Bioelectromagnetic phenomena are affected by aggregates of many radio-frequency photons

Michael Peleg

peleg.michael@gmail.com, michaelp@rafael.co.il, Israel

Abstract

This paper addresses the argument stating that since the energy of a single Radio Frequency (RF) photon is extremely small it cannot influence matter significantly and therefore RF radiation cannot cause cancer. The argument is shown to be wrong since most known phenomena and uses of RF radiation involve many photons acting in unison. For example, in a particle accelerator, a multitude of RF photons act simultaneously on a single elementary charged particle. We show that his holds for particle physics, capacitors, fluorescent tubes, radio communications, RADAR and living tissues. These phenomena are best treated in most cases by considering RF radiation as a wave phenomenon. On the other hand the possibility of a single RF photon per molecule producing a biological effect also cannot be ruled out.[1]

Keywords: radio frequency, photon energy, bioelectromagnetic, cancer, nonionizing radiation, black body radiation

Introduction

Radio Frequency (RF) radiation can be described by classical wave equations and can also be presented as a flow of photons which capture the quantum mechanical attributes. The dual nature of electromagnetic radiation lies at the foundation of modern physics. The individual electromagnetic photons possess energy given by:

$$E_p = h\nu \tag{1}$$

where h is the Planck constant. Equation (1) is Einstein's equation relating the photon's energy E_p in Joules (J) to its frequency ν in Hz.

RF comprises the electromagnetic spectrum of frequencies from about 0.5 MHz to about 200 GHz. In this paper I shall use a RF of 10^9 Hz or 1 GHz as a representative value for cellular transmission frequencies which typically occupy bands centered on 0.9 GHz and on 1.8 GHz. Since the frequency of 1 GHz is lower than that of a visible light by a ratio of about $5x10^5$, the energy of a single RF photon in eq. (1) is lower by the same ratio relative to the energy of a visible light photon. Energy of a visible light photon is about the minimum required to cause ionization, so clearly a single RF

[1] **This is the full paper version of the presentation at the *International Conference on Environmental Indicators (ISEI)*, 11 to 14 Sept. 2011 in Haifa , Israel**

photon cannot cause ionization. The term "non-ionizing radiation" which includes the RF radiation was coined due to this fact. Moreover, since the single RF photon energy is so tiny it should have no significant effect on most molecular level changes in matter. The energy of a photon associated with a power-line electromagnetic field is lower by a further ratio of about $20x10^6$.

The extremely low energy of the single RF photon is the basis of the argument claiming that since a single RF photon can have no significant influence on matter it cannot cause cancer. A recent example of this argument is by (Shermer, 2010). This argument is of great significance. If it would be a scientific fact then the recent classification of RF radiation as a possible carcinogen for humans by the International Agency for Cancer Research (IARC) could be discarded and RF radiation could be used without health concerns at any level permitted by the International Commission for Non-Ionizing Radiation Protection (ICNIRP) thresholds as indeed recommended by (Shermer, 2010). On the other hand, if it is a mistake, it will impede preventive action and endanger human lives as shown in reports indicating a carcinogenic influence such as (Hardell et al., 2007; Stein et al., 2011; Sato et al., 2011; Peleg, 2009) and references therein.

In this paper we shall show that the above argument is fallacious. While it is true that a single RF photon will not affect a biological change, it is erroneous to conclude that cells are not affected by multitudes of photons acting in unison. We shall demonstrate that most the known phenomena and uses of RF radiation on the surface of this planet involve joint action of many RF photons producing effects by their aggregated energies, in some cases those act on a single elementary particle. There is no basis to claim that biological interactions must be different.

