ELECTROMAGNETIC BIOLOGY AND MEDICINE
Vol. 22, No. 1, pp. 15–29, 2003

Viscous Effects on Polar Vibrations in Microtubules

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ABSTRACT

Microtubules form a fundamental organization structure in the cytoskeleton of the cell. Electrical polarity and high deformability at low stress are important physical properties of microtubules. Ions from the cytosol are attracted to tubulin heterodimers with electric dipoles and create a charge layer around the surface of the microtubule. Because of the slip boundary conditions in the surface layers of the microtubule and in the adjacent charge layer dissipative effects of viscous damping on vibrations are diminished. At the frequency 10 MHz the relaxation time may be more than 100 times greater than the period of oscillations. Energy supplied by hydrolysis of GTP (guanosine triphosphate) to GDP (guanosine diphosphate) in the β-tubulins might, therefore, excite vibrations in microtubular structures.

Key Words: Vibrations in microtubules; Viscous damping of vibrations; Electromagnetic activity of microtubules.

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DOI: 10.1081/JBC-120020349
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INTRODUCTION

Eukaryotic cells are structurally and dynamically organized by a protein polymer network—the cytoskeleton—but principles and mechanisms of organization are largely unknown. The cytoskeleton is a highly dynamic structure which reorganizes continually as the cell changes its shape, divides, and responds to its environment (Alberts et al., 1994). The cytoskeleton fulfils the requirements for self-organization (Misteli, 2001) but how it is formed and maintained is unknown. Frauenfelder et al. (1999) claim that the organization mechanisms in biological systems are of electromagnetic nature. The structures of the cytoskeleton with electric dipole moments could generate oscillating electric fields and interact with external electromagnetic fields. Such a structure is formed by the microtubules—protein polymers—with a fundamental role in cytoskeleton organization. The subunits of microtubules—tubulin heterodimers—have electric dipole moments (Satarić et al., 1993; Tuszyński and Brown, 2000; Tuszyński et al., 1995) and energy can be supplied to them by hydrolysis of GTP (guanosine triphosphate) to GDP (guanosine diphosphate) (Caplow and Shanks, 1996; Caplow et al., 1994). The microtubules satisfy the basic requirements for excitation of vibrations (Pokorný, 1999) and generation of endogenous oscillating electric field (Pokorný and Wu, 1998; Pokorný et al., 1998). Fröhlich predicted coherent vibrations of longitudinal polarization modes in biological structures (Fröhlich, 1968, 1980). Energy level of excited Fröhlich's systems does not depend on the manner of energy supply (Šrobár, 2001). Damping of vibrations in biological structures is an important question, particularly viscous damping by surrounding cytosol and by associated structures.

Elementary models of a solid-liquid interface are based on the assumption that the displacement of the solid surface is identical to that of the adjacent liquid layer. This assumption is called the no-slip boundary condition. Coupling of the liquid to the oscillating solid with no-slip boundary condition was described (Currie, 1974; Kanazawa and Gordon, 1985; Rayleigh and Strutt, 1955). The liquid was considered to be viscoelastic and electrical displacement was included in the model presented in Reed et al. (1990). Liquid layer adjacent to the solid is more ordered than the liquid in the bulk because of adsorption. Therefore, it may be difficult a priori to predict behaviour of a vibration system without extensive knowledge of the liquid and interfacial structures (Duncan-Hewitt and Thompson, 1992). The displacement of a liquid particle in contact with the solid surface differs from that of a particle on the surface of the solid. This slip boundary condition at the interface of the solid with the liquid was used (Ferrante et al., 1994). Slip conditions between several layers at the solid-liquid interface and assessment of the damping resulting from liquid medium were described in Hayward and Thompson (1998). Viscosity effects on vibrations in microtubules were analysed in Pokorný et al. (2000). A model with an infinite plane with longitudinal vibrations in the direction parallel with the surface of the plane was used. Properties below the plane surface were assumed to be those of a microtubule and above the surface those of liquid medium (e.g., of water) with an ionic layer in between. This model corresponds to that in Stokes problem II (Wiggins et al., 1998). We assumed that slip boundary conditions occured in a surface layer (a surface stratum) of the microtubule and in the ionic layer (both the layers were considered as one slip layer). Diffusion equation was solved, viscous force acting on the slip layer determined, and

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slip boundary conditions included using experimental value of the shear modulus of microtubules. For dynamic viscosity of water (0.001 Pa.s) the amplitude of oscillation in the microtubule may be even two orders of magnitude greater than the amplitude of oscillations at the upper surface of the slip layer. Consequently, the relaxation time is from one to two orders of magnitude greater than period of oscillations. We concluded that slip boundary conditions enable excitation of vibrations in microtubules. Foster and Baish (2000) used a cylindrical model with circular cross-section but neglected slip boundary conditions and claimed that the relaxation time is several orders of magnitude shorter than period of oscillations in microtubules and that the damping is so strong that it is not meaningful to speak of ''resonance'' at all. We will analyze effects of viscous damping in microtubules as cylindrical structures taking into account slip boundary conditions. It is well-known that energy transfer across slip interface may be perturbed (Duncan-Hewitt and Thompson, 1992; Ferrante et al., 1994; Hayward and Thompson, 1998).

