

Vibrations of Electrically Polar Structures in Biosystems Give Rise to Electromagnetic Field: Theories and Experiments

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Abstract— Mechanical vibrations of electrically polar structures are fundamental mechanism of generation of the electromagnetic field (EMF) in living cells. Overview of the experiments showing existence of the vibrations on the cellular level by measurements with various techniques is given; some of the recent theoretical and experimental achievements of the authors' group are also presented.

1. INTRODUCTION

Electromagnetic field (EMF) in living cells can be generated by various mechanisms. Mechanical vibrations of electrically polar cellular structures are probably the most important for broad range of frequencies from several hundred of Hz to THz. Vibrations on the cellular level have been proved by experiments using various techniques: Vibrations of the cell membrane have been measured up to tens of Hz by optical techniques, measurement of kHz membrane oscillations have been performed by AFM by some authors. Other authors also attempted to measure coherent THz oscillations of living cells by Raman spectroscopy. Some crucial points of the success and failures of this kind of experiments are elucidated.

2. PREMISE

The relation of nanomechanical oscillations of cellular structures to the generation of the EMF is following. Many intracellular structures have polar properties. The majority of proteins are electrically polar molecules [1]. Vibrations may be excited in the protein structures provided that energy is supplied. The spectrum of vibrations may span from low kHz up to GHz region [2–4] and likely also to THz [5].

The most likely candidate for the generation of EMF in a cell is cytoskeleton. Heterodimer of alpha and beta tubulin, which microtubules, one of three cytoskeleton elements, consist of, is a strong electric dipole with dipole moment about 10^{-26} cm [6]. Energy is supplied to the cytoskeleton from three possible sources: Hydrolysis of GTP (guanosine triphosphate) after polymerization of microtubules, motor protein movement and flow of wasted energy from mitochondria [7]. Other possible candidates for EMF generation are proteins in a cellular membrane which are in nonlinear regime due to the electric field created by membrane potential (in human cells up to -100 mV) which is realized on extremely short size of membrane thickness (about 10 nm). It is more than probable, that mechanical oscillations of microtubules and cell membrane generate EMF and it is supposed, that this field plays role in cell physiology [8] and participate in the controlling of the organization of living matter [9]. A few crucial experiments dealing with electromagnetic activity of living cells will be cited.

3. CELLULAR ELECTROMAGNETISM

Characteristics of the electrostatic and current field, causes of the membrane potential and action potential respectively, are widely known [10, 11]. Measurement of the electric component of the field generated is widely used in medical diagnostics (ECG, EEG, EMG e.g.).

Attraction of small dielectric particles to the surface of the living cell as a result of the dielectrophoretic effect was observed by Pohl [12, 13]. The number of attracted particles was dependent on cell cycle and was greatest during the beginning of the M-phase, when the microtubules show extraordinary dynamic instability and form the mitotic spindle.

Electric vibrations of yeast cell membrane in kilohertz range were measured by Pohl et al. and Pokorný et al. [7, 14]. Electromagnetic oscillations in megahertz range were measured by Pokorný et al. [15] ($8 \div 9$ MHz) and by Hölzel and Lamprecht [16] ($1 \div 100$ MHz). Grundler and Keilmann [17, 18] observed nonthermal resonant effects of 42 GHz microwaves on the growth rate of

yeasts. One of the explanations was that external EMF resonantly interacts with cellular vibrational system, thus the cellular electrically polar vibrations could be of comparable frequency. Nevertheless, direct measurement of the electromagnetic activity in the mm wave region by Jelínek et al. [19] has not confirmed the hypothesis. Vos et al. [20] measured coherent spectral lines in stimulated emission from membrane proteins in the sub-millimeter and far infra-red (IR) range of spectra using femtosecond laser spectroscopy. Albrecht-Buehler [21] described the ability of cells to interact in the red or near infra-red range. Biological photon emission in visible and ultra-violet (UV) range is widely accepted and was described and measured e.g., in [22, 23].

4. THEORIES

There are several theories which have been postulated regarding the generation of EMF in biological systems and its possible organizational role. One of the most influential hypothesis connected with transformation of random thermal vibrations to coherent vibrations has been postulated by Fröhlich [24]. Nonlinear conditions allowing this transformation have been assumed. Fröhlich assumed that nonlinearity may be caused by high electric field in the cellular membrane and conjectured therefore that transmembrane proteins are the vibrational centres which transform the thermal energy to coherent. Only recent experimental findings [25] show that there is a high static electric field inside a cell due to protons diffusing from mitochondria. Microtubules are in a strong electric field since mitochondria are aligned near them. Mitochondria are also source of thermal energy and radiation released in the course of citric acid cycle. It is very likely that mitochondrial activity provides necessary conditions for the nonlinear behavior and energy transformation in the cytoskeleton.

5. MECHANICAL VIBRATIONS OF CELLS AND SUBCELLULAR STRUCTURES

We briefly overview published experimental observation of mechanical oscillations and vibrational modes of cellular structures from low to high frequencies in this section.

