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Interactions between radiofrequencies signals and living organisms

The brain is not a radio receiver for wireless phone signals: Human tissue does not demodulate a modulated radiofrequency carrier ☆

Le cerveau n'est pas un récepteur radio pour les signaux de téléphone mobile : Les tissus humains ne démodulent pas une porteuse radiofréquence modulée

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A B S T R A C T

It has been suggested that the low frequency modulations of the radiofrequency (RF) signal from a wireless phone could be demodulated by human tissue. If this occurred it could lead to interactions with ions in the tissue, with possible biological consequences. In recent experiments it has been shown that biological cells do not exhibit significant electrical nonlinearity to be able to demodulate low frequency signals present as modulations of a RF carrier. This makes irrelevant any hypothetical interactions between RF electromagnetic waves and biological systems involving such demodulation mechanisms. Your wireless phone is not an athermal hazard to your brain.

R É S U M É

Il a été suggéré que les modulations basse fréquence des signaux radiofréquences émis par un téléphone sans fil pourraient être démodulées par les tissus humains. Si cela arrivait, cela pourrait induire des interactions avec les ions des tissus et entraîner d'éventuelles conséquences biologiques. Au cours d'expériences récentes, il a été montré que les cellules biologiques ne présentaient pas de non-linéarités susceptibles de démoduler ces signaux basses fréquences. Ceci écarte toute hypothèse d'interactions entre les ondes radiofréquences et les systèmes biologiques liées à de tels mécanismes de démodulation. Le téléphone mobile n'induit pas de risque athermique pour votre cerveau.

1. Introduction

Despite an overwhelming preponderance of evidence to the contrary [1–3], there continues to be some public concern that human exposure to radio frequency (RF) radiation, at the low levels involved with environmental exposure and wireless phone usage, can constitute a health hazard. International safety guidelines have been promulgated that limit human exposure to RF radiation [4,5]. These guidelines generally limit exposure to fifty times lower levels than have been observed to lead to behavioral changes in animals. There is a consensus that exposures that cause behavioral change reflect the an-

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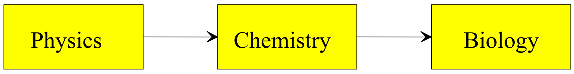

Fig. 1. The essential steps for any physical interaction leading to a biological effect.

imal reacting to the thermal loading of the exposure. Even at exposure levels that lead to behavioral change because of the response of the thermoregulatory system there is no plausible evidence of any health consequences, even for humans exposed to thermal levels of RF [6]. The hypothesis has been advanced that nonlinearities in living tissue could provide an interaction mechanism that might constitute a health hazard at non-thermal exposure levels [7–13]. Despite this hypothesis, and other un-replicated claims to the contrary, no plausible interaction mechanism for health consequences, other than heating at large enough exposure levels, has been demonstrated [14]. There are, however, plausible interaction mechanisms between low frequency electromagnetic (EM) fields and biological systems. Evolution has even provided examples of extraordinary sensitivity of animals to weak electric and magnetic fields, such as in the elasmobranch family of fishes, magnetotactic bacteria, and in the navigation of birds and bees [15–22], but these sensitivities exist only at low frequencies, below about 1 MHz. It has been postulated that low frequency modulations of RF carriers could provide a mechanism for biological interaction [11–13]. It is worth pointing out that in the case of mobile wireless communication devices used to transmit voice and data, there are no low frequency EM fields emitted from the antenna. Only RF carriers with sidebands are present. Nonetheless, the possibility remains that if biological cells are electrically nonlinear, then modulated RF carriers could be demodulated within tissue and provide low frequency fields with potential biological activity. This is akin to ascribing to biological cells the nonlinearity provided by the diode in the front end of a radio receiver. It is the purpose of this article to examine this hypothesis.

2. Interaction mechanisms

As pointed out by Professor Jim Weaver of MIT [23] any biological effect produced by RF radiation *must* follow the sequence of steps shown in Fig. 1. No biological change can result from RF irradiation without a preceding chemical change, and no chemical change can occur without a preceding physical interaction with the RF radiation. These facts are incontrovertible: effect must follow cause. Let us examine the mechanisms by which RF radiation can and cannot interact with a biological system.

