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MICROTUBULES IN BIOLOGICAL CELLS AS CIRCULAR WAVEGUIDES AND RESONATORS

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ABSTRACT

The microtubules in the cellular cytoskeleton have a fundamental role in the living processes of biological cells. They are hollow cylinders which resemble circular waveguides or cylindrical resonators. The cutoff and resonant frequencies of the transverse magnetic and transverse electric modes of the microtubule cavities are in the band of soft x-rays. This suggests the possibility of interaction of electromagnetic cavity modes with inner electrons in atoms (e.g., in carbon, nitrogen, and oxygen). Biological cells (e.g., the yeast cells of spherical shape) may also represent cavity resonators. In this case, the resonant frequencies may be in the infrared region.

INTRODUCTION

Living cells are structurally and dynamically organized by a protein polymer network called the cytoskeleton. The cytoskeleton is composed of intermediate filaments, actin filaments, and microtubules. The filaments and microtubules are connected to a large variety of accessory proteins and form a three-dimensional network in the cell.

The microtubules are the main organizers of the cytoskeleton. They are cylindrical structures (hollow tubes with outer and inner diameters of about 25 nm and 17 nm, respectively) composed of 13 (or 14) protofilaments, which are one-

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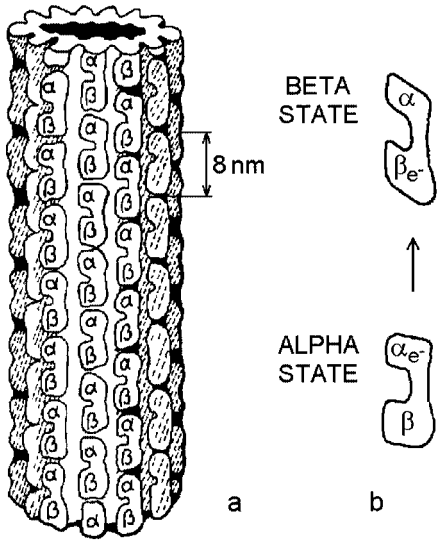


Figure 1. A microtubule.

dimensional chains of heterodimer tubulin molecules. The heterodimers contain α- and β-monomers (1). The structure of a microtubule is shown in Figure 1.

The heterodimer molecule is an electric dipole. Therefore, microtubules are polar structures with plus (fast growing) and minus ends (slow growing) embedded in the centrosome—a center of the cytoskeleton. Tuszyński and Brown determined the dipole moment to be 1700 D (2).

The mechanisms of cytoskeleton activity are still not well understood. The cytoskeleton exerts forces and generates movements without any major chemical change. A physical mechanism is probably responsible for cytoskeleton function. Vibrations in the cytoskeleton are possible mechanisms (3).

As the microtubules are polar entities, their generated electromagnetic field mediates long-range interaction with their surroundings as well as with their interior medium (in their cavities). Mavromatos suggested interaction of oscillation processes (the heterodimer dipole excitations) with coherent modes in the water interior of the microtubule cylindrical cavities (i.e., with the dipole moments of the water molecules) (4).

MICROTUBULES AS CIRCULAR WAVEGUIDES OR RESONATORS

Microtubules form cylindrical cavities of various lengths. The walls of the cavities are formed by the proteins of tubulin heterodimer molecules. Conductivity of a protein may depend on electron transport through the protein by a mechanism of electron hopping through its different parts, which are close together in space

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due to the complicated folding of the protein. The conductivity may be as high as 1 S/m (5).

As a zero order approximation, we will assume that the microtubule wall is a good conductor. Thus, we can consider the microtubule as a circular waveguide or as a resonant cavity of circular cross section.

Two principal modes can be excited in waveguides: the transverse magnetic (TM) and transverse electric (TE) modes. The cutoff frequency of a circular waveguide is given by the relation (6)

$$f_{n,m} = \frac{\alpha_{n,m}}{2\pi\, a\sqrt{\mu\varepsilon}}, \tag{1}$$

where $\alpha_{n,m}$ is the root of the Bessel function (for the TM modes) and of its first derivative (for the TE modes); μ and ε are, respectively, the permeability and the

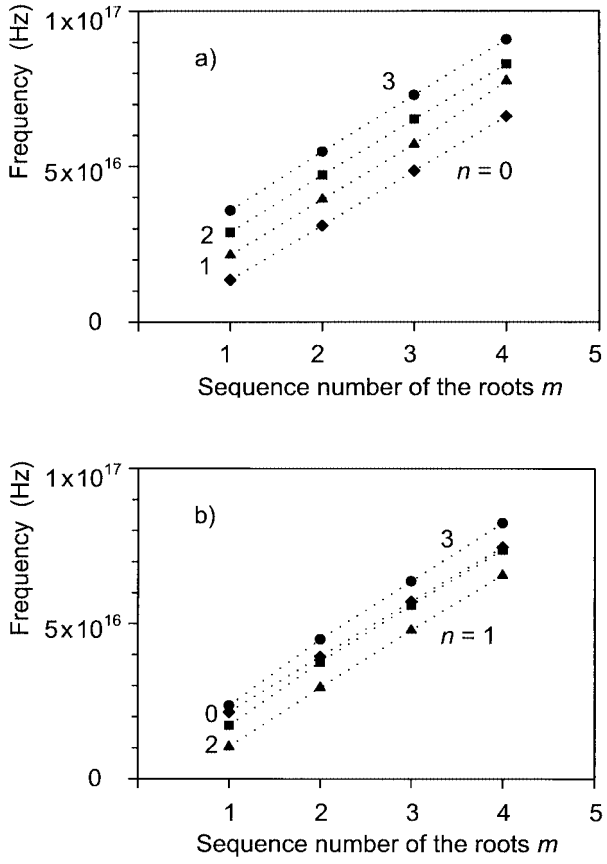


Figure 2. The cutoff frequencies of the model microtubule waveguides as a function of the sequence number of the roots m. The dotted lines connect the values belonging to the same parameter n which denotes the order of the Bessel function. a) TM modes, b) TE modes.

