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Calculation of the Electromagnetic Field Around Microtubule

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Abstract. *Microtubules are important structures in cytoskeleton which organizes the cell. Single microtubule is composed of electrically polar structures, tubulin heterodimers, which have strong electric dipole moment. Vibrations are expected to be generated in microtubules, thus tubulin heterodimers as electric dipoles are oscillating. This gives rise to electromagnetic field, which is detected around the cells. We calculate here the electromagnetic field of microtubules if they are excited at 1 GHz. This paper includes the work done in bachelor thesis of the first author.*

Keywords

bioelectromagnetism, microtubules, endogenous electromagnetic field of biological systems

1. Introduction

Generation of electromagnetic field is not limited to the elite class of electroexcitable cells of higher organisms. Large number of experiments indicates that living cells in general generate electromagnetic field (EMF) in broad frequency spectrum from kHz [1] through MHz [2, 3, 4] to optical region [5]. Generating mechanism vary across the spectrum. The most likely source for cellular EMF generation in radiofrequency region is mechanical vibration of cellular electrically polar structures. This concept was first postulated and theoretically treated by Fröhlich in late 1960ies, for review see [6]. He proposed electrically polar longitudinal vibrations interacting with elastic field giving rise to coherent cellular EMF. It was estimated that oscillating units are located in cellular membrane and oscillate in frequency region of 10^{11} – 10^{12} Hz. After the cytoskeleton was discovered and more information on physical properties of its subunits has been gathered, microtubules emerged as a likely candidate for generation of cellular EMF [7]. Microtubules (MTs) are part of cytoskeleton which is present in every eukaryotic cell [8]. MT resemble hollow rod with outer and inner diameter of 25 nm and 17 nm, respectively. MT composes of tubulin heterodimers which are protein of high electric dipole moment (over 1000 Debye ~ 10^{-26} C.m) with one component aligned partially in the axis of MT. Tubulin heterodimers stack into protofilaments which assemble further to MTs. Oscillations of microtubules have been proposed to be present from MHz to GHz region [7, 9, 10]. Thus tubulin heterodimers can be approximated as oscillating electric dipoles. We show the components of the EMF around elementary oscillating electric dipole and calculate the consequently generated EMF around MTs in this paper.

2. Components of the electric and the magnetic fields of the elementary oscillating electric dipole

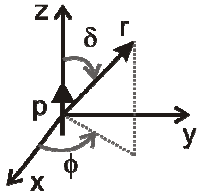

Fig. 1. A dipole in the Cartesian coordinate system.

$$H_\varphi = -\frac{Idl}{4\pi} k^2 \sin\delta \left(\frac{1}{jkr} + \frac{1}{(jkr)^2} \right) e^{-jkr} \quad (1)$$

$$E_r = -\frac{Idl}{4\pi} Zk^2 2\cos\delta \left(\frac{1}{(jkr)^2} + \frac{1}{(jkr)^3} \right) e^{-jkr} \quad (2)$$

$$E_\delta = -\frac{Idl}{4\pi} Zk^2 \sin\delta \left(\frac{1}{jkr} + \frac{1}{(jkr)^2} + \frac{1}{(jkr)^3} \right) e^{-jkr} \quad (3)$$

The electromagnetic field around the elementary electric dipole (thereinafter is known as EED) is defined by equations (1 - 3) [11]. *H* is magnetic field intensity, *E* is electric field intensity, *I* is equivalent current, *dl* is length of the dipole, *k* is propagation constant, *Z* is wave impedance, *j* is imaginary unit (j^2 = -1) and other symbols are according to Fig. 1. None of these equations (thereinafter is known as EQs) are dependent on φ and all EQs include:

$$j\omega\hat{p} = Id\vec{l} \quad (4)$$

where ω is angular frequency and *p* is dipole moment. Intensities of the electric and the magnetic fields are orthogonal to; each other in every point in space. Complicated dependence of intensities with the variable r

denotes that the field has different properties over various distances. There are three parts of the field which differ in the value of power of the product jkr in the denominator of EQs 1-3; i.e. near, intermediate and far zone.

