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Research Article

The Johnson Noise in Biological Matter

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Can a very low intensity signal overcome a disturbance, the power density of which is much higher than the signal one, and yield some observable effects? The Johnson noise seems to be a disturbance so high as to cause a negative answer to that question, when one studies the effects on the cell level due to the external ELF fields generated by electric power lines (Adair, 1990, 1991). About this subject, we show that the masking effect due to the Johnson noise, known as "Adair's constraint" and still present in the scientific debate, can be significantly weakened. The values provided by the Johnson noise formula, that is an approximate expression, can be affected by a significant deviation with respect to the correct ones, depending on the frequency and the kind of the cells, human or not human, that one is dealing with. We will give some examples. Eventually, we remark that the so-called Zhadin effect, although born and studied in a different context, could be viewed as an experimental test that gives an affirmative answer to the initial question, when the signal is an extremely weak electromagnetic field and the disturbance is a Johnson noise.

1. Introduction

Much attention has been devoted over many decades to a problem that arose in the electrocommunications field [1–3], but such that its consequences extend beyond telecommunications, electroengineering, or other specific problems to a general question, that we try to summarize in this way: can a very low intensity signal overcome a disturbance, the power density of which is much higher than the signal one, and yield some observable effects?

A problem of this kind has become a matter of some lively discussions inside the scientific community, in the case of the biological or health effects due to electromagnetic fields of low intensity in the *whole region* of nonionizing radiations (NIR). Just in this context a relevant influence has been played along all these years, in the scientific debate, by the statement of the Council of the APS (American Physical Society), that excluded the promotion of cancers by power line fields [4]. Actually, the directions of the APS statement disregarded not only cancer risks but also almost all risks associated to the exposure to the fields generated by power lines. That statement has been reaffirmed by the Council of the APS in a more recent brief note, with a further consideration: "… *In addition no biophysical mechanism for the initiation or promotion of cancer by electric or magnetic fields from power lines have been identified*" [5].

The aim of the present paper is not to enter this debate. But, among the scientific bases of the APS position paper, recalled in [6], we look at the one that has played a so relevant role up today in the debate concerning physicists and all researchers in bioelectromagnetism, such to merit the name of "Adair's constraint". Really, Adair proposed the concept of "thermal noise electric field" in his papers [7, 8], and his "constraint" extends far beyond the possible cancer effects: "… *any effects on the cell level of fields in the body generated by weak external ELF fields will be masked by thermal noise effects and, hence, such fields cannot be expected to have* any *significant effect on the biological activities of the cells*" [8]. This statement was very strong, despite of important contemporary review papers about the interaction of ELF fields with humans [9], in which hundreds of references had described laboratory and clinical studies of the effects at the cellular level of an exposure to 50–60 Hz electric and magnetic fields: "*a substantial amount of experimental evidence obtained with in vitro cell and organ cultures indicates that pericellular currents produced by ELF (extremely low frequency) fields lead to structural and functional alterations in components of the cell membrane*" [10]. Since the "Adair's constraint" is still working in the scientific discussion (see, e.g., [11]), we mean to show that it can be significantly weakened and, at the same time, to give a contribution to avert a possible generalization of the masking effect to all the NIR spectrum.

In the current literature many articles about the thermal noise in biological cells recur to the approximate expression of the Johnson noise, as the Adair's ones do. We note that a bit of caution is necessary when dealing with that formula, in order to avoid that the mean square values of the noise tension differ significantly from the correct ones. This is the case of the estimates of exposure of a human cell membrane to a VLF antenna, that radiates in the range (14–30) kHz. On the contrary, the Johnson's formula works well when applied to the irradiation of eggs of Salmo lacustris from an oscillating magnetic field in the range (450–1350) kHz, a historical experiment performed by Italian researchers in the Twenties.

Eventually, we remark that the so-called Zhadin effect, although born and studied in a different context, could be viewed as an experimental test proving that an affirmative answer to the initial question can be given, in the particular case when the very low signal is an extremely weak electromagnetic field and the disturbance has just the character of a Johnson noise.

2. The Johnson Noise

Many of the reasoning and the models applied to describe interactions between electromagnetic fields and the biological matter rely on the phenomenon of Johnson noise, when the thermal noise has to be taken into account. And over this case we will focus, even though there are other kinds of noise, in order to compare the results of this paper with those presented in [7, 8]. Thus, it's necessary to recall, shortly, the experiment performed in electronics by Johnson and the corresponding formula.