Nanoscale structure and low frequency (minutes period) dynamics associated with live red blood cells membrane displacements are measured using quantitative phase images provided by Fourier phase microscopy [26]. He et al. [27] observed periodic motion of native human cancer cells on sub-hertz frequencies. Piga et al. [28] revealed nanometre-scale vibrations (up to 30 Hz) of live cells (rat pheochromocytoma line PC12) by the Scanning Near-field Optical Microscope (SNOM). Levin, Korenstein et al. [29] observed nonlinear nano-scale oscillations (at frequencies 0.2–30 Hz) of human erythrocytes membrane with point dark field microscopy and linked them to MgATP-dependent dynamic assembly of the sub-membrane skeleton. The oscillations were also observed in monocytes, lymphocytes, 3T6 fibroblasts, cardiomyocytes and murine lymphoma B and T cell lines [30]. The amplitude of oscillations was of the order of magnitude of tens to few hundreds of nm's depending on the cell type.

Group of Kamimura showed with phase-contrast microscopy [31] and modified atomic force microscopy [32] that axoneme¹ generate vibrations of 300 Hz in presence of MgATP.

Pelling et al. [33, 34] demonstrated a local nanomechanical motion of the cell wall of yeast *Saccharomyces cerevisiae* under physiological conditions using atomic force microscopy (AFM). Oscillatory signal observed with average amplitude of 3.0 ± 0.5 nm was characteristic for about 70% measurements performed. Fourier transforming of signal measured disclosed temperature dependent prominent peak of 0.9 kHz at 22°C to 1.6 kHz at 30°C. Oscillatory character of the motion disappeared after treating the cells with metabolic inhibitor sodium azide. Authors concluded the metabolic origin of the motion with special attention to concerted activity of motor proteins. Measurement of such oscillations was reproduced by Pokorný et al. [7].

Mosbacher et al. [35] reported membrane mechanical motions of HEK293 cells using AFM when AC voltage was applied through voltage clamps. These movements of several nm's amplitude tracked the voltage at frequencies >1 kHz with a phase lead of 60–120°, as expected for a displacement current.

Edwards reported direct coupling of microwave field to acoustic modes of DNA probed by dielectric spectroscopy [36], which was manifested by resonant response of absorption coefficient. The connection between result obtained and microwave coupling was criticized by Foster [37].

Recent advances in THz spectroscopy show existence of THz modes in various biopolymers and biomolecules [38], in DNA, albumin, collagen [39], benzoic acid, aspirin [40], tryptophan [41].

¹Axoneme is a core of whip-like cilia or eukaryotic flagella, in e.g., sperm. The building block of axonemes are microtubules and various protein complexes including motor proteins dyneins.

Experiments with classical Raman spectroscopy [42–44] found that the certain vibrational modes (\sim THz) in *E. coli B* can be nonthermally excited. Although the results weren't accepted and were attributed to fluorescence artifacts by e.g., [45, 46], del Giudice et al. [47, 48] strongly argued for the validity of above interpretation.

Coherent vibrations of proteins were experimentally investigated using femtosecond laser spectroscopy [20, 49–51]. Coherent vibrational nuclear motion in submillimeter band² have been detected in membranes of bacteria (e.g., of *Rhodobacter capsulatus*) with genetically modified photosynthetic systems. Coherent nuclear dynamics in bacterial reaction centers was observed even at room temperature [50].

6. DISCUSSION

There are several technical prerequisites for the measurement setup which is aimed to probe cellular vibrations. One of them was pointed out by Korenstein et al. [29]. They found that the low frequency membrane mechanical oscillations (up to 30 Hz) could only be resolved when measuring from area $0.25 \mu\text{m}^2$ or less. It may be expected that the spatial resolution for detection of high frequency vibrations might be of the order of magnitude of tens or units of nanometers if successful measurement is to be performed. Regarding the possibility of detection of nonthermal excitations of living cells with classical Raman spectroscopy it needs to be noted that there is a fundamental incompatibility of the measured objects with the measurement technique itself. Principally, measurement of ratio of anti Stokes and Stokes line intensities is the most straightforward method to determine the above thermal excitations. The appearance of the anti Stokes lines may also depend on the cell cycle. But there is a principal obstacle to detect far IR biological signals of the Raman systems as far as they are based on macroscopic volume detection. The intracellular processes are based on molecular nanostructures and this property determines requirement for detection systems. One needs new types of Raman spectroscopy which provide sufficient amplification of the signal and point measurement to show if there are coherent vibrations in biological systems in spectral region suitable for Raman spectroscopy. Modification of surface enhanced Raman spectroscopy [52] or Coherent anti-Stokes Raman spectroscopy may fulfill these conditions. Wavelength of excitation laser is preferred to lie in infrared region rather than in visible to minimize possibility of fluorescence and disruption of cells.

Brillouin spectroscopy, fulfilling similar prerequisites as those mentioned above for Raman spectroscopy, may be suitable for the measurement of vibrational modes in microwave region.

7. CONCLUSION

A brief overview of theories and experiments dealing with vibrations of electrically polar structures in biosystems was given. These vibrations are supposed to generate an endogenous biological EMF the existence of which may have deep consequences in organization of biological processes and structures and possible interaction with exogenous EMF.

Comprehensive review of the issue presented is being prepared and will be published soon.

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