2.1 Modifications of EQs (1-3) for the calculations of intensity modulus of the electric field in a lossy medium

There is a dominant electrical component over a magnetic one in the near zone of EED. The near zone demonstrates dimensions far greater than those of the size of a cell in the frequency of 1 GHz. That is the reason why we have decided to work here with the electrical component only.

Modulus was calculated using EQs 1-3 in lossy medium [12]. Phase was omitted to simplify the calculation. This can be done only when the examined distance is much smaller than the wave length to retain validity of the results.

3. The description of the intensity of the electric field around a microtubule

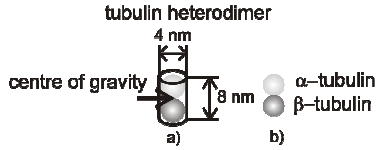

Fig. 2. The aproximation of a heterodimer on EED.

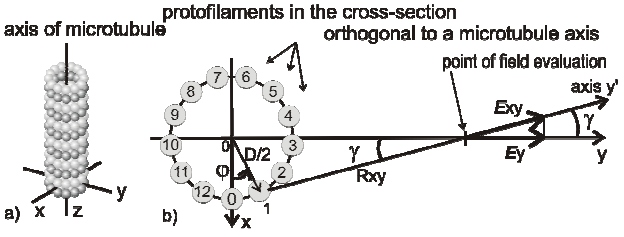

Fig. 3. a) The placing of a microtubule into the coordinate system
b) A section through the xy plane [13]

Fig. 3 depicts a microtubule in section through xy plane. An EQ describing the calculation of an angle φ which forms an angle of axis x with D/2 follows:

$$\varphi = n\frac{2\pi}{13} \tag{5}$$

where n means the order of protofilaments (thereinafter is known as PTs) and is given the values of 0, 1, 2, up to 12. The distance of a PT from the point of field evaluation (PFE) is called Rxy and will be calculated according to the following EQ:

$$R_{xy}^2 = \frac{D^2}{4} + y^2 - Dy\sin\varphi \tag{6}$$

The angle γ can be expressed as:

$$\cos\gamma = \frac{1}{R_{xy}}\left(y - \frac{D}{2}\sin\varphi\right) \tag{7}$$

The size of the vector Ey is defined by the following EQ:

$$E_y = E_{xy}\cos\gamma \tag{8}$$

and using EQ 7 we get another EQ

$$E_y = \frac{E_{xy}}{R_{xy}}\left(y - \frac{D}{2}\sin\varphi\right) \tag{9}$$

An arbitrary axis Y' intersecting PT and PFE will be used for the calculation of contributions of each heterodimer. We can see the cross-section of y'z plane on Fig. 4.

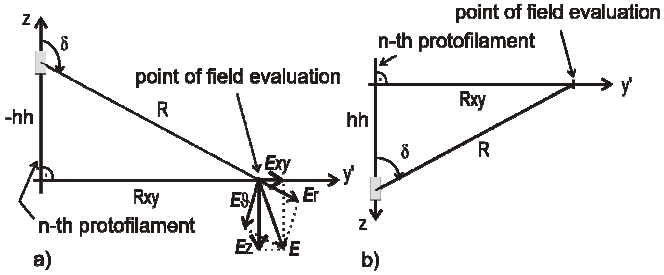

Fig. 4. The cross-section of y'z plane [13].

Components Er and Et are described by EQs 2 and 3. To simplify the calculation, Et and Er are converted into Exy and Ez.

$$E_Z = -E_\delta\sin\delta + E_R\cos\delta \tag{11}$$

$$E_{XY} = E_\delta\cos\delta + E_R\sin\delta \tag{12}$$

where angle δ is defined by the following EQ:

$$tg(\pi - \delta) = \frac{R_{XY}}{hh} \quad \text{or} \tag{13}$$

$$tg\delta = \frac{R_{XY}}{hh} \tag{14}$$

EQ 13 is used in the case that **hh < 0** (Fig. 4a) and EQ 14 if **hh > 0** (Fig. 4b). Parameter **hh** is a distance between the centre of gravity of heterodimer from PFE and is defined by the EQ:

$$hh = z - h \tag{15}$$

where "z" is the z-th coordinate PFE and "hh" is a distance between the centre of gravity of the first heterodimer and the centre of gravity of the examined one.

$$R = \sqrt{R_{xy}^2 + hh^2} \tag{16}$$

EQ 23 – 33 and 1 – 3 describe the intensity of the electric field of a microtubule without a shift of PT.

