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Spectral Perspective on the Electromagnetic Activity of Cells

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Abstract: In this mini-review, we summarize the current hypotheses, theories and experimental evidence concerning the electromagnetic activity of living cells. We systematically classify the bio-electromagnetic phenomena in terms of frequency and we assess their general acceptance in scientific community. We show that the electromagnetic activity of cells is well established in the low frequency range below 1 kHz and on optical wavelengths, while there is only limited evidence for bio-electromagnetic processes in radio-frequency and millimeter-wave ranges. This lack of generally accepted theory or trustful experimental results is the cause for controversy which accompanies this topic. We conclude our review with the discussion of the relevance of the electromagnetic activity of cells to human medicine.

Keywords: Bioelectromagnetism, Electromagnetic activity of cells, Electron excited states, Light, molecular vibrations, Radiofrequency, Terahertz.

INTRODUCTION

Living cells are electromagnetically active. While some electromagnetic processes in cells have been experimentally observed, explained by recognized biophysical phenomenon, and their purpose is known as well as covered in textbooks, there are also phenomena which are either only speculated or not sufficiently proved yet. It is still not clear to which extent may the particular mechanism of electromagnetic activity be understood as a general phenomenon in biology and whether it may be expected to play an important role in the physiology of cells. Generally, the proved or hypothesized mechanisms underlying electromagnetic processes in cells are distinctive in terms of frequency. In this mini-review, we summarize current knowledge about the electromagnetic activity of cells with respect to frequency - we cover the electromagnetic spectrum from extremely low frequencies up to visible light and beyond (Fig. **1**).

Comprehensive knowledge of electromagnetic activity is important for several reasons. Firstly, the deeper understanding of electromagnetically active processes in cells may open a new way for diagnostics. Secondly, we can expect that these processes could be affected by external complementary electromagnetic fields. This would be important for novel therapeutic methods. And last but not least, the approach we advocate here is that if we understand the function of endogenous electromagnetic field in cells, we might be able to modulate this field and its effects perhaps by using chemical substances rather than external electromagnetic fields.

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INTRODUCTION TO ELECTROMAGNETICS

Electromagnetics cover various forms of the electromagnetic phenomena, but all of them are, in fact, connected with the same physical reality - the electric charge. Depending on the most pronounced specific feature of the field, we talk about the electric field, the magnetic field or electromagnetic waves. Here we are exclusively focused on (i) non-stationary electric fields, i.e. the non-radiative electric field which changes over time, and (ii) electromagnetic waves, i.e. electromagnetic radiation. From a classical point of view, generation of electromagnetic radiation takes place when the electric charge, either free or bounded in molecules, undergoes a non-uniform movement; typically oscillation. On the other hand, quantum approach attributes generation of electromagnetic radiation in the form of photons to radiative transition of charged particles from a higher energy level to a lower one.

ELECTROMAGNETIC ACTIVITY OF CELLS VERSUS FREQUENCY

This mini review is structured in terms of frequency. We start with low frequency phenomena and continue through radiofrequency band and millimeter waves up to light. We review the mechanism, purpose and the measure of understanding of electromagnetic phenomena at these frequencies in cells (Fig. **2**). The very well-known phenomena are covered only briefly by references to more comprehensive literature, while less understood phenomena are discussed with more details.

Sub kHz - Ionic Currents

The bioelectromagnetic phenomena in the region between the stationary field and the oscillatory field with the

1873-5294/15 $58.00+.00

frequency up to hundreds of Hz are widely known and very well understood [1,2]. They are caused by electrochemical potentials between two sides of biological membranes. The electric potential difference is established through different concentrations of ions on two sides of the membrane. The lipid bilayer forming the membranes forms the barrier for the diffusion of ions. Using ion channels and ion pumps, which are active protein complexes incorporated into the membrane, cells may actively maintain the concentration gradient of ions between both sides of the membrane. Nonexcitable cells maintain their electrostatic potential stable from the macroscopic point of view, while excitable cells like neurons or muscle cells are able to actively modulate their potential and generate a so-called action potential which serves for signaling purposes. Since the fluctuations of the membrane potential are connected with nonstationary ionic currents, i.e. acceleration of the electric charge, one may expect that electromagnetic radiation will be generated during this process. However, such radiation has very low power and, moreover, it is effectively attenuated by conductive physiological buffers. Therefore, we understand this phenomenon as non-stationary low-frequency electric field.