Previous work by Vistnes and Gjotterud (Vistnes and Gjotterud, 2001) presented an in depth analysis of power-line and RF waves and photons based on well established physical principles and reached essentially the same conclusion as this paper while focusing on power-line frequencies. They showed that, at power-line and also at radio frequencies, an analysis based on waves and fields is more straightforward then the one based on photons since the quantum attributes of the RF fields are irrelevant to many problems and pointed out that photons are rarely useful to analyze interaction between RF fields and molecules and cells also due to the photons being macroscopic objects of diameter of at least a wavelength which is about 30 cm at 1 GHz, and due to simultaneous presence of many identical photons at each point in space in the examples they provided.

The paper (Vistnes and Gjotterud, 2001) showed clearly that interaction of electromagnetic fields with matter is not limited in many cases by the tiny energy of a single photon. However, since claims stating the contrary such as (Shermer, 2010) still do appear, we describe and analyze in the following sections some interactions of RF fields with matter and examine common uses of RF radiation to further validate the conclusion in the RF range.

This article does not attempt to identify the specific cancer causing mechanisms. Those do not have to include direct ionization to cause cancer as evident for example from (Wenner, 2009) which shows that even subtle changes in the positions of chromosomes have a significant biological effect.

Before proceeding to physical considerations it is in order to mention a few biological illustrative counter-examples to this argument. A case-case study (Sato et al., 2011) relating cell phone use and acoustic neuroma estimated the incidence of acoustic neuroma for users of mobile phones for more than twenty minutes a day as three times the national average while advising caution in interpreting the results. Volkow et al. (2011) examined the effects of cellular telephone usage on brain glucose metabolism. The result of this study is that metabolism was significantly higher in the brain region close to the antenna when the cell-phone was on. Friedman et al. (2007) identified activation of a molecular level protein mechanism of a living cell by a low intensity RF radiation. Many other related results were reported.

High energy examples of multi- photon effects

Those effects are not expected to occur in a human body. They are presented to demonstrate the most dramatic interactions known of a multitude of RF photons with one elementary particle.

Particle accelerators: Particle accelerators used in high energy physics research accelerate charged elementary particles to relativistic velocities by transferring energy from RF fields to those particles. Thus RF photons are capable to energize elementary particles to vastly greater levels then required for mere ionization and energies of billions of RF photons are aggregated on a single particle. This does not mean that something similar takes place inside a human body but it does demonstrate the absurdity of the low energy RF photon argument and also shows that the term "non-ionizing radiation" does not imply that ionization by RF radiation is impossible.

Waveguides: High power microwave fields in waveguides and similar structures induce discharge and acceleration of electrons and ions and subsequent emission of X-rays. See (Neuber et al., 1997) for a one example. This is similar in principle to the previous example but it involves lower energies and the transfer of ionizing energy from many RF photons to single elementary particles and X-rays is not a part of the design but an unintentional malfunction.

Fluorescent tubes: It is a well known phenomenon that fluorescent tubes glow with visible light when placed near an antenna of a high power RF transmitter. Here again the aggregated energies of about $5x10^5$ RF photons (see above) are transferred to a single visible light photon by a complex physical process.

Effects at energy levels relevant to the human body

This section demonstrates the possible aggregation of many RF photon energies on a single molecule or a cell in a living tissue when the RF field is strong and the frequency is low and examines the energy available in the RF radiation.

Water-filled capacitor: Let us consider alternating voltage on a water-filled capacitor. The water molecules are rotated by each cycle of the electric voltage and the amplitude and energy associated with each rotation are dependent on the voltage but not on the frequency. This holds for frequencies in the range of zero to 1GHz since the dielectric constant of water is quite stable in the zero to 1GHz frequency range and beyond it. Easy calculation in the appendix shows that water molecule at the highest electric field is capable to hold energy of a few RF photons at 1GHz. If the electric field is represented as photons, then the number of photons required to rotate one molecule is inversely proportional to the frequency because the energy of each photon is proportional to frequency. Thus the number of photons influencing each water molecule tends to infinity for frequency tending to zero. This example shows that the small energy of a single RF photon is irrelevant to arriving at conclusions about the effect of the electromagnetic field on the molecules in this type of setup. It demonstrates too that it is possible to induce energy of more than one photon on any polarized molecule or cell in a living tissue by applying an electric field. In practice a low frequency below that of RF range may have to be used to reduce the required field strength. The actual mechanisms causing the observed biological effects are probably much more complex than this example.