PHYSICAL PROPERTIES OF MICROTUBULES

We will consider two important properties of microtubules—electrical polarity and elasticity. First, we describe electrical properties. The microtubule is a hollow cylidrical structure of circular cross-section formed from tubulin heterodimers (Figure 1)

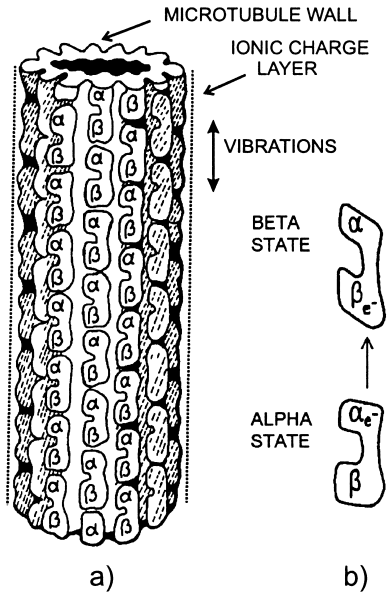


Figure 1. (a) A schematic picture of a microtubule. Tubulin dimers are arranged in threads called protofilaments. The dotted lines near the microtubule surface denote a charge layer of attracted ions. (b) Conformational change of a heterodimer molecule from the α to the β state after hydrolysis of GTP to GDP (b). After (Amos and Klug, 1974; Pokorný and Wu, 1998).

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(Amos and Klug, 1974; Pokorný and Wu, 1998). The tubulin heterodimer is composed of α- and β-tubulins. Each heterodimer has a net mobile negative charge and binds 18 calcium ions (Satari et al., 1993; Tuszyński et al., 1995; Tuszyński and Brown, 2000). The electric dipole moment is about 1000 Debye (10^{-26} Cm). The induced dipole moment per dimer arising only from the motion of mobile electrons or protons was estimated to be 200–400 Debye (Stracke et al., 2002). In the conformational α state the net negative charge is localized predominantly toward the α-monomer. After hydrolysis of GTP to GDP in β-monomer conformation of the heterodimer is changed and orientation of the dipole moment is reversed (the negative charge is localized toward β-monomer). Ionic concentration inside a cell is about 150 mM of cations (K^+, Na^+) and the same concentration of anions (CI^-, HCO^-_3, PO^{3-}_4, charged proteins, metabolites carrying phospate, carboxyl groups) (Alberts et al., 1994). The ions from the cytosol form a charge layer—a cylindrical envelope around the microtubule—as was experimentally demonstrated (Stracke et al., 2002). A charge layer is schematically shown in Figures 1 and 2. The charge layer screens electrical potential generated by the charges in the microtubule (Stracke et al., 2002). The charges in the microtubule are at most at 2 nm distance from the surface and a roughly exponential dependence of their electric potential in the charge layer may be assumed. Within a distance of about 2 Debye lengths the potential is considerably screened. The Debye length is about 0.8 nm, as may be determined from the ionic concentration in the cytosol (Kotyk and Janáček, 1977). One half of the total charge in the tubulin (i.e., 18 elementary charges) may be screened at its upper surface. About 14 elementary charges may be in the first

