $m=40$ amu, 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 m.

But, of course, the ion could be traveling much slower, slow enough to travel around at 5-μ radius orbit that might be fitted into a cell. But the resultant ion energy is then only about 5×10^{-14} eV and very, very much less than the mean thermal energy of $kT=\frac{1}{40}$ eV. Indeed, an estimate suggests that the Brownian effect would typically move the ion randomly 5 μm in any $\frac{1}{100}$ of a second that the ion is to travel to that distance about its circuit. Hence, the thermal Brownian-like motion overwhelms any orbital motion.

4. *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 nonzero 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 s and more. So we have a resonance condition at ELF frequencies with a high Q.

However, 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 $B_e\mu/kT\approx10^{-10}$, 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 noninvasive medical procedure though the patient is bathed in magnetic fields approximately equal to 4 T, about 100 000 times the earth's field.

IV. SUMMARY

A. 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 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 100) reports of experiments that purport to demonstrate that weak ELF fields affect cells. A U.S. Congress Office of Technological Assessment (OTA) report[1] 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 than *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 succintly 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 troubling.[13] 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

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 less than 50-μT fast-rise-time ELF magnetic fields—such as from a 20-kHz sawtooth waveform—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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[3]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 place subject to a vertical field; M. W. Miller, in *CRC Handbook* (Ref. 2), p. 139.

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