The energy available in RF radiation: The energy of a few 1 GHz photons imparted on a single water molecule in the last example is still small, so more energetic interactions should be looked for. The polarization energy in the last example is related to the energy contained in a given small volume at any instant. Since the radiation propagates by the speed of light, the RF energy contained in a given small volume at any instant is much smaller than the energy of the radiation which passes thru the same volume during a short time interval. For example, as a straightforward calculation in the appendix reveals, at radiation level set by the Israeli safety limit of 50 microwatts/cm^2, the energy passing each microsecond thru a sphere of a radius of 1 micron is 9.8 electron-volt (energy of 2.37x10^6 1GHz photons) while the energy inside the sphere at any instant is a mere 4.36x10^{-8} electron-Volt (eV). See the illustration in

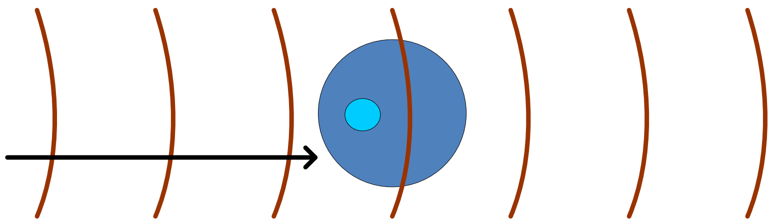

fig.1.

Figure 1, RF radiation passing thru a small sphere

Thus future research should search also for complex interactions capable of accumulating the RF energy over some short time interval comprising many RF cycles.

Relevance to further research: Friedman et al. (2007) identified activation of a specific molecular level protein mechanism of a human cell by a low intensity RF radiation. Other effects on the living tissue were reported. Thus some effects and biological processes initiated by RF radiation are identified accurately at the molecular level.

Still the exact mechanisms of interaction between the RF field and living tissue which causes those biological effects must be found yet. There are large structures in the human body with distinct electromagnetic properties such as blood vessels and nerves which might function as antennas to couple into the electromagnetic field and concentrate the resulting energy in a small volume as is done in a communication receiver. However the results reported in (Friedman et al., 2007) and in other numerous in vitro studies identified biological effects of RF radiation on separated living cells floating in a homogenous solution without any large antenna-like structures. Thus we should look also for direct interactions between RF radiation and cellular or chemical processes. The interaction mechanisms may be expected to be very complex as is the living tissue itself, thus state of the art physics, chemistry and biology will be required to identify them. Indeed, initial interesting research attempting this has been reported, e.g. (Markov, 2011) and its references.

Radio communications and thermal noise

The analysis in this section shows that most observed phenomena and useful effects of RF radiation on the surface of this planet, including cellular phones, involve a joint action of many RF photons the aggregated energy of which usually passes thru a transistor gate of a size comparable to a living cell nucleus. A single photon is noticeable only in environments cooled to near absolute zero temperatures. Thus effects involving many photons are to be expected also in biology.

Black body radiation: The black body (background) radiation is a universal thermodynamic phenomenon present everywhere on the surface of the Earth. Its intensity depends on the absolute temperature only, and is derived analyzing a large black walled enclosure. There are countable possible standing wave patterns in the enclosure (cavity), see fig. 2.

