NEARLY CLOSED LOOPS IN BIOLOGICAL SYSTEMS AS ELECTROMAGNETIC RECEPTORS

D. Eichler

Dept. of Physics, Ben-Gurion University, Beer Sheva, ISRAEL

and

Institute for Theoretical Physics, University of California, Santa Barbara, CA, 93106-4030

It is noted here that when a nearly closed loop in a biological system, such as a self-synapsing (autapsing) neuron or mutually synapsing pair, is exposed to an AC magnetic field, the induced electric fields in the insulating gaps can be many orders of magnitude larger than the average values typically discussed in the literature.\textsuperscript{1,2} It is suggested that animal nervous systems might possibly be affected in selected spots by man-made alternating magnetic fields at weaker levels than previously supposed. Radio and microwave radiation should be considered particularly suspect.
The possible influence of "everyday" electromagnetic (EM) fields on living systems has been a topic of great interest in recent years, with many controversial claims and counterclaims in the epidemiological, laboratory and theoretical arenas. Of particular interest has been the theoretical question of whether, at typical levels experienced from household appliances, trains, etc. such fields could conceivably affect living systems at levels that thermal electrical noise and molecular agitation might appear to override \textsuperscript{1,2}. The claim in these references, which otherwise assume the conservative premise that EM fields are suspect until proven safe, is that fields that are weaker than those caused by thermal noise must be beyond suspicion. It is noted in this letter, however, that if the effective brightness temperature of the alternating electromagnetic field greatly exceeds the temperature of the system - i.e. if the thermally averaged electromagnetic energy per cavity mode is much higher than kT - it cannot be rigorously demonstrated that such fields are entirely safe.

Low frequency electric fields do not, on average, penetrate biological tissue effectively \textsuperscript{1,2,3}. Magnetic fields B, which penetrate effectively, exert a weaker instantaneous force on individual charged particles as compared to electric fields E of the same magnitude (or, equivalently, the same energy density) by a factor of order \((v/c)\), which is much less than unity. Here \(v\) is the velocity of the charged particle and \(c\) is the speed of light. The time averaged effect could of course be a more complicated matter, but this letter in any case focuses on electric fields. Induced electric fields from alternating magnetic fields (AMF) are limited in their curl by Faraday’s law but the electric potential gradient induced by the AMF, via the rearrangement of charges, is not.
Consider a nearly complete, circular loop of electrically conducting material of radius $R$. Assume that the loop contains an insulating notch (a slot gap) of length $\delta$. When the loop is exposed to a time varying magnetic field $Be^{i\omega t}$, the electromotive force around the loop is

$$\oint E \cdot d\ell = \frac{i\omega}{c} \pi R^2 Be^{i\omega t} \tag{1}$$

(We have neglected spatial dependence of the field assuming it to be small on the scale $R$. We have also assumed that the magnetic field penetrates the biological tissue at frequencies well below 1000 Mhz, as is generally recognized to be the case, and for higher frequencies we note that the arguments presented here may apply only within a penetration depth of the surface of the organism. Unless otherwise stated, we use cgs units in which $E$ and $B$ have the same dimensionality, and remind the reader that in free space a 1 Gauss magnetic field has the same energy density as a 1 statvolt/cm electric field, that the statvolt/cm and Gauss have the same physical dimensionality in the primary dimensions of mass, space and time, and that 1 statvolt/cm = 300 V/cm.

If the rate of charge redistribution is larger than $\omega$, the contribution to the integral is dominated by the gap, so that the peak electric field in the gap is

$$E = \frac{\omega}{c} \pi R^2 \frac{B}{\delta}. \tag{2}$$

Now consider a nearly closed biological loop of connected conducting solution, e.g., a neuron of length $2\pi R$ that closes upon itself, making a synapse of width $\delta$ between its axon and one of its own dendrites. A geometric idealization is illustrated in the figure. The resistance across the synapse is probably dominated by the neuronal membrane on either side of it (i.e. where the dashed and dotted line intersect), which has a surface resistivity
of order $10^4$ ohms cm$^2$. Because of ionic currents and polarization in the extracellular fluid at the gap, any potential difference across the synapse is likely to occur mostly in the membrane itself (where in fact its biological significance is possibly the greatest), and with this understanding we shall for brevity refer to it as the potential difference across the gap. The effective value of $\delta$ to be used in equation (2) may in fact be only twice the membrane thickness, and this reduction in $\delta$ will only serve to strengthen the arguments presented here. Assuming a length scale of order several hundred Angstroms, and the area of the synapse to be the square of that, the resistance of the synapse is then of order $10^{15}$ ohms, and easily dominates the total resistance of the circuit. The EMF generated around the loop is then mostly in the synapse. An electric field of

$$E = \left(\frac{\omega}{10^4 \text{hz}}\right) \left(\frac{B}{1 \text{Gauss}}\right) \left(\frac{R}{1 \text{cm}}\right)^2 \left(\frac{10^{-6} \text{cm}}{\delta}\right) \times 314 \frac{V}{\text{cm}}$$