Several processes related to ion oscillations and frequencies exceeding the range of classical electrophysiology and reaching MHz have been proposed. Pohl suggested waves of electric charge as a result of coupling of oscillating chemical reactions with mobile ions in physiological buffers [3,4]. He estimated that the frequency of such oscillations can reach up to about 1 MHz. However, the only experimental tests of this hypothesis were indirect and involved micro-dielectrophoresis [4-10]. Pohl did not investigate the proposed mechanism itself.

Tsong *et al.* proposed electroconformational coupling (ECC) for cellular enzymatic systems [11-15]. In this theory, enzymatic systems, particularly those in membrane structures, are able to receive, process and transmit high and medium level intensity periodic potentials, *e.g.*, electric potentials. The ECC theory describes a four-state enzyme system that converts electric field energy into chemical potential energy if the frequency and the strength of the applied field properly match the characteristics of the system. There is a lot of experimental evidence for the validity of this hypothesis [13,16-18]. Tsong also proposed that the inverse process to that ECC of enzymes described above can generate local oscillatory electric field in kHz - MHz range [19]. This inverse process has not yet been confirmed experimentally.

Radio-Frequency and Lower THz - Unexplored Territory

Electromagnetic activity of cells in the radio frequency band is the least explored and at the same time the most controversial issue. On the one hand, there is no generally accepted theory and undoubted experimental observation of electromagnetic activity of cells in this region. On the other hand, there are high expectations that electromagnetic activity of cells in this region would open a completely new field of cell biology. The controversy of this topic comes from the imbalance of promising implications, that the electromagnetic activity of cells in this frequency region should have, and the absence of defensible experimental evidence for such an activity. Since it is an unproved and at the same time a widely discussed phenomenon, we will discuss it in detail.

Generally, the conditions for generation and propagation of radio-frequency and microwave electromagnetic radiation are optimistic, because the screening by ions does not have such influence on higher frequencies.

Theories Related to Electrically Polar Mechanical Oscillations

Several theories were proposed how cellular processes may give rise to electromagnetic field in the radio-frequency and lower THz ranges**.** The prominent hypothesis, which inspired research in this frequency region, was proposed by Fröhlich [20-23] who postulated that electrically polar intracellular structures may undergo coherent longitudinal vibrations in a non-linear regime. Under certain conditions, the energy would condense in an ordered fashion in few modes of motion and establish long-range correlation on a macroscopic scale. Fröhlich's model implies the existence of an electrodynamic activity of bio-molecules in the range between 100 GHz and 1 THz. There have been attempts to prove the existence of such predicted coherent vibrations by the Raman spectroscopy [24-28], but findings presented in these works were later considered as probable artifacts [29-33]. Fröhlich's hypothesis is not generally accepted nowadays due to the absence of experimental evidence. However, recent theoretical analysis indicates that at least one part of Fröhlich's model is biologically feasible [34]. Despite its controversy, Fröhlich's hypothesis still inspires new studies [35,36].

The very recent view of Fröhlich's hypothesis [35,36] considers microtubules, which hypothetically vibrate due to energy feeding from mitochondria, as structures generating the electromagnetic fields. However, we must repeat that despite the large number of works it inspired, Fröhlich's hypothesis was not experimentally confirmed yet.

Mechanical vibrations of electrically polar structures in cells are, thanks to the straightforward simplicity of the concept, the most popular hypothetical mechanism of generation of an electromagnetic field in cells. Beside Fröhlich's hypothesis, there are several other theories describing electromagnetic activity of cells by this mechanism.