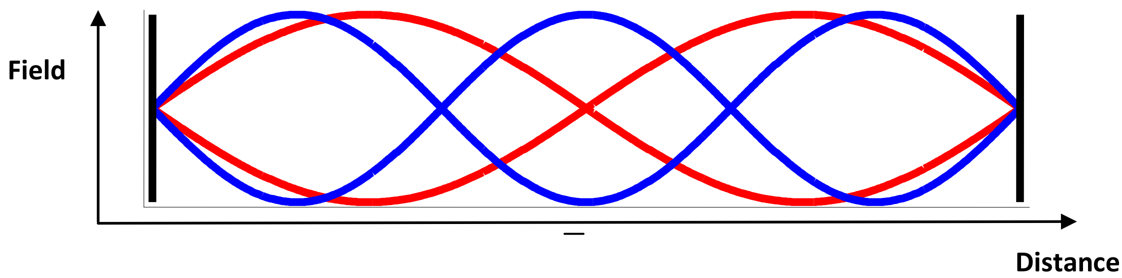

Figure 2 , standing wave patterns in a one-dimmensional enclosure

Each pattern corresponds to a possible photon. There are about $N_n \cong 6250$ identical indistinguishable photons populating each wave pattern at 1GHz at room temperature, see the appendix. This demonstrates that the simultaneous presence of many RF photons at any point acting in unison as described in the examples in (Vistnes and Gjotterud, 2001) is valid for RF anywhere on the surface of the Earth. Almost all useful man-made RF radiation is stronger than the background radiation to avoid being masked by it.

The black body radiation is a prominent example of a phenomenon described very well by classical physics at RF while at ultraviolet frequencies an analysis based on photons and on quantum mechanics is required.

The thermal noise: The thermal noise is a universal limit on the performance of RF receivers. It is received at all antenna terminals as the background radiation above produced by warm objects such as trees, ground, houses and clouds and is generated in all lossy circuits by thermal fluctuations of charges. Thus it is present as varying electrical voltage at all antenna terminals and in all electronic circuits. Its power spectrum density N_0 watts/Hz [2] at a temperature of 300 ^{O}K, see for example (Ziemer et al., 1985), is:

$$N_0 = kT = 4.14 10^{-21} \text{ J} \qquad (2)$$

where T is the absolute temperature and k is the Boltzmann constant. The power spectrum, when at thermal equilibrium, is dictated by temperature and by the laws of thermodynamics. The noise is known to have a Gaussian distribution caused by many RF photons contributing to each noise sample. Typical communication receiver filters and samples the antenna output. The average energy of one sample of the noise in a typical setup, see the appendix, is equal to the noise power spectral density N_0. Thus at RF of 1GHz, each sample of the omnipresent noise carries energy of $N_n = N_0 / E_p \cong 6250$ RF photons where E_p is determined by eq. (1). A similar derivation in the context of matched filters used to optimize reception in communication and RADAR receivers e.g. (Ziemer et al., 1985) shows that the noise energy at each sample of the matched filter output involves again the energies of N_n photons. The communication received signal in most communication receivers cannot

[2] Watts/Hz = J/Sec/Hz --> J

be much weaker than the noise in order to be useful and not masked by the noise. Thus most the observed phenomena and uses of RF radiation such as radio communication and RADAR involve the joint effect of many RF photons acting in unison at each sample. There are a few exceptions to this such as Global Positioning System receivers using sophisticated spread spectrum signals to overcome the noise.

The only way to observe single RF photons would be by getting rid of the thermal noise which can be done only by extreme refrigeration and by pointing large directional antennas towards the cold outer space. This is conceivable in deep space communication and radio astronomy and is irrelevant to RF terrestrial communications.

Photons used to transmit a bit of information: Radio communication systems need some received energy in Joules (J), denoted E_b, to transmit each bit of information in the presence of receiver noise, the spectral density in J of which is denoted N_0. The required minimal ratio at the receiver, denoted E_b/N_0, is a central motive in information theory and in communication engineering. It is well established that E_b/N_0 is larger than ln(2) for any reliable communication. See for example (Ziemer et al., 1985) for an overview of this classic information theory issue.