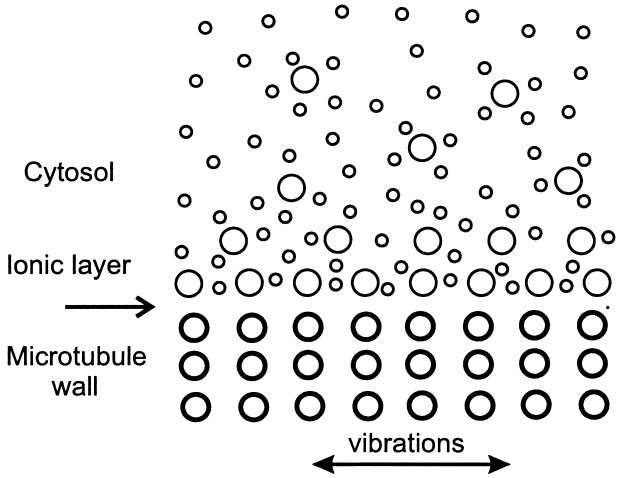


Figure 2. A schematic illustration of the surface of a microtubule with charge layer. The slip boundary conditions may occur in the surface layer of the microtubule and between the surface of the microtubule and the charge layer (Pokorný et al., 2000). Cytosol is in the upper part of the figure. The small and the large circles denote water molecules and ions, respectively. The arrow indicates boundary between the charge layer in the cytosol and the microtubular surface. Atoms in the microtubule wall (the circles in the thick lines) in real microtubules have not a lattice type translation symmetry. The polypeptide chain with side chaine amino acid residues is folded. Every protein structure contains α-helices, β-sheets, and bends. Ions from cytosol can penetrate inside the microtubule structure.

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layer at the tubulin surface with the area of about 13 nm^2. Because of hydration, the ions are surrounded by bound water molecules up to a distance of 0.4 to 0.5 nm. Charged proteins of considerably greater size than ionized atoms may be in the ionic layer, too. The majority of water molecules in the charge layer are not free and its viscous properties are dependent on hydrated ions. The change of energy of an ion in the electrical field of the tubulin charges along a path of 0.1 nm is about one order greater than kT. Some ions can penetrate inside the tubulin structure and behave like a part of the tubulin (as well as water molecules). Ions in the cytosol have small mobility and, therefore, there is slip between the charge layer and the microtubule surface.

The other important property of microtubules is elasticity of the microtubular structure. In contrast with actin and intermediate filaments microtubular networks can be easily deformed and begin to flow without limit when the strain exceeds 50% (Figure 3) (Alberts et al., 1994; Janmey et al., 1991). Dynamic shear modulus G is of 5 Nm^{-2} or less as follows from rheologic measurements at room temperature (Janmey et al., 1991; Sato et al., 1988). The dynamic shear modulus was measured in medium with ionic concentration similar to that in cytosol (Janmey et al., 1991). Because the thickness of the charge layer is comparable with the thickness of the microtubule wall, the measured dynamic shear modulus is an average value representing shear properties of the microtubule together with the charge layer. Therefore, as a rough approximation we will use the measured G value of the shear modulus for slip conditions inside the slip layer which consists of the microtubule surface layer and of the charge layer. Small value of the dynamic shear modulus G (i.e., large deformability of the microtubular structure at low stress) is important property for slip boundary conditions at its surface. The protective influence of the slip layer in the highly deformable solid with polar properties is a unique problem for assessment of the transfer of energy to the liquid surroundings.

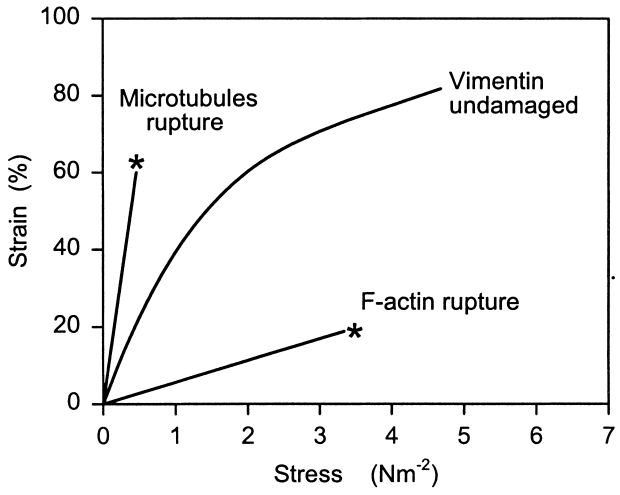


Figure 3. Mechanical properties of actin, vimentin, and tubulin filaments (strain vs. stress). Filaments were exposed to a shear force in a viscometer and the resulting degree of stretch was measured. Microtubule networks are easily deformed at low stress. After (Alberts et al., 1994; Janmey et al., 1991).

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ENERGY SUPPLY TO MICROTUBULES IN A CELL

Energy is supplied to microtubules from hydrolysis of GTP bound to β-tubulin in the tubulin heterodimer (Caplow and Shanks, 1996; Caplow et al., 1994). We may assess the energy supply to microtubules from the rate of growth of individual microtubules, from fluorescent measurements indicating the rate of replacement of microtubules by new ones (formed from heterodimers from the soluble pool with nonhydrolyzed GTP), from the dynamic instability (growth and shrinkage of the microtubules), and from the rate of treadmilling (heterodimers are added continually to one end and lost from the other end) (Alberts et al., 1994). Dynamic instability and treadmilling (Alberts et al., 1994; Mitchison, 1989; Mitchison and Kirschner, 1984) are important processes for continual rebuilding of the microtubular structure in the cell.