Let us consider a conductor, in the interior of which there is a very large number of free to move electrons. At a fixed temperature T (°K), the thermal agitation of electrons implies that the stochastic motion of the charged particles and their collisions produce at some time an accumulation of charge at one end of the conductor, while in a successive instant there will be an excess of electrons on the other end. Therefore, we could find a tension between the two terminals, that is a stochastic variable of the time with a well-defined mean square value: the thermal noise tension. This tension would not depend on a possible continuous electric current flowing in the conductor, since the thermal velocity of electrons is much higher than the drift velocity ($\sim 10^3$ times).

Johnson was the first [1] who observed the fluctuations of tension at the ends of a conductor with a resistance R, realizing that the mean square value $\langle V^2 \rangle$ of the instantaneous noise tension $V(t)$ was proportional to R and to the absolute temperature T. Besides, he found that the ratio $\langle V^2 \rangle / R$ does not depend on the nature or the shape of conductors and assumed that this tension was due to the thermal agitation of the electrons inside the material [1]: the "Johnson noise" tension. Testing different kinds of conductors, he also found $\langle V^2 \rangle / R = kT$, where $k = 1.38 \cdot 10^{-23}$ J/k is the Boltzmann's constant, in a good agreement—within the 8%—with the experimental data [2]. Harry Nyquist had been immediately requested by Johnson of an explanation of the results of his experiment—they were at that time colleagues in the Bell Telephone Laboratories—and answered with an easy and fine conceptual experiment, a fundamental element of which is a "bipole" [3].

A bipole is any electric component with two terminals, characterized by a complex impedance

$$Z(\nu) = R(\nu) + jX(\nu), \tag{2.1}$$

where ν is the frequency (of the signal), j is the imaginary unit and the functions of frequency, R and X, depend on the capacity C and the inductance L of the bipole. Actually, since a pure resistor does not exist as a physical object, we are obliged to schematize a conductor as a bipole, also in a conceptual experiment. For T different from zero, the instantaneous noise tension fluctuates, also in the absence of an electric external field; but, for a pure resistor, its mean value cannot be other than 0:

$$V_n(t) : \langle V_n \rangle = 0, \tag{2.2}$$

where n stands for noise. Thus, over an interval of time we cannot have any electric field nor any electric current inside a pure resistor; only the instantaneous ones, led by the fluctuating tension, are permitted, otherwise we should have created a perpetual motion. And it is not by chance that in his experiment Johnson recurred, substantially, to the measure of the effective value of the noise tension as the available observable, that is the square root of $\langle {V_n}^2 \rangle$. The mean square value, $\langle {V_n}^2 \rangle$, at the ends of a bipole, is given by (see, e.g., [2, 3])

$$\left\langle {V_n}^2 \right\rangle_{\mathrm{TOT}} = 4kT \int_0^{\infty} R(\nu)\, d\nu, \tag{2.3}$$

where ν is the frequency of the noise spectrum. The measure devices do not allow to perform measures over the range of all frequencies as requested in (2.3), thus it is more frequently used as the expression of the noise in a definite frequency band $[\nu_1, \nu_2]$:

$$\left\langle V_n{}^2 \right\rangle_{\text{PART}} = 4kT \int_{\nu 1}^{\nu 2} R(\nu) d\nu = 4kT \int_{\nu 1}^{\nu 2} \left\{ \frac{R}{\left[1 + (2\pi\nu RC)^2\right]} \right\} d\nu, \tag{2.4}$$

where the last equality holds only if the impedance Z reduces to that of an R-C conductor. When $R(\nu) = R$, one has

$$\left\langle V_n{}^2 \right\rangle_{\text{PART}} = 4kTR\Delta\nu, \tag{2.5}$$

with $\Delta\nu = [\nu_1, \nu_2]$. Expression (2.5) is just the Johnson noise formula: it holds when in the last term of (2.4) the condition $(2\pi\Delta\nu RC)^2 \ll 1$ is satisfied (and the integration domain is limited).

Thus, the limits of applicability of (2.5) are clear and it could be useful to emphasize that the thermal noise generated in a conductor for a given frequency band can be analyzed in terms of a pure resistor only if that condition is fulfilled.

3. The "Thermal Noise Electric Field" and the "Adair's Constraint"

Then, let us consider an R-C parallel circuit, that is often used to model biological tissues at thermal equilibrium (T = cost). Really, in most of the models the impedance circuit reduces to an R-C one, because the contribution of inductance results, in general, is experimentally negligible. In this case C is the capacity of the model circuit, and the fluctuation of the tension at the ends of the bipole is given by (2.4).

