A Thermodynamic Perspective on the Interaction of Radio Frequency Radiation with Living Tissue

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Abstract The existence of biological effects of radio frequency (RF) radiation on living tissue is well established, including also effects which are not caused by plain warming. Still the exact mechanisms of interaction between the RF radiation and the living tissue are mostly unknown. In this work a thermodynamic perspective relevant to some aspects of those yet unknown mechanisms is presented. This perspective reveals that living tissue under RF radiation should not be assumed to be in thermal equilibrium since it is governed by two temperatures: The ambient temperature of its surroundings and a vastly higher temperature T_R which is assigned by certain criteria to the RF radiation. The criteria presented here to determine the radiation temperature T_R are not unique and other approaches may lead to different temperature values, however T_R as presented here has an interesting physical significance. The possible relevance of this approach to the interaction mechanisms is presented.

Keywords: radio frequency, thermodynamics, statistical physics, biology, electromagnetic, cancer, nonionizing radiation, black body radiation

INTRODUCTION

The existence of biological effects of radio frequency (RF) radiation on living tissue including those which cannot be explained by plain warming is well established by works such as (Friedman et al., 2007; Mashevich et al., 2003) and many others which identified specific biological effects on cells and organs. Carcinogenic influence was indicated by many researches such as (Hardell et al., 2007), (Stein et al., 2011) and (Peleg, 2009) and RF radiation is classified as a possible carcinogen for humans by the International Agency for Cancer Research (IARC). Still the exact interaction mechanisms between the RF radiation and the living tissue are mostly unknown as pointed out recently also by IARC. Some works such as (Friedman et al., 2007) identified biological effects of RF radiation on separated living cells floating in a homogenous solution without any large antenna-like structures. Thus one should look also for direct interactions between RF radiation and cellular or biochemical processes. The interaction mechanisms may be very complex as is the living tissue itself, thus state of the art physics, chemistry and biology will be required to identify them.

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Indeed, initial interesting research attempting this has been reported, see for example (Markov M., 2011) with it's many references and (Fesenko et. al., 1995).

In this paper I shall present a new thermodynamic perspective which may illuminate some aspects of some of the interaction mechanisms. It shows that a living tissue under RF radiation should not be assumed to be in thermal equilibrium since it is governed by two temperatures: The ambient temperature of its surroundings denoted $T_{\mathbf{A}}$ and a vastly higher temperature denoted $T_{\mathbf{R}}$ which is assigned by certain criteria to the RF radiation. The criteria presented here to determine $T_{\mathbf{R}}$ are not unique and other approaches may lead to different temperatures, however $T_{\mathbf{R}}$ as presented here has a physical significance which will be explained. Hypotheses about possible interaction mechanisms based on this perspective are presented.

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.

THE RADIATION TEMPERATURE

Let us consider man-made RF radiation at some intensity d in watts/m^2 radiated by some transmitter, for example the Israeli safety limit of 50 microwatts/cm^2 at the frequency f=1 GHz. Assigning a temperature value to this intensity is not straightforward because radiation is not a classical closed system in thermodynamic equilibrium. We shall assign the temperature by similarity to the classical black body radiation using the two following ad-hoc rules:

> Rule 1: The radiation temperature $T_{\mathbf{R}}$ will be defined as the temperature at which the classical black body radiation achieves the same energy density in J/m^3 as the man-made radiation in question where J denotes Joule and m is meter.
>
> Rule 2: The energy will be summed over the 0 to f Hz frequency band where f is the maximal frequency used by the transmitter; we shall use 1 GHz in our examples. Thus the energy of the black body radiation outside this band will be discarded.

Deriving T_R by following those rules is straightforward. The energy per unit volume per bandwidth of 1Hz of black body radiation is, by the Rayleigh – Jeans law:

$$U = \frac{8\pi\nu^2 kT}{c^3} \ \mathrm{J/m^3} / Hz \tag{1}$$

where ν is the frequency in Hz, k is the Boltzmann constant in J/^{O}K, c is the speed of light in m/sec and T is the absolute temperature in ^{O}K (Degrees Kelvin). Integrating from 0 to f yields the energy per unit volume in the 0 to f frequency band:

$$E_D(f)=\int_0^f \frac{8\pi\nu^2 kT}{c^3}d\nu=\frac{8\pi f^3 kT}{3c^3}\ \text{J/m}^3 \tag{2}$$

The man made RF radiation comprising plane waves of intensity d watts/m^2 has energy density of

$$E_R=\frac{d}{c}\ \text{J/m}^3 \tag{3}$$

The radiation temperature is obtained by equating the man-made and the black body radiation densities, that is $E_D=E_R$ and using equations (2) and (3):

$$T_R=\frac{3dc^2}{8\pi f^3 k} \tag{4}$$

Using d=50 microwatt/cm^2=0.5 watt/m^2 and f=10^9 Hz yields T_R= 3.89x10^{11} ^{O}K. This extreme temperature does not reflect the total radiation intensity; the transmitted radiation intensity d is vastly lower than the total intensity of a black body radiation at temperature T_R because the frequencies above 1 GHz, which contain most of the energy, are discarded in eq. (2) following the rule 2 above. Still the T_R has a physical significance as shown in the next thought experiment.