The average rate of growth of a microtubule may be determined from histograms of lengths published (Hyman and Mitchison, 1990; Melki et al., 1990). The mean microtubule length in histogram reported by Melki et al. (1990) is about 0.5 μm and, therefore, the rate of growth is about 0.5 μm per 20 sec. Five percent of heterodimers is incorporated into a microtubule in 1 sec. For simplicity we will assume microtubular structure where microtubules have the total length of 1 m, and that 5 % of it is exchanged in 1 sec (i.e., $n = 8 \times 10^7$ of heterodimers may be replaced). From the energy released by hydrolysis of GTP to GDP the amount $\epsilon = 7.1$ kJ/mole (Caplow and Shanks, 1996; Caplow et al., 1994) is stored in the microtubule. Energy supplied within 1 sec (i.e., power) $P_m = \epsilon n/L \approx 10^{-12}$ Wm^{-1} (where L is Avogadro's number). Similar result can be derived from fluorescent measurements. The power P_m represents very likely a standard energy supply. It is difficult to assess the total energy supplied to the microtubular cytoskeleton structure through dynamic instability and treadmilling. These two processes seem to be the major source of energy sustaining certain energy level in the microtubular structure in the cell. We may assume that, because of dynamic instability, the total energy supply may be considerably greater than that given above. In the M phase of the cell cycle the rate of exchange of heterodimers is more than one order of magnitude greater than that in the interphase and energy supply corresponds to this rate.

It is known that energy produced during GTP hydrolysis is delivered to microtubules, but a precise manner in which this energy is used is not well-understood. The energy may be used for increase of tension in the microtubule, may excite solitons, may be transformed into vibrations and excite coherent states of Fröhlich's type. In the last case longitudinal polar vibrations (polarization waves) in the direction of the microtubule axis are of particular interest. These vibrations can excite electromagnetic field around microtubules.

VISCOUS DAMPING

A microtubule may be approximated by a cylindrical layer with circular cross section. A cylindrical cavity is inside the microtubule. The slip layer (which includes microtubule surface layer and attracted charge layer) is also a cylindrical layer that forms an outer envelope and separation from the cytosol. We will assume longitudinal harmonic vibrations along the axis of the cylinder. Because of viscosity oscillations in

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the microtubule excite oscillations in the charge layer and in the liquid medium (in the cytosol) around the microtubule. The viscous effects cause damping of vibration in the microtubule. The viscous force exerted by Newtonian liquid per unit area of the outer surface of the slip layer is given by

$$F_v^1 = \eta\left(\frac{\partial v}{\partial r}\right)_{r=R} \tag{1}$$

where r is the radial variable, R is the value of radius of the surface in question (e.g., of the outer surface of the slip layer), $\mu = \rho v$ is dynamic viscosity of the cytosol (ρ is the density of mass and v is the kinematic viscosity), and v is the velocity of vibrations in the direction of the microtubule axis. The viscous force that one layer exerts on the other layer is equal to the rate of change of momentum. The momentum equation is given by the Navier-Stokes equation (Currie, 1974; Thurston, 1964), which can be simplified if we neglect external forces and gradient of pressure. Then the oscillations in cytosol can be described as diffusion waves by the diffusion equation $\partial v/\partial t = v\bigtriangledown^2 v$. Dependence of the velocity $v = v(z)$ may have form of a propagating or of a standing wave. For the sake of simplicity we neglect dependence of velocity v on the distance z along the microtubular axis. The properties of the assumed cylindrical model do not depend on the angle of revolution along the microtubular axis. If the time dependence of velocity is given by the function $\exp(i\omega t)$ we get from the diffusion equation in cylindrical coordinates

$$r^2\frac{\partial^2 v}{\partial r^2} + r\frac{\partial v}{\partial r} - i\frac{\omega}{v}r^2 v = 0 \tag{2}$$