(3)
is created at the synapse. Independent of the width of the synapse, a voltage of

$$V = 0.3 \text{mV} \left(\frac{\omega}{10^4 \text{hz}}\right) \left(\frac{B}{1 \text{Gauss}}\right) \left(\frac{R}{1 \text{cm}}\right)^2$$

(4)
is created across it. This is similar to the result obtained by Polk (1992) except that he assumes a loop composed of small individual cells so that there are approximately 3000 individual gap junctions in a loop of 1 cm radius. Thus, the electric fields envisioned across a self-synapse can be larger by a factor of 3000 or so than in Polk (1992). While $R$ is likely to be less than 1 cm for a given neuron, it is reasonable that embedded in neural nets are large loops containing $N$ synapses in series (which I term an $N$-cyclic synapse sequence, $N$ at least two), and that $(\frac{R}{1 \text{cm}}) \gg N$. In this case $E \gg \left(\frac{\omega}{10^4 \text{hz}}\right) \left(\frac{B}{1 \text{Gauss}}\right) N^{-1} \text{statvolt/cm}$.

The maximum $\omega$ for which the above is valid is the inverse time scale $\left(\frac{1}{ZC}\right)$ for charge redistribution around the loop where $Z$ is the electrical resistance of the intraneuronal fluid.
(excluding the membrane) and $C$ is the capacitance of the gap (including the membrane).

If the loop has a constant cross-section, then $(\frac{1}{ZC})$ is $\frac{δ^2}{2\pi R \omega_p^2 \tau_c}$, where $\omega_p^2 = 4\pi n q^2 / m$ and $\tau_c$ is the collision time. Here the quantities $n$, $q$ and $m$ are the number density, charge and mass of the dominant charge carriers. By equation (3), the maximum electric field is thus

$$E_{max} = \left(\frac{\delta}{2\pi R \omega_p^2 \tau_c}\right) \frac{\pi R^2 B\eta}{c\delta}$$

$$= \frac{\omega_p^2 \tau_c R}{2c} B\eta$$

(5)

The above assumes that the conducting medium of which the loop is composed is collisional, $i.e.$, $\omega\tau_c < 1$, which is usually the case. For a dissipationless loop the right hand side of equation (5) would be replaced by $\frac{\omega_p c}{c}$ $RB$. A typical value of the conductivity $\omega_p^2 \tau_c$ in biological fluid is $3 \times 10^{10} \text{s}^{-1}$, or equivalently, $1.4 \text{ mho/m} = 1.4 \text{ S/m}$. For intraneuronal fluid in a squid, it can exceed $3 \text{ S/m}$, whereas for mammals, a more typical value is $0.8 \text{ S/m}$.\(^5\) In equation (5), $\eta$ is the effective ratio of cross-sectional areas between the loop – over most of its length – and the gap. One expects that $\eta$ is large. This allows a faster charge redistribution by a factor $\eta$. Estimates for $\eta$ in various physiological networks are beyond the scope of this letter. Large neurons can have cross-sectional radii as high as 10 microns, whereas gap scales could be as small as $10^2$ angstroms, so $\eta$ could get as high as $10^6$. For large arteries, which have cross-sectional areas as large as millimeters, $\eta$ could conceivably be as high as $10^{10}$. Naively, this extends the validity of equations (3) and (4) to include radio and possibly microwave and IR frequencies. However, the overall resistance of the loop depends the hierarchical branching pattern of the network it is a part of, and needs to be evaluated on a case by case basis.