2.1. Dipole relaxation

The electric field of a RF electromagnetic wave polarizes any medium through which it passes. Atoms or molecules acquire an induced polarization: they are made into dipoles. Molecules with a permanent dipole moment will be preferentially aligned along the direction of the applied electric field. All of these phenomena are included in the frequency dependent *dielectric constant* $\epsilon_r(\nu)$ of the medium, which in general is a complex number defined as

$$\epsilon_r(\nu) = \epsilon'(\nu) - j\epsilon''(\nu)$$

where $j = \sqrt{-1}$. The imaginary part of the dielectric constant is responsible for energy absorption from the electromagnetic wave. The induced polarization and the applied electric field in general are not in phase, because the field is oscillating and the dipoles of the medium have to follow this oscillation. The larger a molecule is, the more difficult it is for that molecule to follow the alternating electric field. Water molecules, which are generally abundant in biological systems can follow the oscillating electric field up to frequencies of about 17 GHz, but lag behind in phase even at wireless phone frequencies. The attempts of a molecular dipole to oscillate within a medium inevitably leads to collisions between molecules, a kind of “friction”, which is how a microwave oven heats food. Larger molecules such as proteins can only follow the oscillating electric field at relatively low frequencies, typically below 1 MHz [24].

2.2. How much heating might result from use of a wireless phone?

Typical wireless phones used in mobile cellar-based communication systems emit total RF powers below 1 W. The latest phones available in the market generally emit a maximum of 200 mW, which is automatically adjusted during use, depending on the distance between the user and the nearest base-station and the local operating environment [25]. Since a wireless phone is commonly used in close proximity to the head it is not surprising that public concern over wireless phone safety has focused on brain exposure, and the possibility of brain cancer. Notwithstanding the fact that the incidence of brain cancer is not increasing in those countries where such usage is most extensive and has gone on for the longest time [26], this fear persists. Because it is not practical to actually measure the temperature increase in the brain as a result of wireless phone use, this temperature rise must be modelled. In the simplest of models the entire output power of the phone is imagined to be focused into the smallest volume of the brain allowed by the wavelength of the electromagnetic waves. If the only avenue for heat removal is thermal conduction through brain tissue the estimated maximum temperature increases are on the order of 0.5 °C. More sophisticated modeling that includes the effects of blood perfusion and the heterogenicity of the tissue suggests that the maximum temperature increase anywhere in the brain does not exceed 0.2 °C [27–30] for a phone that is compliant with international exposure standards (a maximum specific absorption rate (SAR) of 1.6 W/kg averaged over any 1 g of tissue) [31]. Such small localized temperature increases are generally regarded as physiologically inconsequential because they lie within the normal range of diurnal body temperature variations [32].

2.3. Ion motion

Free charged particles in biological systems, such as sodium, potassium, or calcium ions will oscillate about their equilibrium position under the action of an oscillating electric field. At any reasonable field strength, however, these oscillations are inconsequential. For example, for a light ion such as Na^+ and a field strength of 10 V/m in an aqueous medium, which corresponds approximately to a wave intensity of 1 mW/cm^2 then the amplitude of oscillation at 1 GHz is about 10^{-12} m if damping is neglected, much smaller than the size of the ion itself. In a condensed medium drag on ion motion reduces this amplitude considerably, and as pointed out by Moulder et al. [33] the amplitude of motion is smaller than the size of an atomic nucleus. Low frequency fields do, however, have the ability to move ions in biological systems, and the possibility of biological effects from such motion cannot be discounted.

2.4. Bond breakage

Biological molecules are connected by chemical bonds, the weakest of which are the hydrogen bonds, for example, between the base pairs in the double helix. Such bonds can be as weak as 1400 cm^{-1} (1 $cm^{-1} = 1.2398 \times 10^{-4}$ eV), which is substantially greater than the characteristic thermal energy in a biological system at 37 °C, which is 215 cm^{-1}. A photon from a wireless phone at a nominal frequency of 1 GHz has an energy of 0.03 cm^{-1}, more than 6000 times smaller than kT. It can be concluded that there is no direct bond breakage of even the weakest chemical bonds by photons from a wireless phone. It has been postulated that large biological molecules such as DNA can have very low frequency vibrational modes that might extend down into the microwave region. If such modes exist they would be very heavily damped and would merely provide another avenue for heating of the underlying material through energy absorption. Multi-photon absorption is insignificant at RF exposure levels within safety guidelines because of the rapid thermalization of any absorbed energy. Molecules in biological systems are always vibrating because of their thermal energy, which is a natural state of any system in thermal equilibrium.