Solution of Eq. 2 can be easily found using Kelvin's functions (Janke-Emde-Lösch., 1960; Watson, 1958). As the solution has to fulfil the requirements at infinity ($\lim_{r\to\infty} v(r) = 0$) we will use

$$\ker_p\left(r\sqrt{\frac{\omega}{v}}\right) \pm i\ \mathrm{kei}_p\left(r\sqrt{\frac{\omega}{v}}\right) = \exp\left(\mp\frac{p\pi}{2}i\right)K_p\left(r\sqrt{\pm i\frac{\omega}{v}}\right)$$

where $K_p\left(r\sqrt{\pm i\frac{\omega}{v}}\right)$ is Macdonald's function and p denotes order of the function. Solution of the Eq. 2 can be written in the form

$$v = \alpha\ \exp\ (i\omega t)K_0\left(r\sqrt{i\frac{\omega}{v}}\right) = v_0\ \exp\ (i\omega t)\frac{K_0\left(r\sqrt{i\frac{\omega}{v}}\right)}{K_0\left(R\sqrt{i\frac{\omega}{v}}\right)} \tag{3}$$

where a is the amplitude determined from the boundary conditions at the outer surface of the slip layer $r = R$ where the velocity is given by the relation $v = v_0\exp(i\omega t)$. The viscous force acts on the outer surface of the slip layer causing damping of its variations. As the first derivative of $K_0\left(r\sqrt{i\frac{\omega}{v}}\right)$ with respect to r equals $-\sqrt{i\frac{\omega}{v}}K_1\left(r\sqrt{i\frac{\omega}{v}}\right)$ we get for the viscous force F_v per unit length from Eqs. 1 and 3

$$F_v = -v_0\ \exp\left[i\left(\omega t + \frac{\pi}{4}\right)\right]\sqrt{\omega\rho\eta}\frac{K_1\left(R\sqrt{i\frac{\omega}{v}}\right)}{K_0\left(R\sqrt{i\frac{\omega}{v}}\right)}S_i = -\beta v_0\ \exp\ (i\omega t) \tag{4}$$

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where β–the force for a unit amplitude–is given by

$$\beta = \exp\left(i\frac{\pi}{4}\right)\sqrt{\omega\rho\eta}\,\frac{K_1\left(R\sqrt{i\frac{\omega}{v}}\right)}{K_0\left(R\sqrt{i\frac{\omega}{v}}\right)}S_i \tag{5}$$

and $S_i = 2\pi R$ is the area of the cylindrical surface of unit length. Vibrations inside the microtubule, which form inner cylindrical layer, excite vibrations in the slip layer (i.e., in the outer cylindrical layer). The excitation force acting on the slip layer depends on the amplitude of vibrations in the inner layer and on the coupling between the inner and outer cylindrical layer. We will consider transfer of vibration energy from the surface of the inner cylindrical layer to the outer surface of the slip layer. The oscillations in a microtubule act on the damped outer surface of the slip layer by the force (per unit length)

$$F_i = f\,Y_0 \exp[i(\omega t + \phi)] \tag{6}$$

where Y_0 is the amplitude of oscillations at the surface of the microtubule (below the slip layer), and f is the elastic force constant per unit length which can be determined from the dynamic shear modulus G in the form

$$f = \frac{GS_1}{\Delta R} \tag{7}$$

(ΔR is the thickness of the slip layer). The angle ϕ in Eq. 6 represents the phase shift between the oscillations in the microtubule and the oscillations at the outer surface of the slip layer (with the Y and y displacements, respectively). The oscillations at the outer surface of the slip layer are damped by the force F_v given by Eq. 4. If we neglect moment of the force F_i force then equation of motion for forced vibrations at the outer surface of the slip layer

$$\frac{\mathrm{d}^2y}{\mathrm{d}t^2} + \frac{\beta}{m}\frac{\mathrm{d}y}{\mathrm{d}t} + \omega_0^2 y = \frac{F_i}{m} \tag{8}$$

(where ω_0 is the characteristic angular frequency, and m is the mass per unit length) together with Eqs. 5 and 6 yields the solution

$$y_0 = \frac{f}{m(\omega_0^2 - \omega^2) + i\beta\omega}\,Y_0 \exp(i\phi) \tag{9}$$

(y_0 is the amplitude of the y displacement). We want to assess the greatest possible losses of vibration energy caused by viscous damping. Therefore, we assume that the whole vibration energy in the outer surface of the slip layer is dissipated. Under this assumption the maximum losses are reached for the maximum value amplitude y_0 regardless of the phase shift ϕ introduced in Eq. 6 (ϕ provides that y_0 and Y_0 are real values). We will evaluate y_0/Y_0 from Eq. 9 for $\omega = \omega_0$ (the effect of the term $m(\omega_0{}^2\text{-}\omega^2)$ is small as will be shown in the discussion). From Eq. 9 we get

$$\frac{y_0}{Y_0} = \frac{f}{|\beta|\omega} \tag{10}$$

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where $|\beta| = \sqrt{\Re(\beta^2) + \Im(\beta^2)}$. The ratio y_0/Y_0 in Eq. 10 corresponds to the interfacial slip parameter defined in (Ferrante et al., 1994). Similar relation is valid for v_0/V_0 where V_0 is the amplitude of velocity in the microtubule.

