IRWIN AND JOAN JACOBS
CENTER FOR COMMUNICATION AND INFORMATION TECHNOLOGIES

Enhanced Absorption of Electromagnetic Radiation by Resonant Sites in Biologic Tissue

L. Schächter and D. Schieber

CCIT REPORT #362

November 2001

Enhanced Absorption of Electromagnetic Radiation by Resonant Sites in Biologic Tissue

L. Schächter and D. Schieber
Department of Electrical Engineering
Technion - Israel Institute of Technology
Haifa 32000, ISRAEL

November 25, 2001

Abstract

It is shown that the local power absorbed in microscopic resonant sites in biologic tissue, may be orders of magnitude larger than the average power absorbed in the background. Further, since the volume of these resonant sites is extremely small relative to the control volume, their effect on the global power absorption is negligible and therefore it is in fact undetectable by an external observer.

The extensive use of cellular phones has triggered some concerns regarding the possible effects of microwave radiation on the human brain. In order to address these public concerns a significant effort has been directed in recent years to the investigation of *thermal* effects [1] of electromagnetic waves on living system. The typical approach relies on the characterization of the various regions of the body in terms of a macroscopic dielectric function that enables to establish the field distribution and thus the amount of power dissipated. And indeed, the guidelines for radiation exposure recommended by the International Commission for Protection of Non-Ionizing Radiation [2] rely on studies that focus on broad-band thermal effects. Although studies indicate that an increase of 1-2C^o in the temperature may cause irreversible change of a micro or macro-biologic system, for a typical radiation exposure the temperature increase is significantly smaller, and thus the impact is not expected to be significant. Moreover, the subjective feeling that the ear warms up when talking with a cell-phone, is most probably associated with the heat dissipation through the air rather than due to the power absorbed by the tissue.

Broad-band absorption of electromagnetic field by tissue is not the most "efficient" way for radiation to affect matter. In fact, it is well known that efficient interaction occurs close to either temporal or spatial resonances. While the latter have been considered [3] and it is well known that the dimensions of the body determine the frequency where maximum absorption occurs, the temporal resonances have been generally discarded. The reasoning is as follows: contrary to an *isolated* molecular system that may have a significant number of resonances in the microwave range, when the same molecule is part of a *biologic system*, thus embedded in a lossy background, the latter dominates, and from the point of view of an external observer the effective width of each resonance is broad and practically undetectable. This statement is correct from the perspective of an *external* observer; however it may be far from accurate from the perspective of a localized resonant molecule or biologic system.

In order to demonstrate this last statement we consider in this study an ensemble of *microscopic* sites that all have one narrow-bandwidth resonance and are immersed in a lossy medium that models part of a biologic tissue e.g. the brain. The radiation absorbed in their small volume may be larger by several orders of magnitude than that absorbed in the lossy background. This in spite the fact that their impact on the *macroscopic* dielectric coefficient is negligible. It should be emphasized that our purpose in this letter is to demonstrate an interaction *mechanism* that apparently has been discarded in the context of the interaction of microwave radiation with the human body; the specific candidates for microscopic resonant sites and their exact characteristics are beyond the scope of this study. However, some similarity may be envisioned by conceiving the equivalent of miniscule (10nm) magnetite crystals discovered [4] in the brain and their interaction, as ferro-magnets, with a static or quasi-static magnetic field.

Consider an electromagnetic plane wave that oscillates at an angular frequency, ω, namely $e^{j\omega t}$. The incident wave propagates in the x-direction and its electric field is in the z-direction only (TE_x) - see Figure 1. For simplicity sake, no variations are assumed to occur in the z-direction and therefore we shall consider a unit length Δ_z. As it in a biologic tissue (modeled by a lossy medium ϵ_r), it encounters a series of microscopic sites of cylindrical shape that have a radius that is much smaller than the wavelength of the radiation field. One may envision a typical frequency of 1GHz i.e. a typical wavelength of a few cm's, whereas the radius of the resonant site (RS) may vary from a few nano-meters to microns. Without significant loss of generality it is assumed that these resonant sites are parallel to the electric field of the incident wave and we shall consider both the interaction of each site with the wave and the intra-coupling between the various sites. The center of each cylinder is located at (x_ν, y_ν) where $\nu(= 1, 2...N)$ is the index that labels the cylinders. In what follows we shall also assume that the typical distance between any two cylinders is larger than the cylinder's radius.