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permittivity of the medium inside the waveguide; and a is the radius of the transverse circular cross section.

Figures 2a and 2b show the cutoff frequencies of the microtubule TM and TE modes, respectively. The cutoff frequencies are of the order of 10^{16} Hz.

The resonant frequency of a resonator with a circular cross section and with length l is given by the relation (6)

$$f_{m,n,p} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{\alpha_{n,m}}{a}\right)^2 + \left(\frac{p\pi}{\ell}\right)^2}, \tag{2}$$

where p is an integer ($p = 0, 1, 2, \ldots$). The frequencies determined from Equation (2) for resonators and from Equation (1) for waveguides are nearly equal to one another for length l from 0.1 to 10 μm. The cutoff and resonant frequencies are of the order of 10^{16} Hz; that is, they are in the region of soft x-rays. This suggests the possibility of interaction of inner electrons in biologically important atoms (such as carbon, nitrogen, and oxygen) with the cavity electromagnetic modes of the microtubules.

The x-ray spectra are given by the relation (Moseley law)

$$f = R(Z - S)^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right), \tag{3}$$

where R is the Rydberg number, Z is the atomic number, S is the screening constant (in this case we assume that $S = 1$), and n_i, n_f are the principal quantum numbers of the initial and final states, respectively.

Fig. 3 shows x-ray spectra of biologically important atoms, i.e., of carbon, nitrogen, and oxygen. The K_α and K_∞ lines correspond to the transition of electrons

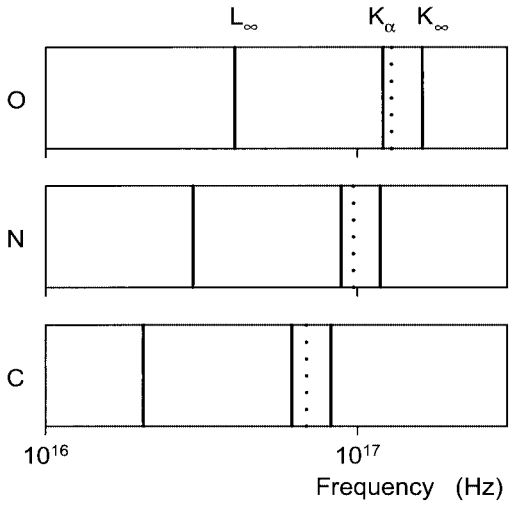


Figure 3. The x-ray spectra of oxygen, nitrogen, and carbon evaluated from the Moseley law (solid lines) and experimental values of the K level terms (dotted lines).

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from the L shell and from infinity, respectively, to the K shell. The L_∞ lines represent transition from infinity to the L shell.

CELLS AS SPHERICAL CAVITIES

A similar analysis can be applied to biological cells (e.g., the yeast cells of spherical shape). The cell membrane separating the cell from the surroundings is a lipid bilayer whose thickness is about 5 nm. In the classical radio frequency bands, the membrane conductivity is low and it behaves like a capacitor. A wide variety of shapes of cells may exist. Nevertheless, we will assess resonant frequencies of a model cell with a spherical cavity. The interior of the sphere is assumed to be a perfect dielectric and the boundary surface a good conductor.

The relations for resonant frequencies for spherical cavities (7) are very similar to the relations for cutoff frequencies given above. For a cell with radius $a = 5$ μm the fundamental resonant frequency is 4.3×10^{13} Hz and 2.62×10^{13} Hz for TE modes and TM modes, respectively. The resonant frequencies are in the infrared region.

DISCUSSION AND CONCLUSIONS

We assumed that walls of biological cavities (of microtubules and of cells) are good conductors. This assumption is very likely not satisfied, as all of the incident electromagnetic energy is not reflected. The electric properties of the walls differ from the properties of the surrounding medium, but the conductivity need not be the main difference.

In the case of biological cells, the membrane is a dielectric medium whose permittivity differs from the permittivity of the ambient medium. The conductivity is lower than the conductivity of the exoplasm and cytoplasm. This is valid for frequencies below 1 GHz. We may assume that the membrane does not represent a perfect conductor (a medium with high absorption) in the infrared region. We have to emphasize that different permittivity and conductivity of various parts of biological cells make possible a resonance excitation of the cavities by external electromagnetic fields.

A certain amount of the energy quanta of the cavity modes of the electromagnetic field that impacts the walls of the microtubules may penetrate through the walls into the surroundings. This case may be described by a model of a cylindrical waveguide with dielectric or semiconducting walls. The medium outside the cylinder has to be included in evaluation. Nevertheless, the effective conductivity representing energy absorption in the walls is not known.

Regardless of this, microtubules can be considered as waveguides and resonators with cutoff or resonant frequencies in the soft X-ray band. We would like to point out the possibility of interaction of inner electrons in biologically impor-

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tant atoms (such as carbon, nitrogen, and oxygen) with the cavity electromagnetic modes of the microtubules.

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