The total vibration energy stored in the microtubule per unit length may be determined from the kinetic energy in the form

$$E = \frac{1}{2}\pi(R_m^2 - R_{m0}^2)\rho V_0^2 \tag{11}$$

where R_{m} and R_{m0} are the outer and the inner radius of the microtubule. The average rate of energy loss per unit length caused by viscous damping may be determined from the relation $\frac{1}{T}\int_0^T F_v v\, dt$ where $T = 2\pi/\omega$ is period of vibrations and F_v is given by Eq. 4. We get (Foster and Baish, 2000)

$$E' = -\frac{1}{2}|\beta| v_0^2 \tag{12}$$

Using Eqs. 11 and 12 the relaxation time τ may be evaluated from the relation (which corresponds to a similar relation in (Foster and Baish, 2000))

$$\tau = \frac{E}{|E'|} = \pi(R_m^2 - R_{m0}^2)\rho|\beta|\frac{\omega^2}{f^2} \tag{13}$$

We will use the relative value of the relaxation time in number of periods of oscillations given by the relation

$$\tau_{\mathrm{rel}} = \frac{\omega\tau}{2\pi} \tag{14}$$

Figure 4a shows the relative relaxation time as a function of frequency for η in the range from 10^{-4} to 2×10^{-3} Pa.s (ΔR = 1 nm, R_{m} = 12.5 nm, R_{m0} =8.5 nm, $R = R_{\mathrm{m}} + \Delta R$, and the shear modulus $G = 5\ \mathrm{Nm}^{-2}$ (Janmey et al., 1991; Sato et al., 1988). We assume that viscosity of cytosol is equal to the viscosity of water (Luby-Phelps, 2000) and, therefore, greater than 5×10^{-4} Pa.s for temperatures smaller than about 40°C. At the frequency 10 MHz the relative relaxation time τ_{rel} is greater than 100. In this case the thickness ΔR of the cylindrical slip layer is 1 nm and we may assume that the slip is in the charge layer.

If the slip effects of the charge layer at the microtubular surface are neglected and the same procedure as in the previous case applied we can evaluate the relaxation time for a slip in the microtubule surface layer. In this case $R = R_{\mathrm{m}}$. The radial distance ΔR between two ''atomic layers'' may be out 0.25 nm. The upper layer of the microtubule is assumed to be damped by a viscous force. Figure 4b shows the relative relaxation time τ_{rel} as a function of frequency for this case. At the frequency 10 MHz τ_{rel} is about 10. The slip boundary conditions inside the microtubule considerably decrease the effect of viscosity damping too.

Figure 5 shows τ_{rel} versus frequency for the shear modulus G values in the range from 1 to 10 Nm^{-2}. Figure 5 visualizes the effect of deformability of microtubules on excitation of vibrations. Figures 4 and 5 prove that the shear modulus is small enough

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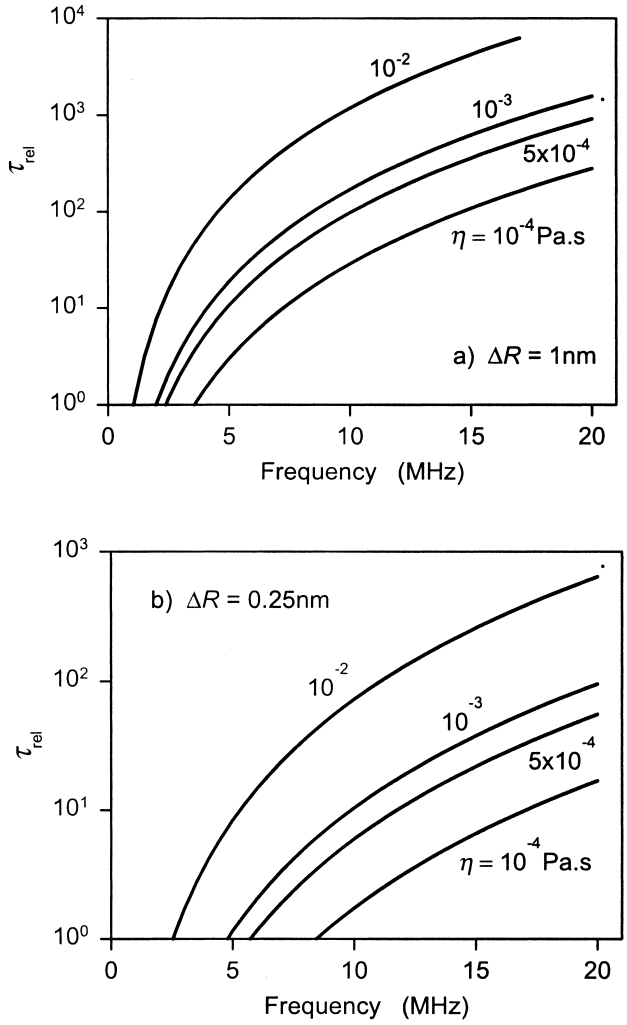