Adair introduced the concept of "electric noise field", in a paper [7], and confirmed it in a subsequent work [8], in order to describe and quantify the observed phenomena. The aim was to take into account that "*in any material the charge density fluctuates thermally according to thermodynamics imperatives generating fluctuating electric fields*" [8]. After having named the mean square value of the noise tension: $\langle V_{kT}{}^2 \rangle$, the main assumption which he applies to the model is that the mean square value of the tension is given, also for biological tissues or cellular membrane, by the expression (2.5).

Therefore, in the case "*of a hypothetical measurement of the voltage across the plates of a parallel plate capacitor where a cube of tissue of length d on a side is held between the plates ... The time-average noise voltage* $\langle V_{kT} \rangle$ *can then be expressed as* $\langle V_{kT}{}^2 \rangle = 4TkR\Delta\nu$, $E_{kT} = \langle V_{kT} \rangle / d$" [8].

For a cubic volume of the tissue, d^3, the time-average noise voltage is $\langle V_{kT} \rangle = (4\rho kT\Delta\nu/d)^{1/2}$, correspondingly $E_{kT} = (4\rho kT\Delta\nu/d^3)^{1/2}$. Assuming $d = 20\,\mu\text{m}$, $T = 310°\text{K}$, $\rho = 2\,\Omega \cdot \text{m}$, and for a frequency span $\Delta\nu = 100\,\text{Hz}$, one gets

$$E_{kT} = 20.6 \cdot 10^{-3} = 0.02\,\text{V/m}, \tag{3.1}$$

"*which is about 3.000 times larger than the field induced by a 300 V/m external field*" [8].

For a cubic section (this choice undergoes a criticism [12]) of a cellular membrane with the same temperature T and values $\rho = 10^6\,\Omega \cdot \text{m}$, $d = 5 \cdot 10^{-9}\,\text{m}$, "*... the thermal noise electric field is then* $E_{kT} \approx 3.7 \cdot 10^6\,\text{V/m}$, *which is about* $2 \cdot 10^8$ *times that from a 300 V/m external field*" [8].

For the sake of commodity we report the latter figure as [8]

$$E_{kT} \approx 3.7 \cdot 10^6 \text{ V/m} \tag{3.2}$$

and observe that following these theoretical estimates, mainly (3.2), the only one conclusion to be drawn is that we have already quoted [8] in our introduction about the masking of all biological effects on the cell level by the thermal noise effects (consequently, the weak ELF fields will not have observable effects on the cells).

Even if one could agree with a model that represents a biological object as a bipole of electronics, one can obtain (3.1) and (3.2) only if $R(\nu) = R$, that is, when a tissue of the human body or the cell membrane could be considered as a *pure resistor*. But there is no reason why this occurrence, denied to the materials of electronics at a point that Johnson and Nyquist were obliged to make use of a bipole (i.e., an impedance) for their experiments, also the conceptual ones, can take place in biology.

Besides, it is easy to check that the value of R used to get (3.2) does not fulfill condition $(2\pi\Delta\nu RC)^2 \ll 1$, that allows the use of (2.5) instead of (2.4).

Thus, since the literature does not provide any reason why a simple electronics model should behave differently if it deals with biology, it remains true that "*the time-average noise voltage* $\langle V_{kT}\rangle$" is 0 for a pure resistor (as we noticed at the beginning of this paper). Consequently, the electric field, that is, the mean value $\langle V_{kT}\rangle$ divided by the length d of the conductor, does the same thing.

The Adair's theoretical estimates were incorporated in the background paper [6]; further, Adair himself has repeated his arguments and kept on his "constraint" in more recent papers [13–15]; and those estimates have been taken into serious account for many years, standing as "Adair's theoretical exposure limits" also in recent papers (see, e.g., [11]).

4. A Result and Some Observations

Replying to an opponent of his theses [12], Adair says: "*my discussion was not original but taken largely from the paper of Weaver and Astumian*" [13], referring to the paper [16]. In that work, Weaver and Astumian deal, among other things, with the problem of calculating the mean square of the noise tension of a cell membrane and the corresponding electric field, using the same data underlying the expression (3.2), but obtaining different figures.