Cell membrane related theory of high frequency electromagnetic field generation considered vibrations of the polar cellular membrane as a mechanism for generation of acousto-electrical waves [37,38]. The deformations of membrane were predicted to cause (i) departure from symmetry and consequently (ii) a nonzero electromagnetic radiative component where its intensity depends on the deviation from the healthy state; in the case of healthy non-dividing cells, both the radiation from and the electromagnetic sensitivity of the cells is lowest. Vacuum wavelengths of the generated electromagnetic waves fall into the region of millimeter waves due to geometric and mechanical properties of the cellular membrane.

A prominent role in the hypothetical electromagnetic activity of cells is, from historical reasons, played by microtubules. Nano-electromechanic properties of microtubules make them good candidates for the generation of an electromagnetic field, if they vibrate. Besides Fröhlich's hypothesis, also other experimentally proven phenomena were considered to drive these vibrations [39]. *In silico* calculations of the electromechanical vibrations of microtubules have shown that the vibrations generate very high intensities of electric field, but only in the region within a few nanometers around the microtubule [40-42]. However, there is an ongoing debate about the possibility of microtubule vibrations *in vivo*. Foster and others argue that the damping by cytosol precludes microtubules to vibrate [43]. On the other hand, it was argued that the damping may be significantly lower due to interfacial effects [44]. It is important to note, that the microtubules do not necessarily need to have the character of the oscillator in order to be brought into vibrations, but the energy transfer into vibrations of a specific frequency would be highly inefficient in this case.

Another proposed mechanism of generation of a microwave electromagnetic field in cells is connected with the hypothetical electrosolitons in proteins. This proposed mechanism involves both vibration of molecules and electron transport. The original inspiration comes from the work of Davydov [45], who predicted solitons in alpha-helices of proteins. This work was further developed and modified into the concept of electrosoliton by Brizhik *et al.* [46-49] in the context of electromagnetic activity of cells. But at the same time, there are still open theoretical questions about the existence of Davydov soliton itself [50,51]. Experimental tests did not bring evidence for Davydov soliton in biological systems [52] and there are no direct experimental tests of electrosolitons existence up to our knowledge.

Theories Related to Electron Oscillations

It is still not clear what are the actual mechanisms and frequency ranges for charge oscillations in biomolecules which could give rise to an electromagnetic field. Ions within cells and electrons / polarons with sufficient mobility in biomolecules could be able to oscillate in the kHz - THz region (up to only MHz for ions). One of the necessary conditions for the oscillation of electrons in bio-molecules is their electronic conductivity, which is being intensively studied. One bio-molecule that is known to conduct electrons is DNA [53,54]. One speaks (for DNA) of a so-called phonon assisted conductivity attributed to polarons [55-57], which are quasiparticles that involve a charge (here electron) and associated deformation of the lattice (cloud of phonons). The DNA polaron-based conductivity is now a widely and intensively studied scientific field. Due to these conductive properties, a collective of authors label DNA as an antenna for electromagnetic fields [58].

While proteins were generally accepted to be nonconducting for a long time [59], some theoretical predictions propose conduction or semiconduction to occur in them [60,61]. Indeed, there is strong current evidence that metaloproteins enable enhanced electron transfer [62]. It has also been shown that aromatic amino acids, such as tryptophan, promote electron conduction [63]. There is, furthermore, a very recent example of semiconduction of a metal-reducing bacterial polypeptide named geopilin [64-66] also found in other types of bacteria [67], which led the authors to propose that conductive bacterial polypeptide nanowires represent a common bacterial strategy for efficient electron transfer and energy distribution. Unless mechanisms and feasibility of electronic conductivity in the high frequency region in biomolecules and bio-molecular structures are elucidated, any generation of a cellular electromagnetic field based on electron oscillations will remain only a speculation.

Recent experimental results indicate that microtubules could play a role in cellular electromagnetic field generation not only through their electrically polar vibrations but also through their electronic conduction. It has been shown in the measurement with the four probe connection on a single microtubule that, at a certain frequency of applied AC voltage bias, DC resistance of the microtubule drops to about 10% [68]. However, no mechanism explaining this phenomenon has been proposed yet.