3.1 Shift of protofilaments

The lattice with intensity shift of PTs simulates more realistic projection of the organization of PTs in the microtubule [14]. This gives us more accurate information about the way the intensity of the electric field around MT. We have chosen the configuration in A-lattice, this is a lattice with a longitudinal shift of PTs of 4,92nm (Tab. 1 and Fig. 5-6).

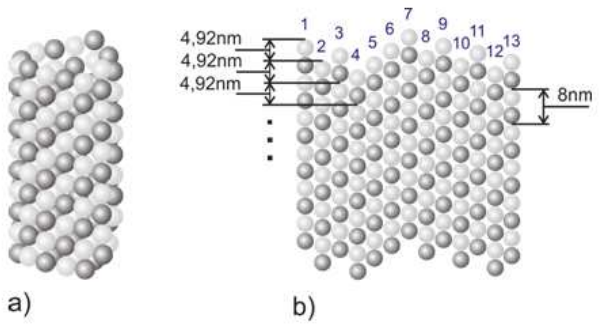

Fig. 5. a) Microtubule with longitudinal shift of 4,92nm.
b) Shell of MT with longitudinal shift of PT.

number of PT	2	3	4	5
shift to 1. PT [nm]	-4,92	-1,84	-6,76	-3,68

number of PT	6	7	8	9
shift to 1. PT [nm]	-0,6	2,48	-2,44	0,64

number of PT	10	11	12	13
shift to 1. PT [nm]	-4,28	-1,2	-6,12	-3,04

Tab. 1. Longitudinal shift of PT in A-lattice.

3.2 The coherent and random excitation

All dipoles (heterodimers) are excited in phase when excited coherently. We have also attempted to simulate incoherent (thermal) oscillations by two means using a randomly oriented dipole moment. For the first approximation randomly generated matrix which turned the dipole moment either to positive or to negative axis z was used (+-). For the second approximation the matrix of random numbers from 0 to 1 was generated (p*sin). The size of the dipole moment was defined by function:

$$pp = p \cdot \sin(2\pi \cdot n) \tag{17}$$

where n is the value of the matrix element corresponding to certain heterodimer and for p see Tab. 2.

3.3 Material constants and the dipole moment

Dipole moment:	**$p = 10^{-26}$ Cm (1000 Debye) [14]**
Relative permittivity (non-conductive medium):	**εr = 81 (water)**
Relative permittivity (conductive medium):	**εr = 60 [15]**
Conductivity:	**σ = 1 S/m [15]**

Tab. 2. Material constants and the dipole moment

3.4 Depiction of direction and magnitude of the electric field

The size of the electric field (EF) was drawn by function surf, see e.g. Fig. 6. For depicting the direction of EF which is slightly more complicated function, a *vectarrow* [16] was used. The vector describes only the direction of EF. The magnitude of EF is expressed by color scale in the picture.