Let us try to give an answer, accepting to represent a cell membrane as an R-C circuit. The relationship between the tension at the terminals of the capacitor, V_C, and its stored energy, E, is given by

$$E = \left(\frac{1}{2}\right) C{V_C}^2. \tag{4.1}$$

For the equipartition theorem, the probability dP of finding the system in the voltage interval $(V, V + dV)$ is proportional to $e^{-E/kT}$,

$$dP = P_0 \cdot \exp\left[-\frac{(1/2)C{V_C}^2}{kT}\right] dV_C. \tag{4.2}$$

After normalizing to fix the value of the constant P_0, one gets

$$\left\langle V_C{}^2 \right\rangle = \left(\frac{C}{2\pi kT}\right)^{1/2} \int V_C \cdot \exp\left[-\frac{(1/2)C\left\langle V_C{}^2\right\rangle}{kT}\right] dV_C \tag{4.3}$$

and performing the integration on $(-\infty, \infty)$ one obtains

$$\left\langle V_C{}^2 \right\rangle = \frac{kT}{C}. \tag{4.4}$$

At the balance, the expression (4.4) leads to a value equal to that given by (2.3).

In order to obtain the value of C for a cellular membrane the thickness of which is d, it is almost natural to think of a capacitor made of two concentric spheres with radii r and $r + d$, respectively, instead of referring to the situation of two parallel planar plates (in this case, in fact, the capacity could depend on the number N of squares, in which the plate can be divided to perform the calculation; and the corresponding expression of C will depend on N^2 [17]). Then, the value of C is

$$C = \frac{\varepsilon_r \varepsilon_0 4\pi r^2}{d}, \tag{4.5}$$

where ε_0 and ε_r are, respectively, the values of dielectric constant in vacuum and in a specified matter. From (4.4) it follows for the electric field

$$E = \frac{\left(\left\langle V_C{}^2\right\rangle\right)^{1/2}}{d} = \frac{(kT/C)^{1/2}}{d}; \tag{4.6}$$

if the same values as in the expression (3.2) are assumed for the parameters, that is $\varepsilon_r = 2.5$, a value drawn from literature, and $r = 10^{-5}$ m, $d = 5 \cdot 10^{-9}$ m, $T = 310°$K, one obtains

$$E \approx 5.5 \cdot 10^3 \text{ V/m}. \tag{4.7}$$

The value given in (4.7) is implicitly referred to the whole spectrum of frequencies; if only ELF effects are investigated, then one has to calculate the finite integral of the expression (2.4) in the interval $[\nu_1 = 0\,\text{Hz}, \nu_2 = 100\,\text{Hz}]$. Performing the integration on the interval $[\nu_1, \nu_2]$ one obtains

$$\begin{aligned} \left\langle V_n{}^2 \right\rangle_{\text{PART}} &= 4kT \int_{\nu 1}^{\nu 2} \left\{ \frac{R}{\left[1 + (2\pi\nu RC)^2\right]} \right\} d\nu \\ &= \left(\frac{kT}{C}\right)\left(\frac{2}{\pi}\right) \text{arctg}\left\{ \frac{[2\pi(\nu_2 - \nu_1)RC]}{\left[1 + (2\pi RC\sqrt{\nu_1\nu_2})^2\right]} \right\}. \end{aligned} \tag{4.8}$$

If we take for resistivity the same value as in [8, 16], $\rho = 10^6\,\Omega \cdot \mathrm{m}$, in the assumed frequency band the expression (4.8) gives

$$E \approx 260\,\mathrm{V/m}; \tag{4.9}$$

that is a value, for the electric noise field, 10^{-4} times minor than (3.2) (and $10^{-4} \div 10^{-5}$ times minor of the cell membrane electric field—the measures give about $14 \cdot 10^6\,\mathrm{V/m}$—as it is reasonable to expect).

In conclusion, it is not arbitrary to argue that if a cell membrane is represented not as a pure resistor but as a conductor, then the value for the noise electric field is much lower than that given by (3.2); correspondingly, the "Adair's constraint" results significantly weakened.

Furthermore, one could reasonably expect that also the mean value of the noise tension at the ends of a "bipole" be zero, just as that at the ends of a resistor. Thus, the figures (4.7), (4.9) would constitute more an estimation to determine possible peak values than theoretical data to compare with the experimental ones.