3. Demodulation of modulated RF signals

It has been postulated that low frequency modulations of RF carriers could provide a mechanism for biological interaction [11–14,34]. If a biological system were sufficiently nonlinear, and this mechanism could operate, then modulated RF carriers could be demodulated within tissue and provide low frequency fields with potential biological activity. This is akin to ascribing to biological cells the nonlinearity provided by the receiving diode in the front end of a radio receiver. Balzano has proposed an experimental test to determine whether biological systems are significantly nonlinear at wireless phone frequencies for this mechanism to be a cause for concern [35]. Of great importance is not so much showing whether cells ever behave nonlinearly or not, but over what frequency range they exhibit such behavior, and at what input RF flux levels. Any asymmetric ion transport process in a cell, for example, the transit of an ion through a membrane ion channel, could exhibit diode-like behavior, and at sufficiently low frequencies the electric properties of the membrane would appear nonlinear. For example, Barsoum and Pickard [36] showed that the cell membrane in electrogenic cells of *Chara braunii* and *Nitella flexilis* showed rectification properties at frequencies up to 10 MHz, limited by ion transit times through the membrane. Rectification by ion channels has been observed at higher RF frequencies at intense field levels for artificial channels in bilipid membranes by Ramachandran et al. [37].

4. The RF signals emitted by wireless phones

The RF electromagnetic waves transmitted from the antenna of a mobile wireless communication devices are modulated to transmit voice and data. But, they contain no low frequency EM fields. Only RF carriers with sidebands are present. Consequently, for the low-frequency demodulation of these modulated RF carrier waves an appropriate nonlinearity must be present in the biological system. There are many different modulation formats used in wireless communications, for example FDMA (*Frequency Division Multiple Access*), TDMA (*Time Division Multiple Access*), GSM (*Groupe Spécial Mobile*), CDMA (*Code Division Multiple Access*), UMTS (*Universal Mobile Telecommunications System*), etc. It is beyond the scope of this article to describe the spectral content of these different schemes, but in every case the wireless signal uses a specific RF or channel frequency. The ITU (*International Telecommunications Union*) has allocated various bands for wireless phone service: 806–960 MHz, 1710–2025 MHz, 2110–2200 MHz and 2500–2690 MHz with different frequency allocations for phone to base-station links (uplinks) and base-station to phone links (downlinks). The specific frequency bands used by UMTS phones are 1885–2025 MHz for the wireless phone-to-base-station (uplink) and 2110–2200 MHz for the base-station to-wireless phone (downlink). In the USA, 1710–1755 MHz and 2110–2155 MHz are used. TDMA, and CDMA use 825–845 MHz for uplinks and 869–894 MHz for downlinks; GSM uses various frequency bands in the range 851–1990 MHz for uplinks and downlinks, CDMA uses various frequency bands in the range 860–2400 MHz depending on the country of operation. The GSM protocol is the most used worldwide. Because this protocol transmits its RF signals in bursts, called "frames," which occur at much lower repetition frequencies than the RF carrier, there is a common misconception that the wireless signals transmitted by a phone contains low frequencies, which is entirely incorrect.

5. Nonlinearity and rectification in a biological system

It is a necessary condition for a modulated RF carrier to generate low frequency electric fields in a biological system that a nonlinearity must be present. In the most general case a nonlinearity is specified in terms of the nonlinear polarization produced by the electromagnetic field as

$$\mathbf{P} = \epsilon_0\left(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{E}.\mathbf{E} + \chi^{(3)}\mathbf{E}.\mathbf{E}.\mathbf{E} + \cdots\right)$$

where ϵ_0 is the permittivity of free space, $\chi^{(1)}$ is the linear susceptibility, $\chi^{(2)}$ is the second order nonlinear susceptibility, and so on. In general $\chi^{(1)} \gg \chi^{(2)} \gg \chi^{(3)}$, etc. The second order nonlinear susceptibility is absent in a centrosymmetric system such as a gas, liquid, or cubic crystal. If a biological system is significantly nonlinear, this should arise from $\chi^{(2)}$, and its presence would lead to demodulation of an RF carrier to generate low frequency fields in the system, and simultaneously the generation of the second harmonic frequency of the RF carrier.