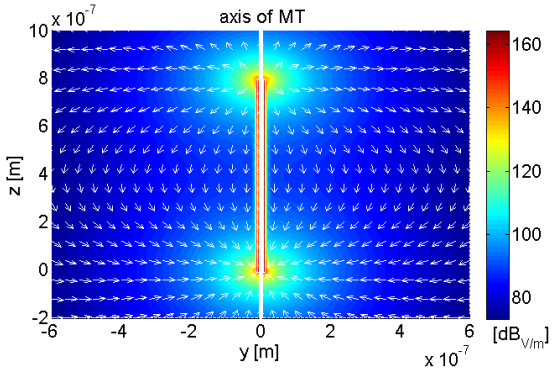

Fig. 6. The excitation in phase

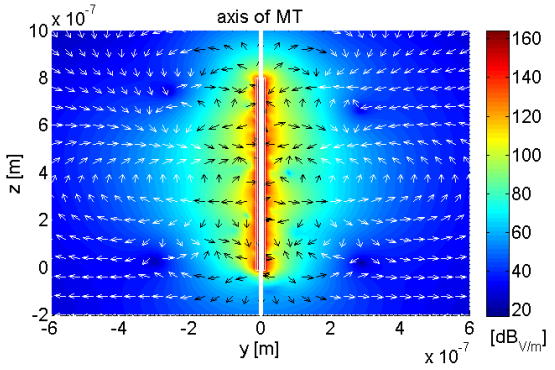

Fig. 7. The random excitation with function „+-“

4. Results

A schematic depiction of the EF around MT in a immediate surroundings (6. 10^{-7} m) and in distance comparable to cell size (6. 10^{-6} m) can be seen in Fig. 6., 7., 8. and Fig. 9., 10., respectively. Every PT is composed of 100 heterodimers (HDs) and there is a longitudinal shift of each PT of about 4,92nm (see Fig. 5a). MT has the length of 800nm and is situated

in a lossy medium. HDs are excited at a frequency of 1GHz and the type of excitation is always specified in every picture. Arrows on the pictures depict direction and the color describes the magnitude of the EF.

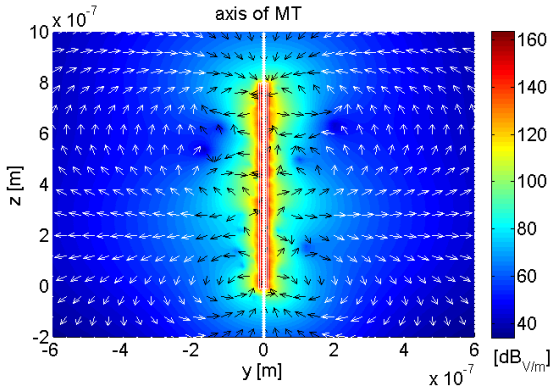

Fig. 8. The random excitation with function "p*sin"

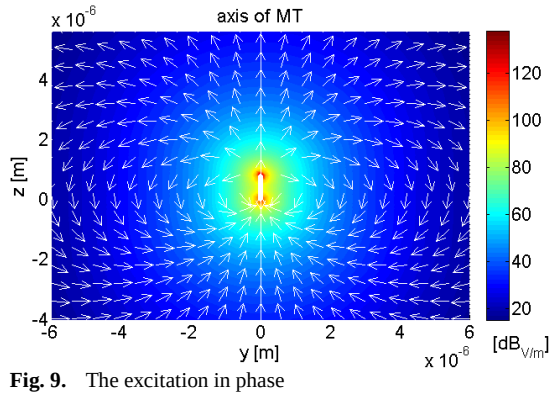

Fig. 9. The excitation in phase

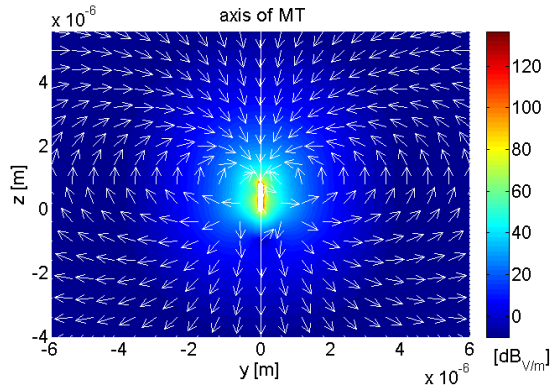

Fig. 10. The random excitation with function "+-"