Then the number of photons $N_p = E_b / E_p$ used by a cellular phone to receive each single bit of information is at least

$$\mathrm{N_p} \geq \mathrm{N_0} \cdot \ln(2) / \mathrm{E_p} \cong 4300$$

That is, every cell-phone system operating at 1GHz uses at least 4300 radio-frequency photons operating in unison to receive each bit of information. The combination of the photon energies happens in the receive antenna, there is no subsystem in the cell-phone receiver engineered to combine photons. Furthermore, all the combined energy is funneled by a simple metal-insulator transmission line structure thru a space smaller than 1 micron (base of a transistor in an amplifier) which is comparable to a size of a chromosome and is smaller than a human living cell nucleus. (The actual number of photons at a given instant is influenced somewhat also by error correcting codes and is usually larger than the one stated above due to operating margins of the receiver.)

Human exposure to radiation related to communications and to RADAR: In many communication systems the exposure levels of humans are vastly higher than the thermal noise which the signal must overcome at the receiver, especially if the exposed human is significantly nearer to the transmitter then the intended receiver. This happens, see fig.3, when transmitting with a cell phone held against the head of the user to a distant base station or if the humans are in the vicinity of a base station transmitting to distant cellular phones.

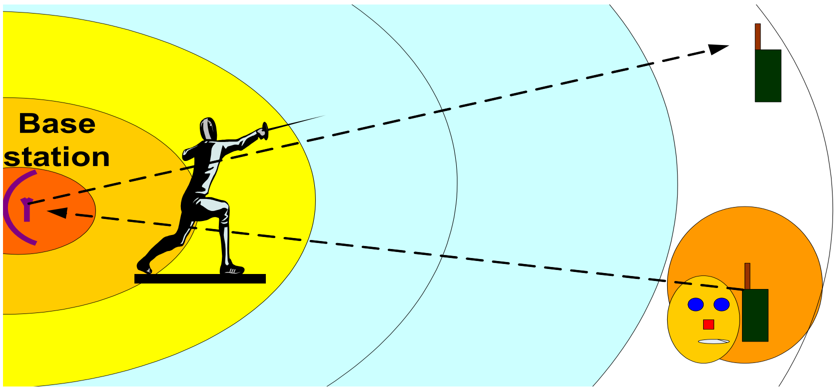

Figure 3, RF communication scenario

In those cases the RF energy available to cause biological effects is vastly larger. For example the probably safe radiation level threshold of 0.1 microwatt/cm^2 recommended recently by the Parliamentary Assembly Council of Europe (PACE), see (PACE, 2011), is higher by a factor of 5x10^6 relative to the radiation density of the thermal noise summed over all frequencies up to 1 GHz, see the appendix. The current exposure limits are usually higher than the PACE recommendations, examples in microwatts/cm^2 at 1 GHz are: Switzerland: about 3; Israel: 50; ICNIRP general: 500; ICNIRP occupational: 2500.

In RADAR systems the exposure levels are still higher due to the need to reflect a tiny portion of the radiated energy to the receiver by the target.

The relevance of the RF photon concept to some phenomena

Single RF photons do interact with molecules in some cases, mainly in atomic clocks, in Microwave Amplification by Stimulated Emission of Radiation (MASER) devices, and millimeter wave absorption lines. In these phenomena the energy states of molecules govern the exact energy which is transferred per molecule when interacting with the RF field. The transferred energy and the frequency of the RF field are related by eq.(1), thus the energy per molecule exchanged with the RF field is the energy of a single RF photon. This is different from the other phenomena described in this paper, some of which exhibit energy transfer of many RF photons to a single molecule. The strength of the RF field does not influence the very small energy transferred to each molecule, however, as well known, it does increase the rate of such photon emission and absorption events by a factor equal to the ratio of the energy density of the RF field to that of the black body radiation, for example by 5x10^6 as presented in the human exposure section above. Also those transitions may be synchronized between the molecules by the RF field similarly to MASER. I think that the biological effects of such influence of single RF photons on the very complex molecules such as DNA cannot be ruled out.