Even if high frequency conductivity of charges in biomolecules is demonstrated, it remains to be shown if there is any endogenous metabolic process taking place which can excite oscillations of bio-molecular electrons/polarons and thus generate a cellular electromagnetic field.

The important question concerning electromagnetic activity of cells is whether a radio-frequency electromagnetic field from cells would have radiative character. Surprisingly, this question is analyzed only superficially in literature. Pokorný and Wu [69] expected the cellular electromagnetic field at radio-frequency range to have mostly near-field nature without highly pronounced radiative behavior. According to Havelka [41], who analyzed the radiative electromagnetic power from vibrations of microtubules, the radiative component forms only a very small part of the total energy in the electromagnetic field caused by this phenomenon. The expectation of a non-radiative character of the field has fundamental implication for the detection of such a field [70].

Experiments

There have been reports claiming direct electronic detection of electrodynamic cellular signals since 1980. Measured from a single cell or a suspension of cells, positive experimental reports have been published concerning the subject of electromagnetic activity of yeast cells in the range around **1** kHz [71], 8 MHz [72-74], 1-52 MHz [8,9,75] and 7-80 MHz [76,77]. Positive reports also exist on alga *Netrium digitus* with peaks around 7 and 33 kHz [78]. Experiments aimed at the detection of cellular electrodynamic signals within the GHz range [79-81] have not delivered strong evidence for such signals. It has recently been discussed that experimental setups used in the above mentioned experiments have not met all the necessary technical prerequisites for such systems, based on the predicted biophysical properties of cellular electrodynamic fields [70]. It explains a very limited success of experiments within the GHz range and suggests that reported positive results were, with high probability, mainly artifacts.

Electrodynamic activity of cells was also suggested as an explanation of the attraction or repulsion of dielectric particles to or from cells [3-7,82-85]. This dielectrophoretic effect was observed for several types of samples such as bacteria, fungi, algae, nematodes and mammalian cells including human leukocytes. The interpretation of the dielectrophoretic effect as a result of a cellular electrodynamic field would serve as indirect evidence for an electromagnetic activity of cells within the range of MHz. Unfortunately, there are no reports with more details on this topic in recent years to our knowledge.

Within the large number of experimental works on the external electromagnetic field effects on biological systems, there were some works interpreting obtained results as proof of internal cellular electrically, namely polar vibrations being affected by external fields [86-88]. This interpretation was based on the idea that the obtained resonant effects are possible under the condition that there are structures in the cells which already exhibit oscillatory behavior. Such structures should be able to vibrate with a high quality factor at the same frequencies as those applied externally. Indeed, if there is a cellular structure able to resonate with an external electromagnetic field, then it is also able to generate electromagnetic oscillations if energy is supplied [86,89]. Since, however, the reported effects are not specific or explainable also by other mechanisms, we cannot consider the reports a proof of electromagnetic activity of cells.

Higher THz and Infrared Radiation

Matter of any phase, chemical composition and structure, emits electromagnetic radiation as a result of thermal movement of charge in that matter. Near the thermodynamic equilibrium, the emission follows the famous Planck's law. This law states the maximal amount of radiation that the body may emit from its surface. The actual emission is influenced by the thermodynamic state of the body and the emissivity of the interface between the body and the surrounding medium, which is effected by the chemical and structural composition of the body. The higher the temperature, the higher the emitted electromagnetic power and frequency of emission. For physiological temperatures, the emission maximum lies in the infrared range.

There are only a few reports in the related literature regarding direct measurement of infra-red (IR) light in biology with intensity above that of the thermal blackbody radiation. One of these reports was from Fraser and Frey who measured infra-red activity from electrically stimulated crab nerves [90]. Non-thermal sub-millimeter wavelength radiation was detected by Gebbie and Miller [91] from electrically stimulated frog gastrocnemius muscle.