Figure 4. Relative relaxation time τ_{rel} caused by viscous damping in microtubules as a function of frequency. Parameter is the dynamic viscosity η. Viscosity of water is greater than about 5×10^{-4} Pa.s at temperatures smaller than 40 °C. The shear modulus G is 5 Nm^{-2} (Janmey et al., 1991; Sato et al., 1998). (a) The thickness of the slip layer ΔR = 1 nm. This case may correspond to the slip in the charge layer. At the frequency 10 MHz th relaxation time is more than two orders of magnitude greater than the period of oscillations. (b) The thickness of the slip layer ΔR = 0.25 nm. This case may correspond to the slip in the surface layer of the microtubule. At the frequency of 10 MHz the relaxation time is about one order of magnitude greater than the period of oscillations.

to enable significant slip at the surface of the microtubule and excitation of vibrations in the microtubule.

The average rate of energy loss is given by Eq. 12. We determine v_0 from Eq. 10 for amplitude of oscillations in the microtubule 0.5 nm. At 10 MHz power lost per 1 m length is about 3.3×10^{-12} W/m ($\eta = 5 \times 10^{-4}$ Pa.s). This power is of the same order of magnitude as the power P_m supplied by hydrolysis of GTP to GDP.

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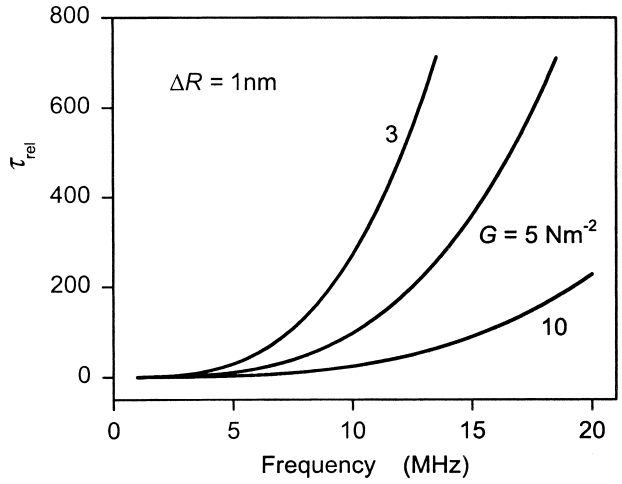


Figure 5. Relative relaxation time τ_{rel} caused by viscous damping in microtubules as a function of frequency. Parameter is the shear modulus G. The dynamic viscosity η is 5×10^{-4} Pa.s. The greater the deformability (i.e., the smaller the shear modulus) the greater the relaxation time. ΔR = 1 nm.

DISCUSSION

Viscosity causes strong damping of vibrations in bodies immersed in liquids. An overview of the properties of cytoplasm, in particular of its viscosity, was reported in (Luby-Phelps, 2000). The main characteristics may be summarized in the following way. Values of cytoplasmic viscosity were measured as high as 0.011 Pa.s—10 times greater than viscosity of water. Other measurements indicated that apparent solvent viscosity was not significantly different from that of bulk water (water is the major part of cytosol—a typical cell contains about 70% of water). On the other hand surface associated layers of ordered water up to the thickness of 200 nm may exist. Therefore, properties of water in living cells do not appear to be greatly altered compared with pure water but significant layers of more or less ordered water may exist. Consequently, properties of cytosol around microtubules may considerably differ from those of pure water. Low damping of vibrations by viscosity may exist. Nevertheless, even for the viscosity of water excitation of vibrations is possible on account of the slip boundary conditions.

We analyzed a model of the microtubule with slip boundary conditions. Slip can occur inside a microtubule in a layer adjacent to the surface, and at the interface of the microtubule surface with the charge layer. We showed that viscous damping in neither case can quench vibrations in the microtubule. Both cases may be effective in microtubules in living cells.