Conclusions

The energy imparted by RF radiation to objects and to particles is not limited by the quantum energy of a single RF photon.

RF radiation interaction with objects at temperature at Earth surface is in most cases better represented by waves then by photons and most of the associated analytical work uses waves rather than photons with some exceptions such as MASER.

Most of the research into effects and uses of RF radiation at Earth surface temperature starting with the early radio communication is done on effects involving many photons. Thus the idea of confining the research on carcinogenic influence of RF radiation to the effects of single RF photons would be absurd.

Combination of energies of many radio-frequency photons inside the human body is relevant to research on biological processes as it is to almost all the other known effects of RF radiation. Still there is also a possibility that single photon effects mentioned in the last section are relevant to biology.

The exact mechanisms of interaction between the RF fields and living matter are an intriguing subject for further research.

Acknowledgment

I wish to thank Zvi Weinberger for his valued expert advice which improved the quality of this paper.

Appendix: Calculations of the values used in the paper.

All the numerical values are rounded.

Constants:

Boltzmann constant	1.38×10^{-23} J/^{O}K
One electron Volt (eV) is	1.6×10^{-19} J
Photon energy at 1 GHz, eq. (1):	$E_p=6.626*10^{-25}$ J=4.14*10-6 eV
Avogadro constant:	$a=6\times10^{23}$/mole
Vacuum permittivity:	$\varepsilon_0 = 8.85\times 10^{-12}$ F/m

Number of RF photons per polarized water molecule in the capacitor example:

Energy density related to polarization of a dielectric such as pure (distilled) water is given by

$$u = \frac{1}{2}\varepsilon\varepsilon_0 E^2$$

where E is the electric field strength. Calculating u for the approximate breakdown field strength of water of E=40x10^6 Volts/m and relative dielectric constant of ε =80 yields 5.66x10^5 J/m^3. Multiplying by the mole volume of water of 18x10^{-6} m^3 and dividing by the Avogadro constant yields 1.7x10^{-23} J/molecule. Dividing the result by the photon energy yields the count of about 26 photons. This result depends on the breakdown field strength of water which may be even higher than the conservative value used here.

Energy in a small sphere, see figure 1.

Here it is convenient to use the cm instead the m length units. Let us examine a RF radiation comprising plane waves of intensity d microwatts/cm^2 crossing a small sphere of a radius R cm. The energy passing thru the sphere in a second is d times the cross section of the sphere. Over T seconds this is:

$$E_{pass} = T\pi R^2 d \qquad (3)$$

Since the radiation moves at the speed of light of 3x10^{10}cm/sec, the energy density will be

$$u = \frac{d}{c} \qquad (4)$$

micro-joules/cm^3. The energy E_{sphere} of the radiation present at any instant inside the sphere is u times the sphere volume,

$$E_{sphere} = \frac{d}{c}\frac{4\pi R^3}{3} \qquad (5)$$

Substituting into the equations (3) and (5) the values d=50 microwatts/cm^2, R=10^{-4} cm, T=10^{-6} seconds and translating to eV yields the results used in the article for the R=1 micron sphere and a time of T=10^{-6} seconds.

Number of photons per standing wave pattern at 1 GHz in the black body radiation section:

By standard thermodynamics the energy per thermodynamic degree of freedom is kT/2. Each standing wave pattern supports 2 degrees of freedom due to 2 waves with a quarter of 1/f time difference. Thus at T=300 ^{O}K the number of photons per wave pattern is:

$$\mathrm{N_n} = kT/\mathrm{E_p} \cong 6250 \ .$$

Thermal noise energy related to a single received sample in a communication receiver in the thermal noise section:

The noise with spectral density N_0 is filtered to an arbitrary bandwidth B. The sampling is carried out at the standard Nyquist frequency which also equals B. The power of the noise filtered to a bandwidth B is N_0B. The energy per sample is integral of the power over the sampling interval of length 1/B resulting in N_0B/B = N_0.