Visible Light - Luminescent Phenomena

Living cells may emit visible electromagnetic radiation by several luminescent mechanisms, including bio-, auto- and photo- luminescence. Bio-luminescence, i.e. the emission of light as a result of a chemical reaction, is quite common in some marine bacteria and also in larger marine organisms including vertebrates and invertebrates, and terrestrial fungi and insects. Bio-luminescence is governed by specific photoproteins or luciferin-luciferase complexes. The principle of light emission resides in the relaxation of the electron excited state which is produced by oxidation of the substrate.

Less known and understood is auto-luminescence, a by-product of oxidative reactions, which is common to virtually all metabolically active systems. Other common terms in related literature for this phenomenon are also *ultra-weak photon emission* or *biophoton emission.* As the name suggests, it has a much weaker intensity and no specific substrates are required. It is spontaneously generated within an organism without any external stimulation by light. The origin of auto-luminescence is derived from chemical reaction of molecular oxygen during the oxidative metabolism of lipids and proteins. At its beginning, reactive oxygen species (ROS) are produced and lead to the formation of electronically excited species, which at their decay from excited state to the ground state emit a photons. The intensity of such emission is in the range from tens to several hundreds of photons s^{-1} cm^{-2} [92].

Diverse living forms were examined for the presence of auto-luminescence, starting with algae [93,94] and a variety of microorganisms such as yeast [94-97] or bacteria [94-99]. Leaves [100,101] and germinating seeds [102,103] of higher plants were also studied, whereas auto-luminescence monitoring could be among other applications exploited in agriculture. Obviously, a great number of papers have been already carried out on vertebrates including humans. The topic of auto-luminescence from animals was intensively studied by Russian scientists, who performed experiments on amphibians [104,105] and fish [106,107] or also by a Japanese research group which studied the dependence of auto-luminescence on the oxidative metabolism of a rat brain [108]. Since the current scientific activities put a significant importance to the cancer research, thus a significant amount of works is focused on auto-luminescence from tumor formations and cancer cells [109-111]. Finally, part of the work focused on auto-luminescence deals with *in vivo* measurements from human skin from different parts of the body [112-115]. The fact, that auto-luminescence reveals a general physiological and oxidative state of the human body [115,116] provides an opportunity of potential applications in human medicine, including dermatology, neurology or oncology.

Extremely High Frequencies - Ultraviolet and Beyond

There is a limited number of reports on ultra-weak photon emission in the far UVA and UVB regions (< 350 nm) [96]. However, there are no established mechanisms for any chemical generation of excited species at such high energies.

There is no relevant reason to expect cellular electromagnetic activity on frequencies higher than that of visible light, because (i) such very high energy processes are unlikely to take place in biological systems and (ii) photons of such high frequencies carry energy which may cause damage to bio-molecules and subsequentially to cells.

The energy carried by a photon increases with the frequency. Ultraviolet photons carry energy high enough to cause molecular excitation which may lead to a permanent rearrangement of that molecule. This mechanism may act on vitally important molecules like DNA either directly or indirectly by the influence on the production of reactive oxygen species. Beyond the UVC range, photons reach such high energy levels that they are able to cause ionization, i.e. to liberate an electron from atom, and result in molecular damage. X-ray and gamma ray radiation is therefore termed as ionizing radiation [117].

RELEVANCE TO HUMAN MEDICINE

The role of an endogenous electromagnetic field in physiology and patophysiology remains a subject of speculations. The molecular interaction is in its nature governed by electromagnetic forces, but here we focus only on the non-stationary and/or radiative electromagnetic fields. Again, we may skip widely known electrophysiological issues.

Tsong proposed that oscillatory electric fields (kHz - MHz range) generated at the level of cell membrane can serve as signals for cellular communication [19,118]. Tsong refers to the oscillatory electric field of cells as the “language of cells” [19].

It was predicted that the endogenous cellular electrodynamic field with a frequency between kHz and GHz range may have a role in (i) the transport of reaction components and (ii) in the influence of the kinetics of chemical reactions [119,120], for instance for signaling purposes [121,122]. Long-range molecular interactions by electrodynamic fields have been subject to several studies [23,123-125]. Since certain cellular structures are predicted to create spatially and dynamically complex patterns (local minima and maxima of field intensity) of the electrodynamic field [39-42], this inhomogeneity in the pattern of the electric field should act by force on molecules. A deterministic component added to the diffusion movement of molecules would help organize the movement of the reaction components [126]. Similarly, the spatio-temporal organization of larger structures in the cell could be influenced by the electrodynamic field [127].