The slip between layers depends on the elastic properties of microtubules. Viscoelastic properties of biological polymers are evaluated from measurements using methods based on a torsion pendulum (Janmey et al., 1991; Sato et al., 1988), thermal fluctuations and hydrodynamic flow (Venier et al., 1994) (each method of measurement

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determines elastic properties in different frequency region). Only limited knowledge is available about elastic properties of tubulin globules, of tubulin heterodimers, and of the microtubular cytoskeleton structures in the frequency range 1–100 MHz. But the mechanism underlying the viscoelastic properties does not seem to vary too much in the frequency ranges in question.

Losses of energy by viscous damping depend on the transfer of energy across the slip layer which may be determined from the ratio y_0/Y_0 of the amplitudes of vibrations. The ratio y_0/Y_0 was evaluated for $m(\omega^2{}_0 - \omega^2) = 0$ from Eq. 9. We also evaluated y_0/Y_0 for $m(\omega^2{}_0 - \omega^2) \neq 0$ in the frequency range 1 MHz $\leq \omega_0/2\pi \leq 20$ MHz, $\omega/2\pi = 5$, 10, 15 MHz, $\eta = 10^{-4}$, 5×10^{-4}, 10^{-3}, 10^{-2} Pa.s, and $\Delta R = 0.25$, 0.5, 0.75, 1, 1.5, 2 nm. The differences of the y_0/Y_0 values for $m(\omega^2{}_0 - \omega^2) = 0$ and of those for $m(\omega^2{}_0 - \omega^2) \neq 0$ are at most of the order of magnitude of 1%. The important parameter is the characteristic angular frequency ω_0. To determine ω_0 we should take into account the ionic forces, the London forces, and the hydrogen bonds. We do not know viscoelastic properties of the surface layers of microtubules with coupled ions from the cytosol. We used the experimental value of the shear modulus measured for the whole microtubule. Its magnitude may depend on the binding energy between tubulins in protofilaments. A more accurate method using a stratified cylindrical model should solve boundary conditions between cylindrical layers with different viscoelastic and electrical properties. Nevertheless, the results of evaluation of viscous damping in this article may be considered as a zero-order approximation to the solution.

Energy supply is a fundamental matter concerning excitation too. The energy supply by hydrolysis of GTP to GDP seems to be comparable with energy losses. In the M phase of the cell cycle energy losses may be smaller on account of a dense protein matrix between microtubules in the mitotic spindle forming highly branched and cross-linked lattice (Scholey et al., 2001). On the other land, only a part of the energy that we considered can be supplied to vibrations and then the excitation is low.

Ions from the cytosol can penetrate into the structure of microtubule and form stronger coupling between the ionic layer and the microtubule surface. The tubulins have a spherical shape, and a surface of the microtubule in '' corrugated,'' which alters the energy transfer. Space structure of tubulin globules is not homogeneous. Each protein contains α-helics, β-sheets, and bends folded in a unique way (Schulz and Schirmer, 1979). Water molecules are also important parts of protein structures.

The model assuming infinite medium around microtubules is only an approximation. The distance between microtubules and between microtubules and other polymer structures in a cell is much smaller than the distance at which the diffusion wave is considerably attenuated. We have to analyze superposition of excitations of cytosol from several sources (the cytosol between microtubules might exert vibrations). This is a new aspect concerning properties of the cytosol and energy losses. Nonetheless, the model presented in this article shows good possibility of oscillations in microtubules.

We analyzed vibrations in the frequency range around 10 MHz, which corresponds to the vibrations of whole tubulins in the microtubule structure. In this case the theory presented in reference (Pokorný and Wu, 1998) predicts the frequency of vibrations in the range up to about 100 MHz. The measured emission of yeast cells (of the tubulin mutants of Saccharomyces cerevisiae) supports the theoretical predictions

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(Pokorný et al., 2001). In the higher frequency bands, in particular in the GHz region, vibrations of parts of tubulins have to be considered.

CONCLUSIONS

The theory presented by Foster and Baish (2000) is based on the assumption that no-slip (stick) boundary conditions exist at the surface of the microtubules. Under this assumption the authors conclude that excitation of vibrations in microtubular structures is not possible. The no-slip boundary conditions neglect real physical properties of microtubules as highly deformable and polar structures immersed in cytosol with 0.15 mM concentration of ions. Solution using the slip boundary conditions proves possibility of excitation of vibrations in microtubules at least in the frequency domain 1−20 MHz (nevertheless, at higher frequencies, too). Excited polar vibrations in microtubules and generated electromagnetic field may have fundamental role in organization of a cell. As these structures are electrically polar they are capable of interaction with exogenous electromagnetic fields that may contribute to their excitation.

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