A THOUGHT EXPERIMENT

We construct a large enclosure and place it on the Earth's surface near a cellular base-station at a distance where the radiation density is d=50 microwatt/cm^2. The following reasoning is rigorous if the spectral power density of the transmitter over frequencies in the 0 to f band has the same shape as that of the black body radiation and if the radiation power is distributed among many components, each arriving at the enclosure from different direction as does the natural black body radiation; otherwise it is an approximation. As explained later on, a very rough approximation is sufficient for our purpose.

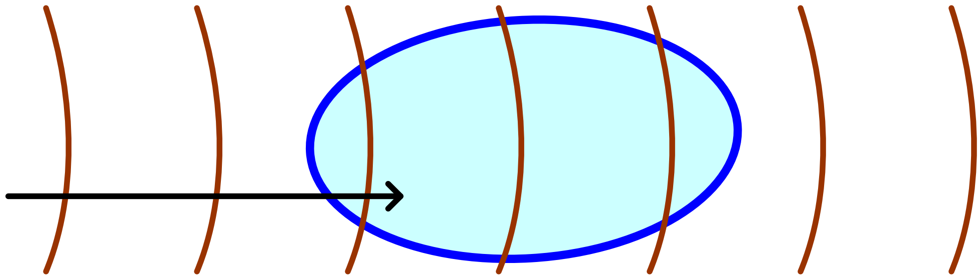

Figure 1: Large enclosure in an RF radiation field

The walls of the enclosure will be made of an ideal material with the following properties:

Property 1: Perfect thermal insulator.

Property 2: Perfect reflector at all frequencies except for the 0 to f band.

Property 3: Transparent or partially transparent to radiation in the 0 to f band.

We shall begin our experiment with our base-station switched off. Then the enclosure interior and exterior will be in a common thermodynamic equilibrium. Thus according to classical statistical physics the energy inside the enclosure is evenly distributed between modes (thermodynamic degrees of freedom) such as for example kinetic energies of individual molecules, changing shapes of molecular electronic clouds, many others and also the electromagnetic standing wave patterns permitted by the geometry which account together for the classical black body radiation. Each mode acquires on average the energy of $kT_A/2$ while the probability density of the individual modes energies follows the Boltzmann distribution. In the following we shall denote the standing wave patterns as RF modes and the other modes as non-RF modes. All the modes can exchange energy among themselves while, due to the particular properties of the enclosure envelope material, the black body radiation in the 0 to f band is the only energy exchange mechanism between the interior and the exterior. The standing wave patterns inside the enclosure will be shaped by the enclosure if the walls are only slightly transparent and by the whole system if the walls are fully transparent, the difference is not qualitatively significant to our reasoning.

According to the black body radiation theory, each standing wave pattern (RF mode) at temperature of 300 ^{O}K and above is occupied by a multitude of RF photons while the black body radiation is not governed by the energies of individual photons unlike the black body radiation in the ultraviolet range where photon energies become relevant and eq. (2) is replaced by the Planck's law. This irrelevance of photon energies is similar to many known RF phenomena as pointed out by (Vistness et. al., 2001; Peleg, 2011).

Now let us power up our base station transmitter. Following the definition of T_R above, the energy density of the RF radiation in the 0 to f band inside the enclosure is the one associated with T_R, that is $kT_R/2$ per RF mode and it is constantly replenished by the external radiation, see details in the appendix. After sufficient time, as is clear from statistical physics considerations and from the properties of the enclosure ideal material, all the other non-RF modes will acquire the same average energy. If the walls are only slightly transparent at RF then the interior will be very near a thermodynamic equilibrium at T_R and its real temperature will be indeed T_R. This is the physical significance of T_R.

The concentration of the RF power in a narrow band as characteristic for a cellular base-station and in one direction only as depicted in figure 1 would not change the temperature much, certainly not by orders of magnitude.

With the walls more transparent at RF, the system will not be a closed one at equilibrium but the energies of all the modes will be still roughly similar to those corresponding to T_R.

Next let us change the wall material to one having some thermal conductivity. Then the system comprising the non-RF modes in the interior will be at an intermediate temperature T_I somewhere in the range between T_A and T_R. The temperature will depend on the coupling between the radiation and the enclosure interior which will determine the energy transfer rate from the incoming radiation to the interior non-RF modes and on the thermal conductivity of the enclosure walls which will determine the thermal energy transfer rate from the interior.