Pokorný recently speculated that cancer is connected with disruptions of cellular electromagnetic fields generated according to Fröhlich’s model [35,128]. In his view, during the cancerogenesis, the decline of the zone of the strong static electric field and of the space charge layer of protons around mitochondria leads to a diminished level of water ordering around microtubules. The damping of microtubule oscillations is then increased. Nonlinear properties of the microtubule system are weakened, which together with decreased efflux of the non-utilized energy from mitochondria leads to small power of electrical oscillations. Coherent processes in the cells are disturbed and random components play more important role.

The role of electromagnetic properties of microtubules in the formation of the consciousness is a keystone of the very famous, yet controversial, hypothesis by Penrose and Hameroff [129]. This topic, however, goes beyond the scope of this review.

Since the first pieces of evidence of biological auto-luminescence [130-132], scientists have been trying to find the biological purpose of auto-luminescence in organisms. No effort is being spared to prove the possibility of bio-communication via the optical region of the electromagnetic field within a single cell, between individual cells or even between entire organisms. A number of experiments were performed to examine the potential role of photons in cell-to-cell communication [133-138]. In such experiments, two biological samples are in close distance separated from each other by a chemical barrier; nevertheless the optical connection remains possible. Moreover the chemical barrier can be designed to be permeable just for selected frequencies. The impact of cell interactions on neighboring samples is studied after a certain time period; one can observe change in cell division, energy uptake, gene expression, orientation in space, *etc*. When the optical path is disabled, the effects disappear.

However, the significance of auto-luminescence as one of the means of bio-communication still remains a delicate topic for passionate discussions, on account of physical limitations primarily due to the high intensity of surrounding noise (background light), which is usually several orders of magnitude higher than the intensity of spontaneous auto-luminescence. It is yet unknown, if there is a certain mechanism within organisms, which enables the detection of such low doses of light and use them as a kind of information transfer [139].

DISCUSSION AND CONCLUSION

The electromagnetic activity of living cells is a highly controversial topic because literally decades of intensive research of this topic has not brought defensible experimental results yet. With the exception of well-established electrophysiology and auto-luminescence, there are no trustful experimental data showing any electromagnetic activity of cells. For frequencies between few hundreds of Hz and hundreds of THz we do not even have experimentally well-established indication that cells may generate an electromagnetic field significantly higher than that of thermal noise. Despite this fact, a large number of theories has emerged concerning the generation of an electromagnetic field in cells and also an employment of this hypothetical field by cells.

Beside hypotheses which are quite far-fetched, there are, of course, solid theories based on widely accepted physical mechanisms. However, when we put numbers in these theories we find that the intensities of the generated fields are very low or rapidly decreasing with the distance from the generating structure. Therefore, the direct force effect of such a field in biological processes, if any, is very likely to be limited to very local areas in the vicinity of the generating structure.

If we admit that electromagnetic fields play a role in the physiology of cells, we must conclude that any alteration of this field will lead to a modification in physiological processes. And we should concurrently ask whether any alteration of the field of cells can be done by an external electromagnetic field which could interfere with the internal one, because such mechanism would have evident medical applications.