5. Some Examples about the Johnson's Formula in Biology

We have just observed in the previous formulae that it is crucial to use a correct value of R, thus one could think that, if this request $(2\pi\Delta\nu RC)^2 \ll 1$ is satisfied, not a relevant gap between the estimates from (2.5) and (4.8) can occur not only in the ELF region but also in other bands of the spectrum of frequencies. That is, our criticism about the representation of a conductor as a pure resistor could be right in principle but poor of effects on the results of experiments. On the contrary, it is not true when one deals with human cell membranes, *the parameters of which have values around those used by Adair and Weaver*, as it is immediate to check. In fact the recalled condition is not well fulfilled already in the region of tens kHz, where the Johnson's formula (2.5) gives a significant deviation from the correct value of the square mean tension as given by (4.8), as we will see just after; and for larger frequencies obviously only the formula (4.8) can be applied.

Let us consider a high power transmitter operating in the band (14–30) kHz; a VLF antenna such that: "...induces currents and fields in people living in the urban area within 2 km of the antenna that are greater than those in people living very close to high voltage power lines..." [18]. It follows that an intensity of electromagnetic field equal to that of power lines is reached at much shorter distance, but the effects will be the same in correspondence to the same value of the irradiated field. In any case, these different behaviours, significant for the health impact, do not affect the calculus of $\langle {V_n}^2 \rangle_{\mathrm{PART}}$: it depends only on the electrical properties of the cellular membrane—we'll keep the values of the parameters of the previous example—and on the frequency of the emitted signal. We take $\Delta\nu$ equal, as usual, to one tenth of the range of operating band. Thus, just because the condition $(2\pi\Delta\nu RC)^2 \ll 1$ is not well satisfied, in fact $(2\pi\Delta\nu RC)^2 = 0.045$, from (2.5) one can obtain the hypothetical estimate

$$\left\langle {V_n}^2 \right\rangle_{\mathrm{PART}}^{(2.5)} = 109 \cdot 10^{-12}\,\mathrm{V}, \tag{5.1}$$

while the calculation performed by (4.8) gives

$$\left\langle V_n{}^2 \right\rangle_{\text{PART}}^{(4.8)} = 21 \cdot 10^{-12}\,\text{V}. \tag{5.2}$$

Consequently, the corresponding values of electric noise field differ about 130%:

$$E^{(2.5)} = 2087 \cdot 10^3\,\text{V/m}, \qquad E^{(4.8)} = 912 \cdot 10^3\,\text{V/m}; \tag{5.3}$$

obviously, only the minor one being correct.

It is easy to verify that for such a cell membrane, the electric noise field decreases, as one could expect, when frequency grows. Thus in the region $(0.5 \div 1.5)$ MHz, frequently used in laboratory experiments, one can find $E^{(4.8)} \approx 137\,\text{V/m}$; in the region $(50 \div 60)$ MHz, where are operating a lot of broadcasting and telecasting devices, it will be $E^{(4.8)} \approx 6.8\,\text{V/m}$, and for the frequencies of mobile phone or radar bridge $(2 \div 3)$ GHz, $E^{(4.8)} \approx 1.5\,\text{V/m}$.

For nonhuman cell membranes, it can happen that also at high frequencies the parameters satisfy $(2\pi \Delta\nu RC)^2 \ll 1$, so that the deviation will be negligible and it will be easier to compute the square mean tension by the Johnson's formula.

In an experiment realized indeed many years ago to test the effects of electromagnetic fields on the embryonic development of eggs of Salmo lacustris [19] the authors formulated the hypothesis that the deformations revealed on the irradiated eggs and on the embryonic development of Salmo lacustris with respect to those not exposed should be caused by the magnetic field. In fact, they took care of measuring a constant temperature during the time of exposition of the eggs, so that an alteration of the embryonic development due to the heat released by the irradiating field could be excluded.

Let us look at the figures that one could have obtained for the thermal noise tension in that experiment. The eggs of Salmo lacustris were exposed to an oscillating magnetic field in the range (450–1350) kHz and the values reported in literature for those eggs give $r = 2.5 \cdot 10^{-3}\,\text{m}$ [20, 21], $d = 50 \cdot 10^{-6}\,\text{m}$ [22, 23] and $\rho = 5 \cdot 10^3\,\Omega \cdot \text{cm}^2$ [21]. Now, the condition $(2\pi \Delta\nu RC)^2 \ll 1$ is fulfilled for $\Delta\nu = 100\,\text{kHz}$, thus the approximated formula (2.5) can be applied obtaining

$$\begin{gathered} \left\langle V_n{}^2 \right\rangle_{\text{PART}}^{(2.5)} = 2.18 \cdot 10^{-12}\,\text{V}, \\ E^{(2.5)} = 29.5\,\text{mV/m}; \end{gathered} \tag{5.4}$$

out of curiosity, the values given by the formula (4.8) are, respectively,

$$\left\langle V_n{}^2 \right\rangle_{\text{PART}}^{(4.8)} = 2.062 \cdot 10^{-12}\,\text{V}, \qquad E^{(4.8)} = 28.7\,\text{mV/m}. \tag{5.5}$$