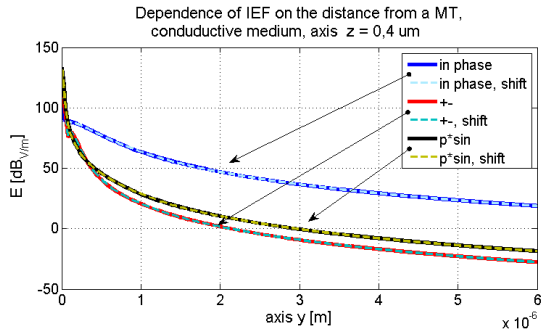

Fig. 11. Dependence of IEF on the distance from a MT

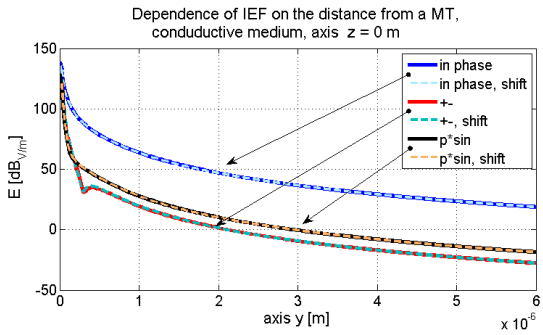

Fig. 12. Dependence of IEF on the distance from a MT

5. Discussion of results

First, simplifications we applied in our calculations are to be discussed. We used only the modulus of the intensity for the calculation of the field. As mentioned in section 2., this simplification is valid only when the distance between sources of the EMF is very small compared to the EMF wavelength so the phase shift and possible interference can be neglected. Excitation frequency was chosen arbitrary to be 1 GHz. Physically it has substantiation in estimated frequency range of MT oscillations, which was calculated to be from kHz to GHz region [7, 9, 10].

We clearly see the difference between the random and in phase (coherent) oscillations. Although EF intensity (denoted as IEF in figures) is higher in the middle of the MT length (z = 0,4 μm) for random excitation, it falls off faster with the distance compared to the in phase excitation (Fig. 11). The EF intensity is higher on the poles of MT (z = 0 μm, z = 0,8 μm) for in phase excitation compared to random one (Fig. 12). There is difference by two orders of magnitude between the EF intensity of randomly and in phase excited EMF in the distance larger than ca. 100 nm. Furthermore, random excitation may exhibit local minima of the EF intensity, see e.g. Fig. 7 and Fig. 12. In the case of in phase oscillations, microtubule acts as one giant dipole. More realistic calculation should take into account that thermally excited oscillations do not hold the phase not only between oscillators but also in the wave train of single oscillator. Regarding the in phase oscillation of large number of dipoles, question arises if there is any physical foundation for phase synchronized oscillations of many dipoles which manifests as a single giant dipole. Actually, similar behavior (giant dipole like oscillation [17]) might be obtained if the oscillation of MT would be of zero wave number mode. In the case of weak nonlinear coupling of chain of oscillating units, energy indeed tends to condense in lowest mode - reminiscent of Fermi-Pasta-Ulam problem [18]. Mechanical coupling of individual tubulin heterodimers in MT may be rather strong, condensation to lowest mode, if occurs at all, is therefore more probable due to coupling of individual MTs. More realistic model of the EMF around MT should take into account also higher longitudinal, circumferential and radial modes and their mutual

interactions as was analyzed in orthotropic MT model of Wang et al. [10]. The possibility of MT oscillations in physiological conditions was questioned due to viscous damping of oscillations in cytosol [19]. Significant viscous damping does not necessary need to be the case if the slip layer condition is applied for analysis of MT vibrations [20]. This seems to have solid physical foundation, since the physical properties of cellular water differ significantly from that of bulk water; this applies also for viscous damping. Coherent quantum electrodynamics in matter [20, 21] predicts that rather large fraction of bulk water and majority of cell water is composed from distinct coherent domains which have different physical properties (viscosity, density, etc.) than the rest of the water volume. Especially remarkable is that microvolumes of water surrounding biomolecules may exhibit drastically lower damping and viscosity than bulk water [21]. To confirm the existence of MT generated EMF, in vivo measurements are necessary. Either direct nanoelectrical detection or indirect optical detection with electric field intensity dependent fluorescent dyes would be suitable.

6. Conclusion

Microtubules may be a source of endogenous cellular EMF. We presented here a simple model of MT EMF geometry and properties. Endogenous cellular EMF may contribute significantly to dynamic and spatial organization of cellular processes and structures [23]. Future work will include more realistic field excitation conditions and field distribution according to the modes of vibrating orthotropic cylindrical shell [10] and the phase into the calculations.

7. Abbreviations

EED – elementary electric dipole, EF – electric field, EMF – electromagnetic field, HD – heterodimer, IEF – intensity of electric field, MT – microtubules, PT –protofilament, PFE – point of field evaluation.

8. Acknowledgments

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