A very large number of papers was published on the effects of radio-frequency and microwave electromagnetic fields on cells and living organisms generally. Besides the well-known thermal effect of the electromagnetic field, there has been also an effort to show specific non-thermal effects of weak radio-frequency electromagnetic radiation. Many experimental reports followed by theoretical explanation using hypothetical mechanisms were published over several decades. A critical analysis of these papers reveals that the reported effects are difficult to put in a unified framework [40], some of them being subtle, rather non-specific and, in numerous cases, also hardly reproducible. Despite their critical view, Apollonio *et al.* identified in their recent review [140] a few specific mechanisms of non-thermal effects

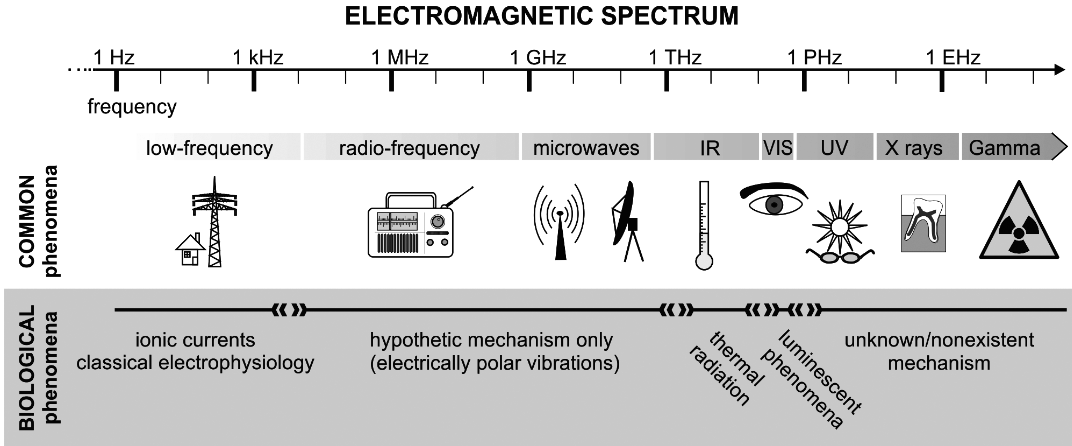

Fig. (1). The electromagnetic spectrum. The common physical phenomena are shown in the upper part of the figure; the biological phenomena are displayed below.