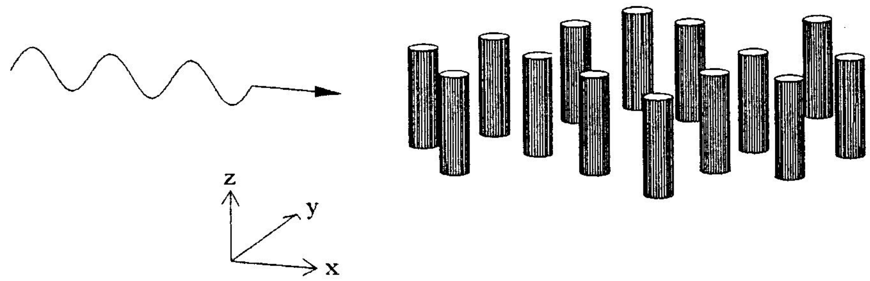

Figure 1: Schematic of the system. A plane electromagneic wave impinges upon an ensemble of thin cylinders that have electromagnetic characteristics significantly different than the background; the radius is much smaller than shown.

For our present purposes, the resonant sites are electromagnetically characterized by a constitutive relation that relates the local electric field and the current density,

$$J_z = j\omega\epsilon_0 \frac{\omega_{\rm p}^2}{\omega_0^2 - \omega^2 + 2j\omega\omega_1} E_z\,, \tag{1}$$

where ω_0 is the resonance angular frequency of the site, ω_1 is the resonance bandwidth and ω_p is a frequency that characterizes the medium density as well as its oscillating dipoles. For the present purpose it should be emphasized that the interaction with the electromagnetic field at resonance is determined by all three parameters ($\omega_{\rm p}$, ω_0 and ω_1),

$$\frac{1}{2}{\rm Re}\left[E_z J_z^*\right] = \frac{1}{2}\omega\epsilon_0 \frac{2\omega\omega_1\omega_{\rm p}^2}{[\omega_0^2-\omega^2]^2 + [2\omega\omega_1]^2}|E_z|^2 \simeq \frac{1}{2}\omega\epsilon_0\left(\frac{\omega_{\rm p}^2}{2\omega_0\omega_1}\right)|E_z|^2\,. \tag{2}$$

The expression in bracket is the imaginary part of the dielectric coefficient of the resonant site (subscript s) and it is therefore convenient to define ${\rm Im}(\epsilon_{\rm s})=\omega_{\rm p}^2/2\omega_0\omega_1$. Since the radius of the cylinders (R) was assumed to be very small and the tangential electric field is continuous, we may define the current in each one of the cylinders as

$$I_\nu \equiv J_z\left(\pi R^2\right) = j\omega\epsilon_0\,{\rm Im}(\epsilon_{\rm s})\frac{2\omega_0\omega_1}{\omega_0^2-\omega^2+2j\omega\omega_1}E_{z,\nu}\left(\pi R^2\right)\,, \tag{3}$$

where $E_{z,\nu}$ is the average electric field across the cylinder. These currents generate in the entire space an electromagnetic field that may be derived from the z-component of the electric field that in turn is given by

$$\begin{aligned} E_z(x,y,\omega) = &\; E_0 e^{-j\sqrt{\epsilon_{\rm r}}\omega x/c} \\ &-j\omega\frac{\mu_0}{2\pi}\sum_{\nu=1}^{N} I_\nu {\rm K}_0\left[j\sqrt{\epsilon_{\rm r}}\frac{\omega}{c}\sqrt{(x-x_\nu)^2+(y-y_\nu)^2}\right]\,. \end{aligned} \tag{4}$$

The amplitude of the incident electric field is denoted by E_0 and ${\rm K}_0(\zeta) \equiv \int_0^\infty {\rm d}u e^{-\zeta\cosh(u)}$ is the zero order modified Bessel function of the second kind.

We may now establish the average field across the RS by integrating Eq. (4) over the cross-section of a specific cylinder (C_ν)

$$\begin{aligned} E_{z,\nu} \equiv \frac{1}{\pi R^2}\int_{C_\nu}{\rm d}x\,{\rm d}y\,E_z(x,y) &= \frac{1}{\pi R^2}\int_{C_\nu}{\rm d}x\,{\rm d}y\,E_0\,e^{-j\sqrt{\epsilon_{\rm r}}\,\omega x/c} \\ &\quad -j\omega\frac{\mu_0}{2\pi}\sum_{\mu=1}^{N} I_\mu\frac{1}{\pi R^2}\int_{C_\nu}{\rm d}x\,{\rm d}y\,{\rm K}_0\left[j\sqrt{\epsilon_{\rm r}}\frac{\omega}{c}\sqrt{(x-x_\nu)^2+(y-y_\nu)^2}\right] \\ &= \mathcal{E}_\nu - j\omega\frac{\mu_0}{2\pi}\sum_{\mu\neq\nu} I_\mu {\rm K}_0\left[j\sqrt{\epsilon_{\rm r}}\frac{\omega}{c}\rho_{\mu,\nu}\right] \\ &\quad -j\omega\frac{\mu_0}{2\pi}I_\nu\frac{2}{R^2}\int_0^R {\rm d}r\,r{\rm K}_0\left(j\sqrt{\epsilon_{\rm r}}\frac{\omega}{c}r\right) \end{aligned} \tag{5}$$