Thermal noise radiation density in the human exposure section

Black body radiation density at RF is given by the Rayleigh–Jeans law, the low frequency approximation of Planck's law:

$$D = \frac{2\pi\nu^2 kT}{c^2} \qquad (6)$$

D is radiation density in watts/m^2/Hz, ν is frequency in Hz, k is the Boltzmann constant, T is temperature in ^{O}K and c is the speed of light in m/second. The last equation applies at the wall of a cavity, the radiation passing thru a (two sided) unit area inside the cavity is twice as large. Integrating eq. (6) over frequency yields the power density in the frequency band of zero to f:

$$P_D(f) = \int_0^f \frac{4\pi\nu^2 kT}{c^2} d\nu = \frac{4\pi f^3 kT}{3c^2} \text{ watts/m}^2 \qquad (7)$$

where f is the maximal frequency. At f=10^9 Hz and T=300 ^{O}K this yields 1.9x10^{-8} microwatts/cm^2 used in the comparison with the PACE threshold of 0.6v/m which corresponds to 0.1 microwatt/cm^2.

References

Friedman J., Kraus S., Hauptman Y., Schiff Y., Seger R.: "Mechanism of short-term ERK activation by electro-magnetic fields at mobile phone frequencies" *Biochem* J. 2007; 405(3):559-568.

Hardell L. O., Carlberg M., Söderqvist F., Mild K.H. and Morgan L.L., "Long-term use of cellular phones and brain tumors", *Occup. and Environm. Medicine 2007;64:626-632.*

Markov M." Nonthermal mechanism of interactions between electromagnetic fields and biological systems: a calmodulin example" Environmentalist 31:114–120. (2011) DOI 10.1007/s10669-011-9321-1

Neuber, Dickens, Hemmert, Krompholz, Hatfield and Kristiansen: "Window and cavity breakdown caused by high power microwaves", IEEE *International Conference on Plasma Science*, 19-22 May 1997, San Diego, p. 191

PACE (Parliamentary Assembly Council of Europe), "The potential dangers of electromagnetic fields and their effect on the environment" , Doc. 12608, 6 May 2011

Peleg, M.: "Report on a cancer cluster in an antenna ranges facility," *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems (COMCAS), 2009.* , 9-11 Nov. 2009

Sato Y., Akiba S., Kubo O., Yamaguchi N.: "A case-case study of mobile phone use and acoustic neuroma risk in Japan" *Bioelectromagnetics*, 2011, 32:85-93.

Shermer M. : "Can You Hear Me Now? The Truth about Cell Phones and Cancer; Physics shows that cell phones cannot cause cancer", *Scientific American* 303, 98 , October 2010

Stein Y., Levy-Nativ O., Richter E.D.: "A sentinel case series of cancer patients with occupational exposures to electromagnetic non-ionizing radiation and other agents", *Eur. J. Oncol.* - Vol. 16 - N. 1 - March 2011

Vistnes A. I. and Gjotterud K.; "Why Arguments Based on Photon Energy may be Highly Misleading for Power Line Frequency Electromagnetic Fields" *Bioelectromagnetics* 22:200^204 (2001)

Volkow N. D., Tomasi D., Wang G. J., Vaska P., Fowler J. S., Telang F., Alexof D., Logan J. Wong C.: "Effects of Cell-phone radiofrequency signal exposure on brain glucose metabolism" *Journal of the American Medical Association* **305** 808-813 2011

Wenner M.: "Nuclear Architecture" *Scientific American* , Oct. 2009, 301(4): 9-10.

Ziemer R.E. and Peterson R. L.: *Digital Communications and Spread Spectrum Systems*, Macmillan publishing company, New York, 1985