A special kind of nonlinearity could arise through asymmetric ion transport processes. For example, if membrane ion channels behaved in this way the membrane channel would have the characteristic of a diode. A diode nonlinearity is the kind used to demodulate the RF carrier in a radio receiver. Whether the nonlinearity in a biological system results from diode-like behavior or from a general nonlinear susceptibility the consequences would be the same: demodulation and second harmonic generation would occur. This does not preclude higher order nonlinearities being present at the same time, but a third order nonlinearity, for example, would not produce low-frequencies through demodulation, although it would produce the third harmonic of an RF carrier. If there is diode-like behavior in the system, whether this leads to half wave or full wave rectification, a second harmonic signal results but in neither case is a third harmonic generated.

Magnetic nonlinearities are generally weaker then electrical nonlinearities, but if, for example, magnetite in a biological system provided the nonlinear response the consequences would be the same: demodulation and generation of the second harmonic. Therefore, as proposed by Balzano [35], the presence of nonlinearity in a biological system can be tested by a search for the second harmonic frequency generated by an irradiated biological system.

6. A search for nonlinearity in biological systems

To test whether biological cells and tissues are significantly nonlinear we have designed and carried out experiments to search for second harmonic generation from cells and tissues exposed to RF electromagnetic fields. We expose cells to low-level RF fields in a Petri dish placed in the center of a doubly-resonant cavity [38]. The cavity is designed to be resonant near 900 MHz in a TE111 mode and also at double this frequency in a TE113 mode. There is an antinode of both these modes in the center of the cavity where a biological sample is placed. The hypothesis is that if cells are nonlinear at frequency f, then they will generate frequency $2f$. This type of nonlinearity is what occurs in a radio receiving diode and is a prerequisite

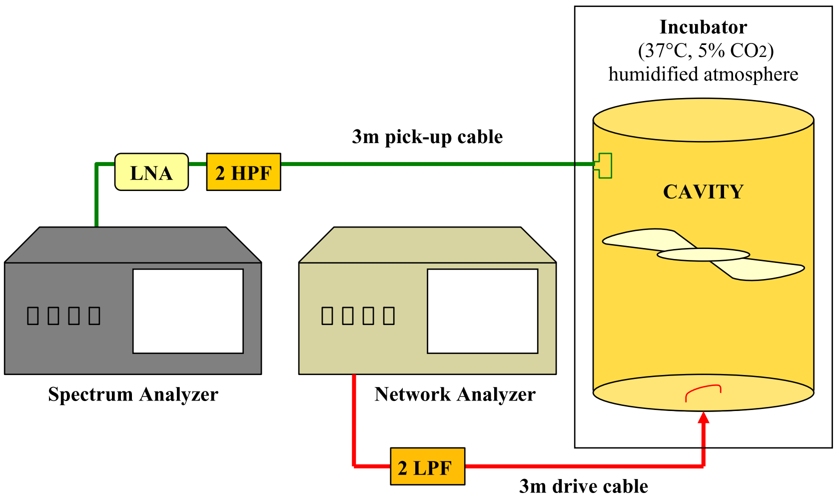

Fig. 2. Experimental arrangement for driving the cavity, measuring its Q, and detecting generated second harmonic. LNA – low noise amplifier, HPF – high pass filter, LPF – low pass filter. Structures indicated within the cavity are: the drive antenna for frequency f in the center of the bottom plate; the receive antenna for frequency $2f$ at the top left of the cavity; and the low dielectric loss support structure for the Petri dish in the center of the cavity.

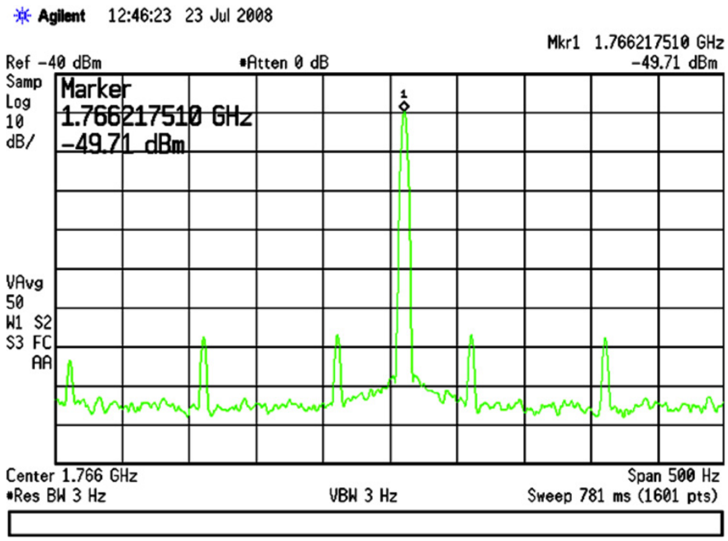

Fig. 3. Second harmonic signal at 1.7662 GHz produced by a miniature Schottky diode driven at frequency 883.1 MHz. The second harmonic signal is 80 dB above the measurement noise floor.