where $\rho_{\mu,\nu} = \sqrt{(x_\mu - x_\nu)^2 + (y_\mu - y_\nu)^2}$ is the distance between the various RS's and $\mathcal{E}_\nu$ represents the electric field at the location of the RS when these are absent. Note that it was tacitly assumed that the distance between two rods is much larger than the radius of one rod.

The next step is to replace the current term on the right hand side with the explicit expression, in terms of the local electric field, as determined by Eq.(3). The result can be formulated in terms of the following algebraic equation

$$\sum_\mu \mathcal{H}_{\nu,\mu} E_{z,\mu} = \mathcal{E}_\nu \tag{6}$$

where

$$\mathcal{H}_{\nu,\mu} = \begin{cases} -\frac{1}{2}\mathrm{K}_0\left(j\sqrt{\epsilon_\mathrm{r}}\frac{\omega}{c}\rho_{\nu,\mu}\right)\left(\frac{\omega}{c}R\right)^2 \frac{\omega_\mathrm{p}^2}{\omega_0^2 - \omega^2 + 2j\omega\omega_1} & \nu \neq \mu \\ \\ 1 + \frac{1}{\epsilon_\mathrm{r}}\frac{\omega_\mathrm{p}^2}{\omega_0^2 - \omega^2 + 2j\omega\omega_1}\int_0^{j\sqrt{\epsilon_\mathrm{r}}\omega R/c} du\, u\mathrm{K}_0(u) & \nu = \mu \end{cases} \tag{7}$$

Eq.(6) determines the average electric field across each RS.

Once the electric field across each RS has been established, it is possible to determine the average power dissipated in each site, namely,

$$P_\nu = \frac{1}{2}\left(\pi R^2\right)|E_{z,\nu}|^2 \frac{\omega_\mathrm{p}^2(\omega\epsilon_0)(2\omega\omega_1)}{(\omega_0^2 - \omega^2)^2 + (2\omega\omega_1)^2} \simeq \frac{1}{2}\left(\pi R^2\right)|E_{z,\nu}|^2(\omega_0\epsilon_0)\mathrm{Im}(\epsilon_\mathrm{s}) \tag{8}$$

which should be compared with the average power in the absence of the resonant sites

$$P'_\nu = \frac{1}{2}\left(\pi R^2\right)|\mathcal{E}_\nu|^2(\omega\epsilon_0)\mathrm{Im}(\epsilon_\mathrm{r}). \tag{9}$$

When examining the ratio of the two,

$$\bar{P}_\nu \equiv \frac{P_\nu}{P'_\nu} \simeq \frac{|E_{z,\nu}|^2}{|\mathcal{E}_\nu|^2}\frac{\mathrm{Im}(\epsilon_\mathrm{s})}{\mathrm{Im}(\epsilon_\mathrm{r})} \leq \frac{\mathrm{Im}(\epsilon_\mathrm{s})}{\mathrm{Im}(\epsilon_\mathrm{r})}, \tag{10}$$

we find that the maximum is determined by $\mathrm{Im}(\epsilon_\mathrm{s})/\mathrm{Im}(\epsilon_\mathrm{r})$ as will be illustrated next.

Consider an ensemble of N resonant sites, immersed in a lossy medium characterized by ϵ_r=45-19.78j which is the dielectric coefficient of *gray matter* at 1GHz [5]. The radius of the RS's is $R = 1\mu$m whereas its length (Δ_z) is of the order of 1cm. Figure 2 illustrates the location of N=36 RS's distributed randomly over a 1cm^2 area - the circles do not represent the actual size of the cylinders. The darker, the colour, more power is absorbed and in the brackets we indicate the actual normalized power ($\bar{P}$) defined in Eq.(9) for $\mathrm{Im}(\epsilon_\mathrm{s})/\mathrm{Im}(\epsilon_\mathrm{r}) = 100$. It clearly shows that there are RS's where the *local* absorption is almost 100 times larger than the absorption at the same location in the absence of the RS's.