The radii of loops, and the effective slot gap widths $\delta$ within such loops that can exist in large mammals (e.g. humans) is a non-trivial physiological question that is well
beyond the scope of this letter. Loops many (of order 10, say) cm in radius may exist in
the circulatory and nervous systems. The possibility of multiple coiling, as in a sparkplug,
would further extend the range in the effective value of the loop area. By equation (3) and
subsequent discussion, electric fields could be created in slot gaps that are even greater in
magnitude than the alternating magnetic fields if the latter are applied at frequencies near
\[
\omega \sim \frac{\omega_0^2 \tau_0 \delta}{2\pi R} \sim 5 \times 10^3 \left( \frac{\delta}{10^{-6} \text{cm}} \right) \left( \frac{1 \text{cm}}{R} \right) \text{ hz}.
\]

If the loop is a bacterial chromosome, or any large, closed polymeric molecule, we
suggest in a highly speculative spirit that there exists the possibility of persistent (dissi-
pationless) current being excited. Defects in the polymer could act as slot gaps. In this
case, the frequency of collective electronic oscillations could be of order \(10^{15-16} \text{s}^{-1}\). If the
scale of the polymer is \(10^{-5} \text{ cm}\), and the defect of order 1Å, electric fields at the defect
could be comparable to applied alternating magnetic fields at infrared frequencies, and in
any case higher than the average value allowed by Faraday’s law. Though infrared light
would not penetrate deeply into biological tissue, it may nevertheless be an issue for, say,
epidermal cells.

Field strengths of order of several Gauss, and frequencies \(\omega\) of order \(10^3\), which obtain
in some household appliances, can give EMF’s of order a millivolt over a scale of several
cm. Sources of high frequency RF, such as magnetic resonance imaging (MRI) devices,
cellular phones, and microwave ovens are especially suspect. Consider microwave emission
at about 2500 Mhz at the standard safety ceiling of 1 milliwatt cm\(^{-2}\). This corresponds
to a magnetic field strength in air (essentially free space) of about 2 milligauss. The
penetration depth into biological tissue of waves at this frequency is of order 1 cm. The
EMF generated in a loop of 1 cm radius is about $4 \times 10^{-3}$ gauss cm, or about 1 volt. If this EMF is concentrated across a single or even several neuronal membranes, its physical significance could not be safely dismissed, as it is more than an order of magnitude more than the natural range of membrane potentials. Similar concerns would exist for the RF fields from magnetic resonance imaging (MRI) devices, and cellular phones at a distance of several cm, where the field can change at a rate as high as $10^6$ gauss/s.

It is not claimed here that even the maximal electric fields derived here are dangerous, or that various claims of carcinogenic effects can be accounted for via the electric field concentration mechanism discussed here. We also note that the estimates\textsuperscript{1,2} on the maximum average field strength do not contradict the arguments presented here, and it is emphasized that the field attains significantly higher than average values only in small selected spots that comprise a small fraction of the total volume. It is worth noting, however, that neural network viability in theoretical models depends on sensitive balance between inhibition and excitation. Slight systematic changes in the firing rates of large numbers of neurons could qualitatively change the behavior of the net in a similar way that, say, bubble chambers and cloud chambers are affected by very weak perturbations. In each case, arguably, the system records information by existing in a delicate state. It is also conceivable that self-synapsing neurons, because they can be efficient feedback loops, play a significant role in the "personality" of the neural net in which they are embedded. Systematic interference in the function of self-synapsing neurons might therefore affect the global behavior of the network in addition to the chemistry of individual synapses.

In conclusion, the thermal noise limit needs to be used with caution when applied as
a safety guarantee for exposure to time varying magnetic fields. The physiology of living systems may employ the same principles as the meters and oscilloscopes that measure “safely weak” fields while at room temperature. Strictly speaking, the thermal noise threshold is not necessarily established by the Johnson noise or thermal agitation \(^1,^2,^3\) when the brightness temperature of the EM radiation exceeds kT.

*note added:* Autapsing neurons have been grown in culture and, though the autapses have long been suspected to be an artifact of the culture growth, it has very recently been reported \(^6\) that they are common in developing neocorticies of young rats. Most neurons of the investigated class (level 5 pyramidal) are found to autapse and have on the average more than two autapses per neuron. The spatial dimensions of the autapse circuit can be as large as several hundred microns across. A reasonable scaling to large mammals would be that the spatial dimensions are roughly a factor of 3 to 20 larger. This estimate is based on the fact that cell bodies are a factor of 3 or 4 larger in large mammals than in small rats, and the axonal lengths could scale more in proportion to the linear size of the animal (E. White, private communication). It is conjectured here that cyclic sequences of synapses will eventually be found on still larger scales.

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Figure Caption: The idealized representation used in the text of a self-synapsing neuron or other nearly closed loop is illustrated. The dotted line denotes the circuit of integration in equation (1). The solid line denotes the neuronal membrane. The figure is not drawn to scale and the solid boundary should in fact comprise a significant fraction of the gap.