Clearly the enclosure interior is not in a thermal equilibrium since the RF modes are at higher energies than the non-RF modes.

TWO MODELS REPRESENTING A LIVING TISSUE

Let us examine the relevance of the thought experiment to a living tissue in a realistic setting with no enclosure. We shall focus on the distribution of energy between the modes as discussed above while using the homogenous and non-homogenous models presented next.

The homogenous model: The non-RF modes in the living tissue can exchange energy freely among themselves and their coupling to the RF modes is existent but weak. Then the energy between the non-RF modes is distributed evenly. The system comprising the non-RF modes will be near to thermal equilibrium at some temperature T_I; all the non-RF modes will achieve typically the same average thermal energy of $kT_I/2$. With the weak RF coupling and high thermal conductivity typical to the human body, the temperature T_I will be only slightly above the usual 36.5 ^{O}C (degrees Celsius) at radiation intensities below the thermal limits set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). This is the model fitting the ICNIRP assumptions

The non-homogenous model: Now suppose that some non-RF mode, due to the structure of some special molecule, is more strongly coupled to the RF radiation field then the other modes and is more loosely thermally coupled to the other non-RF modes. The energy per RF mode will be still $kT_R/2$. The energy transfer from the RF modes to this special non-RF mode will be faster and the rate at which this energy is dissipated to the other modes will be slower than the average. Thus this mode will acquire more energy from the radiation field than the average $kT_I/2$ energy set by the temperature T_I of its surroundings.

EXAMINING RELEVANCE TO KNOWN BIOLOGICAL EFFECTS

The minimal energy required to change a living tissue is hard to estimate. One clue is the fact that the human body feels well at 36.5 ^{O}C and ill at 40 ^{O}C, thus ΔT=3.5 ^{O}K temperature difference has a significant influence on some tissues in the human body. This corresponds to incrementing the average energy per mode by kΔT/2, this is 1.47×10^{-4} eV (electron-Volt).

It is conceivable that in the presence of RF radiation some special modes will acquire more energy than dictated by the average temperature T_l as described above and a biological change will occur. Such a process will be impeded by the weak coupling of the RF field to the non-RF modes and by the strong thermal coupling between the non-RF modes, and, on the other hand, it will be driven by the huge temperature $T_{\mathbf{R}}$ which is vastly larger than the small temperature difference ΔT capable of inducing a biological change. The interaction mechanism may operate on a few molecules out of many taking them out of the thermal equilibrium without noticeable increase in the average tissue temperature.

Such processes are not identified yet at the detail of the interaction between the RF field and a particular molecule; however, using (Friedman et al., 2007) as a prominent example, it was established that a biological process in human cells starting with the activation of NADH oxidase and identified exactly at the molecular level was initiated by a weak RF field, thus there was some mechanism of interaction. As stated in the introduction, the existence of non-thermal effects of RF fields is firmly established, the only open question are the mechanisms of interaction themselves. The thermodynamic perspective presented here may be relevant to some of the mechanisms of interaction; other mechanisms to which this perspective is less relevant are possible such as the hypotheses on interaction with groups of water molecules examined for example by (Fesenko et. al., 1995).

There are many other sources of non-equilibrium in the living tissue apart of the RF radiation discussed here such as utilization of chemical energy for life processes. Some of those have a profound influence, so may the RF radiation.

CONCLUSSIONS

A new thermodynamic perspective on possible interaction mechanisms between electromagnetic radiation and the living tissue has been presented.

Significant interaction between RF radiation and the living tissue at sub-thermal radiation levels is compatible with this perspective.

This paper did not discover a new mechanism of interaction; rather it showed possible attributes of such a mechanism and demonstrated that the existence of such an interaction mechanism is well compatible with known physical principles. It is also possible that an actual mechanism will turn out to be very different.

Appendix: The energy of the RF modes inside the enclosure

The transparency of the enclosure wall, that is the ratio between the energy passing thru the wall to the energy incident on the wall is similar in both the incoming and the outgoing directions. This is guaranteed under very mild conditions by the well-known reciprocity of RF propagation. Also, after sufficient time, the total flow of the RF energy into the enclosure must be equal to the flow escaping from the enclosure to reach a steady state. Thus the radiation intensity inside the enclosure is similar to that outside it.

When the transparency of the wall is low, most of the RF energy inside the enclosure is stored in the RF modes. The classical black body radiation theory exhibits one to one relationships between the temperature and between the RF energy density and the average energy per RF mode. Since the interior and the exterior radiation density is related to T_R by eq. (1) where $T=T_R$, the energy per RF mode is $kT_R/2$.

With higher transparency the energy density inside the enclosure cannot change much as explained above, only the standing wave patterns are modified and more coupled to the outside radiation, this will modify the details of the coupling of the RF modes to the other modes but will not change drastically the coupling magnitude.

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