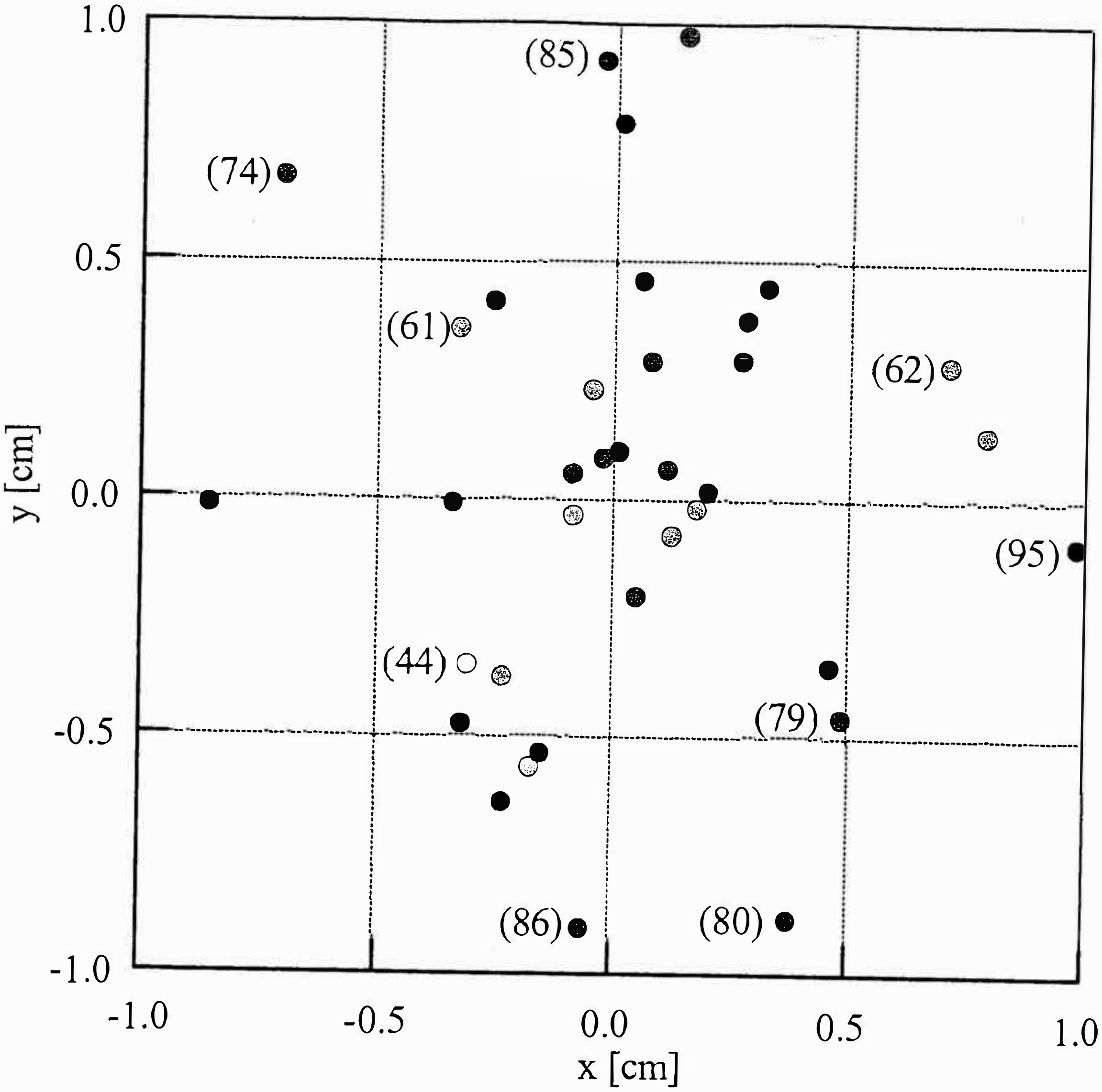

Figure 2: Configuration space of the resonant sites. Normalized power as a function of the location of the cylinder. The darker, the colour, more power is absorbed and in the brackets we indicate the actual normalized power ($\bar{P}$) defined in Eq.(9) for $\mathrm{Im}(\epsilon_s)/\mathrm{Im}(\epsilon_r) = 100$.