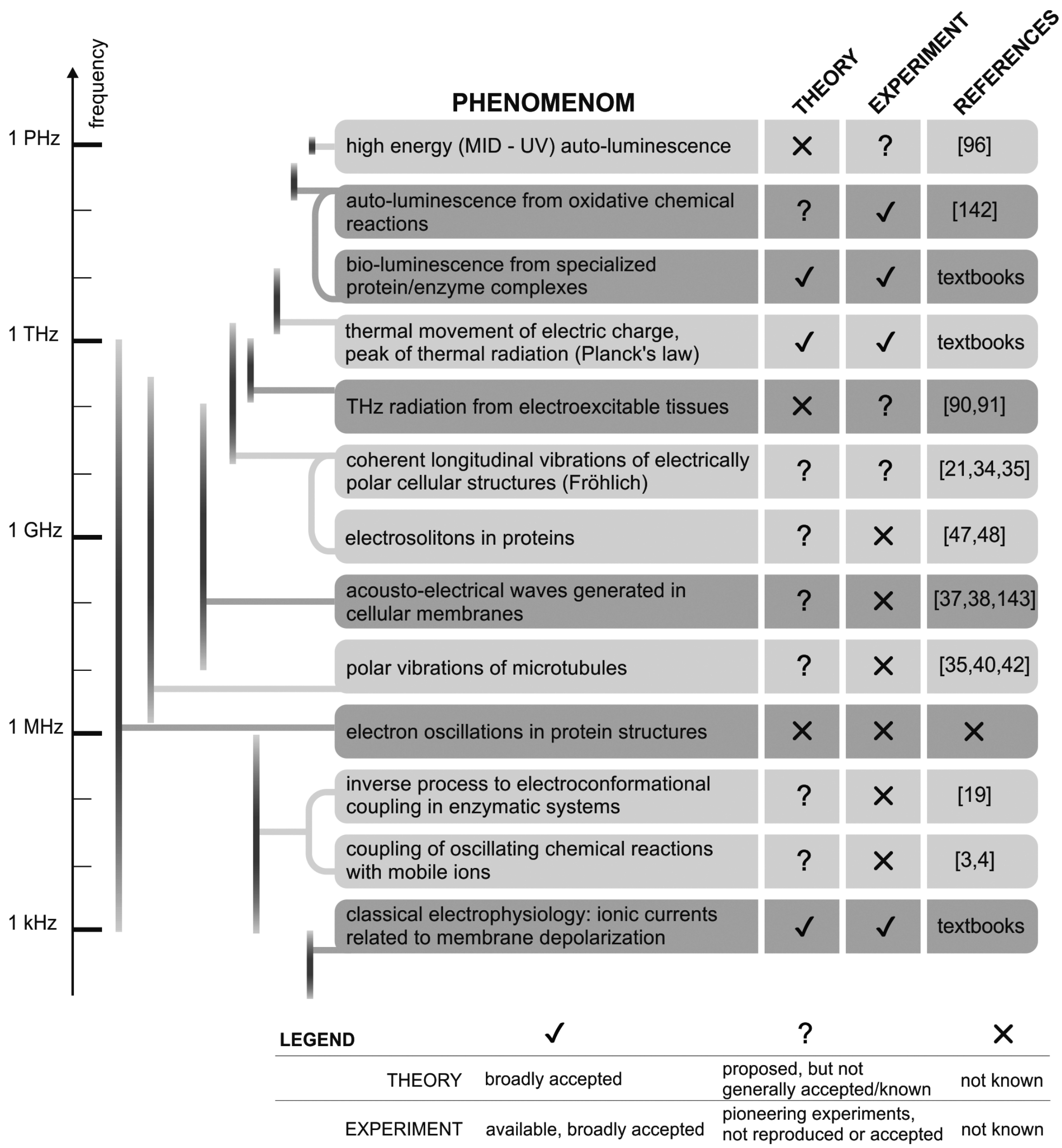

Fig. (2). A detailed distribution of the bio-electromagnetic phenomena within the electromagnetic spectrum. If the experiments proposed to confirm the theory mentioned in the text were only indirect or not giving mechanistic explanation we do not consider them in this figure.

which may provide a plausible explanation of the observed experimental results. These mechanisms include selective/micro-thermal heating and specific physical-chemical mechanisms involving effects on activation energy of chemical reactions, hydrogen bonds in the hydration layer, radical pairs and iron ions. Even if all of those effects were coming around, the weak field may very probably result only in an unspecific effect in such a complex system like the living cell.

The effects of electromagnetic radiation within frequencies beyond microwaves are also mostly pronounced by heating. Low intensity light has biological effect by frequency-specific absorption in bio-molecules [141]. However, the issue of alteration of the function of internal optical-band electromagnetic activity, if any biologically relevant function of such a field exists as a general phenomenon, is rather problematic because the measured intensities of endogenous light emission from cells are extremely low, usually far below the ambient noise [142].

In conclusion, we argue that the relevance of electromagnetic activity of living cells to physiology seems overestimated in the majority of the suggested theories. Rather than speculating about endogenous electromagnetic waves on the level of cells and tissues and their hypothetical role in physiology, which seems to be far-fetched based on the current knowledge, we encourage first to research electromagnetic events on the micro and nanoscopic level involving molecules and macromolecules to provide solid foundations for electromagnetic phenomena on a larger scale. Local events fit better to the current state of knowledge in biophysics and they are also better candidates for experimental testing and potential applications.

Due to low specificity of the effects of external electromagnetic fields on cells, we may expect that there is only a limited possibility to influence internal electromagnetic fields of cells by a complementary field. If endogenous fields have some role within the physiology and patophysiology, as some hypotheses suggest, chemical alteration of the molecular substrate which generates those fields would have been the only way to influence their function.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Authors acknowledge the support from the Czech Science Foundation, grant no. GA13-29294S, and the Grant Agency of the Czech Technical University in Prague, grant nos. SGS13/138/OHK3/2T/13 and SGS14/189/OHK3/3T/13.

CONTRIBUTIONS

Conceived the research: OK. Wrote the paper: OK, KC, MC, MN. Prepared the figures: MN.

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Received: March 13, 2014 Revised: September 22, 2014 Accepted: October 27, 2014