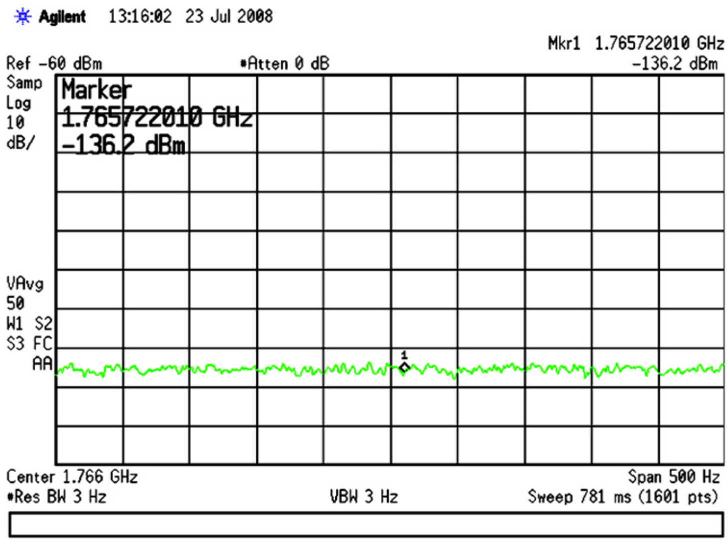

Fig. 4. Spectrum analyzer trace of the cavity response when it is loaded with IMR-32 human neuroblastoma cells showing no second harmonic at the expected frequency, in this case of 1.7657 GHz.

for the ability to demodulate an RF carrier. The characteristics of the cavity are: radius = 125.0 mm, length = 275.4 mm, unloaded Q $\simeq$ 1250, with dominant modes $TE_{111} \simeq 883$ MHz, $TE_{113} \simeq 1766$ MHz. As shown in Fig. 2 the cavity is driven with a very pure fundamental signal near 900 MHz, and the (high pass filtered) second harmonic signal is detected with a spectrum analyzer. Second harmonic generation is the lowest order nonlinearity that would demodulate an RF carrier. To verify the ability of the system to detect this we place a small Schottky diode in the center of the cavity, drive the cavity at its fundamental frequency f and record the strength of the second harmonic signal. Such a detected signal is shown in Fig. 3. The system can easily detect the second harmonic of a miniature Schottky diode with its leads removed, as well as showing that this second harmonic disappears when the diode is rotated to be orthogonal to the electric field in the cavity.

In contrast to Fig. 3, Fig. 4 shows the absence of any detectable second harmonic from a preparation of IMR-32 human neuroblastoma cells. We have studied several cell lines, and tissues. The samples studied have included: high density cell suspensions (human lymphocytes and mouse bone marrow cells); semi-confluent mono-layers of adherent cells (IMR-32 human neuroblastoma, G361 human melanoma, HF-19 human fibroblasts, N2a murine neuroblastoma (differentiated and non-differentiated), and CHO cells); and thin sections or slices of mouse tissues (brain, kidney, muscle, liver, spleen, testis, heart, and diaphragm). Viable and non-viable (heat killed or metabolically impaired) samples were tested. Further details of these biological experiments are provided by Kowalczuk et al. [39].

7. Conclusions

We have detected no second harmonic generation from any cells or tissue tested at levels down to the noise floor of our system at about −160 dBm with a fundamental drive power into the cavity of 0 dBm (1 mW). These inputs provide specific energy absorption rate (SAR) values ranging between 3 and 15 W/kg. Based on our measurements of many cell lines and tissue types it is clear that any nonlinearity they possess is far too small to be of any biological significance at the field levels involved in personal wireless communications. It would appear that evolution has not provided the functionality of a radio receiver in biological systems, despite the emergence of low frequency electromagnetic sensitivity in the animal kingdom.

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