In spite the fact that locally the average absorbed power may be a few orders of magnitude larger than the average power absorbed in the background, for an *external* observer the change in the absorbed power due to RS's is practically undetectable. The *change* in the average power (δP) relative to the average power (P_0) absorbed in the absence of the RS's is

$$\frac{\delta P}{P_0} \simeq \frac{\mathrm{Im}(\epsilon_s)}{\mathrm{Im}(\epsilon_r)} \frac{N(\pi R^2 \Delta_z)}{V}, \tag{11}$$

where V is the volume of reference and it is of the order of 1cm^3. For the parameters mentioned above the volumes ratio is $\frac{N(\pi R^2 \Delta_z)}{V} \sim 10^{-6}$ and for $\text{Im}(\epsilon_\text{s})/\text{Im}(\epsilon_\text{r}) = 100$, the relative power change is anticipated to be less than

$$\frac{\delta P}{P_0} \leq 10^{-4} \,. \tag{12}$$

Clearly intrinsic fluctuations, for example those associated with the blood flow, may cause changes that are larger than this value and as such, an external observer will be unable to detect such variations. Moreover, the expression in Eq.(10) is an upper limit at resonance. Off resonance, the relative change in the absorbed power is significantly smaller. With this regard, the mechanism presented here differs from effects investigated in the past [6-8] where broad band quasi-static electromagnetic pulses were applied outside the scull in order to stimulate nerves that activate limbs [6] or the auditory system [7]. For the activation of the resonant sites considered in this study a narrow band spectrum is sufficient.

Beyond the local increase in the dissipated power, the increase in the local current density reflects also an increase in the local *magnetic field*. The effect of the latter may be significantly more profound than the local increase in temperature since the magnetic field may, affect the interaction rates of chemical or even biological processes e.g. free radicals [9]. Moreover, the increased current density that may develop in these resonant sites, may affect internal cells or molecules via non-thermal effects since the motion of the charge (e.g. electron) along microscopic distances may become ballistic. Consequently, chemical bonds may be broken as the kinetic energy of a local charge may easily exceed $k_B T$. Recall that in our example the local power absorbed exceeds the average by a factor of 100 thus so is the kinetic energy of the charge.

In conclusion, we have demonstrated an interaction mechanism by which microscopic resonant sites of high quality factor immersed in a lossy background may *locally* absorb electromagnetic power that is by orders of magnitude larger than that absorbed in the background. In parallel, since the volume of these microscopic resonant sites is assumed to be very small relative to the control volume, an external observer will detect no change in the *global* absorption. Nevertheless, the motion of the charge may become ballistic therefore non-thermal effects may become crucial.

References

[1] Michaelson S.M. and Elson E.C.; *Modulated Fields and "Window" Effects*, In Polk C. and Postow E. editors "Biological Effects of Electromagnetic Fields", Boca Raton, FL: CRC Press 1996 p.435-533.

[2] International Commission on Non-Ionizing Radiation Protection, *Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300GHz)*, Health Physics, **74**(4), p.494-522 (1998).

[3] "Biological Effects and Exposure Criteria for Radio-Frequency Electromagnetic Fields", National Council on Radiation Protection and Measurements, 7910 Woodmount Ave.Bethesda, MD 20814; NCRP Report N0. 86, Issued April 2, 1986, p. 277. See also Barber P.W., Gandhi O.P., Hagmann M.J. and Chatterjee I.; *Electromagnetic Asorption in a Multylayered Model of a Man*, IEEE Trans. on Miomedical Engineering, Vol. **BME-26**, p.400 (1979).

[4] Kirschvink J., Kirschvink A.K. and Woodford B.; *Magnetic Biomineralization in the Human Brain* Proceedings of the National Academy of Science **89**, p. 7683 (1992). see also *Giving Personal Magnetism a whole New Meaning* Reported by Barinaga M.; Science, **256** p.967 (1992).

[5] Poster K.R., *Dielectric Properties of Tissue* in " The Biomedical Engineeing Handbook", Editor in Chief Bronzino J.D., CRC Press, Boca Raton, FL, 1995, p.1385

[6] van der Kamp W., *Magnetic Stimulation of the Brain: Starting or Stopping.* Clinical Neurology and Neurosurgery, **94**, p. 159-160 (1992).

[7] Counter S.A., Borg E., Bredberg B., Linde G. and Vainio M.; *Electromagnetic Stimulation of the Auditory System of Deaf Patients* Acta Otolayngol. (Stock) **114** p. 501-509 (1994).

[8] Beric A., *Transcranial Electrical and Magnetic Stimulation* in "Electrical and Magnetic Stimulation of the Brain and Spinal Cord", edited by Devinsky O., Beric A. and Dagali M., Raven Press Ltd., New York, 1993 p. 29.

[9] McLauchlan M., *Are Environmental Magnetic Fields Dangereous* , Physics World, January, p. 41-45 (1992).

The *Center for Communication and Information Technologies* (CCIT)

is managed by the Department of Electrical Engineering.

This Technical Report is listed also as

EE PUB #1296, November 2001.