This occurrence is not amazing why the variations of resistance and capacity, in function of frequency, of cell membranes have been investigated for a long time [24] and it is well known that for the cell membrane of an egg of Salmo lacustris the resistance is much lower than that of a spherical human one; and its conductance increases rapidly at high frequencies [21]. Therefore, for a nonhuman cell this example shows that when it is exposed to high frequencies, the electric noise field, if does exist, is not a barrier to mask such effects at the cell level of an external field; since, as a matter of fact, the alterations of eggs and their embryonic development were experimentally revealed not as caused by the release of thermal energy.

6. Concluding Remarks

One of the key problems in bioelectromagnetism is to explain the mechanism of the influence of weak electromagnetic fields on biological objects; it remains unclear, in spite of numerous experimental data. In particular, it is not clear how low frequencies or static fields, magnetic or electric, can lead to the "resonance" of biochemical reactions, even when the energy of such fields is very small in comparison with the energy kT of the process. The lack of a theoretical explanation, that is satisfying or shared among researchers, is now called "kT problem" or "kT paradox" [25].

On this subject, after a very long-time referees' action Michail Zhadin reported the alteration of electric properties of a nonbiological system, made up by an aqueous diluted solution of amino acids (glutamic acid) [26], in correspondence of the frequencies of an ion cyclotron resonance.

A direct current voltage of 80 mV was applied to the solution contained in a electrolytic cell, near to the value of the cell membrane potential. The solution was exposed to the combined action of two parallel magnetic fields, one weak and static (B_0 = 20–40 μT = micro Tesla), the other extremely weak and alternating (B_c = 10–80 nT = nano Tesla), both applied orthogonally to the electrolytic current direction.

A very narrow intensity peak in the electric current can be measured, when the frequency ν of the alternating magnetic field B_c matches the ion cyclotron resonance of the ionized solution; this frequency ν is given by the well-known formula

$$\nu = \frac{qB_0}{2\pi m}, \tag{6.1}$$

where m, q are, respectively, the mass and the charge of the electrolytic ion. The frequency windows found by Zhadin were at 4 Hz for B_0 = 40 μT and B_c = 10, 20, 30 nT; in the interval [2, 4] Hz, spaced by 0.5 Hz, when B_0 = 20, 25, 30, 40 μT and B_c = 25 nT.

Many authors refer to this result as the *Zhadin effect*, that has been successfully replicated in Italy [27–29] and in Germany [30]. Several attempts to give a theoretical explanation of the physical mechanism underlying that effect have been made [27, 31] in the framework of the quantum electrodynamics of condensed matter proposed by [32], also by Zhadin himself [33], after a previous analysis performed in terms of the semiclassical resonance theory [34].

The Zhadin effect, born and actually studied in another context, is, in the limits of that experiment, a positive answer to our opening question: an extremely weak magnetic field—the very low intensity signal—can overcome, in correspondence of a frequency window, the noise tension—the disturbance—the energy density of which is very lager than that of the field. This eventuality suggests that a similar effect could take place also when biological cells are irradiated by very weak electromagnetic fields; that is, the masking effect on the cell level by thermal noise could have a break down.

This suggestion could be the reason why Adair has criticized the previously quoted paper [34], going on with his argument: the equivalent electric field acting on the ion thermal motion is many times minor than the electric noise field [35]. But, in his indications does not appear the estimate (3.2). An analogue reasoning is developed in [25], whose criticism versus the theoretical analysis performed in [34] is focused on the energy of a particle motion at the cyclotron resonance frequency, directly compared with the thermal agitation energy kT.

Thus, the problem is leaded to the properness of the models that try to explain the Zhadin effect. In fact, Zhadin asserts about the attempts to interpret his experiment in terms of resonance: *"... Unfortunately, for free ions such sort of effects are absolutely impossible because dimensions of an ion rotation radius should be measured by meters at room temperature and at very low static magnetic fields used in all the before experiments. Even for bound ions these effects should be absolutely impossible for the positions of classic physics because of rather high viscosity of biological liquid media..."* [34]. But on another side, the recalled attempts to bring that experiment within the conceptual framework of the theory formulated by Preparata have not yet met a general sharing among the insiders.

In few words, a very complex and up to now open problem.

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