TRANSPORT OF MOLECULES AND ELECTRONS BY ELECTRIC FIELD IN BIOLOGICAL SYSTEMS

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ABSTRACT

Microtubules in the cytoskeleton in eucaryotic cells are electrically polar polymer structures with energy supply. Extraordinary elastic deformability at very low stress and high polarity are essential conditions for formation of interfacial slip layer at the surface protecting vibrations in the microtubule from cytosol viscous damping. Microtubules satisfy conditions for excitation of coherent polar vibrations and generation of endogenous electromagnetic field with a strong electric component in their vicinity. The electric field exerts forces on charges, dipoles, multipoles, and on dielectrical particles (through dielectrophoretic effect) and may provide the driving force for coherent motion. The Wiener-Lévy process with symmetry breaking is used for description of motion of electrons and molecules. Thermally driven motion and motion driven by deterministic forces (with inseparable thermal component) are analyzed. Probability density as a function of distance and of time and probability as a function of time of random and directed transport of molecules and electrons are evaluated under different conditions. Analysis of probability displays dominant effect of the electrical forces on directed transport of electrons and molecules. We assume that directed motion driven by electric field might be important at short and medium distances up to about 50 – 100 nm and may provide supplementary transport to that of motor proteins.

INTRODUCTION

Physical processes in living matter participating in its organization are still not adequately understood. A.M. Turing [1] assumed that morphogenesis in living matter is not only a chemical phenomenon, but that also well-known physical processes based on mechanical and on electrical forces are operating in living matter. Fröhlich [2] postulated existence of long range quantum mechanical phase correlations and that biological systems exhibit relative stability in a way in which some modes of behavior remain very far from thermal equilibrium although from an atomic point of view the majority of the degrees of freedom behave like being close to thermal equilibrium. Excited longitudinal oscillations were assumed to play a role as stabilizing modes. Measurement of coherent vibrations in the submillimeter range are described in [3] and in the frequency range from 0.8 to 2 kHz in [4].

Organization in biological systems include organization of morphological structures, of chemical reactions, and of physical fields. Physical fields may have effect on behavior of all structures in connection with the space-time dynamic functional order. As the majority of biological molecules and structures are electrically polar, electromagnetic mechanism of organization was suggested. H. Frauenfelder et al. [5] claimed that in biological physics, the force is well known, it is the electromagnetic interaction. We assume that especially the electric component of the endogenous electromagnetic field may be important for organization. Electric component can exert forces on charges, on dipoles, and also on neutral particles through dielectrophoretic effect. The electric field may be static, quasi-static, and oscillating whose amplitude may be large if the vibrations generating the field are excited.

Directed transport of molecules and charges may play important role in organization [6-8]. Mass and charge transport conditions biological activity. Motor proteins transport vesicles with material along microtubules on the cell scale distances. Information system governing the transport is not known. Electric field may be important for transport of molecules in cytoplasm between different reaction compartments, for active transport of molecules across plasma membrane, and for transfer of electrons. Electron can be carried by small diffusible molecule or transported along the molecular chains in proteins and protein complexes. Motion of electrons in the biological molecules may be—to a certain extent—similar to that in solids with translation symmetry but with the deformed energy band structure. Directed motion is significant for the cytoplasmic contents of the cell to become organized. Random transport driven by thermal motion is isotropic if a condition for symmetry breaking is not satisfied.

Eucaryotic cells are structurally and dynamically organized by a protein polymer network called the cytoskeleton. The basic structure is formed by microtubules composed of tubulin heterodimers that are strong electric dipoles. Extraordinary elastic deformability at low stress was measured on microtubules. When the strain exceeds about 50%, the microtubule loses its elasticity and flows without limit. Mechanisms of dynamic instability in the interphase and of treadmilling in the M phase exchange heterodimers in the microtubular structure. Large energy supply into the microtubule is provided by hydrolysis of GTP (guanosine triphosphate) to GDP (guanosine diphosphate) in the heterodimers after polymerization [9-10] (of about 10^{-14} $\mathrm{Wcm^{-1}}$ in the interphase and more than one order of magnitude greater value in the M phase). Activity of motor proteins is assumed to be connected with supply of energy too [4]. Weak interaction in the microtubule corresponding to extraordinary elastic deformability, formation of ionic charge layer, and proteins attached to the surface of the microtubule participate in formation of an interfacial slip layer separating the inside of the microtubule from cytosol and its viscous damping [11-12]. Microtubules satisfy conditions for excitation of vibrations and generation of endogenous electric field [13]. Nevertheless, as the majority of proteins are electrically polar, local electromagnetic fields may be formed in various parts of a cell.

We will assess the role of electric field in directed transport of molecules and charges in the living cell. Transport aimed to a certain target can have a considerable impact on probability of encounter and on organization of chemical reactions and structures in the cell.

WIENER-LÉVY PROCESS WITH SYMMETRY BREAKING

Transport of mass and charges in biological systems may be driven by the random force of thermal motion and by the deterministic force exerted by the electric field. Brownian random motion may be described by the Wiener-Lévy process which is a limiting form of the random walk [14]. The processes of the random walk type may be used for description of the Brownian motion with symmetry breaking, that can provide directed transport. The breaking symmetry effect may be caused e.g. by different probabilities or different lengths of steps in different directions, by a deterministic force, etc. The Wiener-Lévy process with symmetry breaking that can describe motion of charges and molecules in the mesoscopic world has two components: the random thermal motion and the deterministic motion. We will use one-dimensional approximation. The probability density $f(x;t)$ of the Wiener-Lévy process with a symmetry breaking term is given by the relation [8]

$$f(x;t) = \frac{1}{\sqrt{2\pi\alpha t}} \exp\left[-\frac{(x-vt)^2}{2\alpha t}\right] \quad , \quad v = \frac{F}{6\pi\eta r} \quad , \quad \alpha = \frac{k_B T}{3\pi\eta r} \tag{1}$$

where t is time, x is distance, α is variance parameter, F is deterministic force, T is temperature in K, k_B is the Boltzmann constant, η is dynamic viscosity, and r is radius of a particle. For the mass transport of spherical particles the velocity v and the variance parameter α are determined from the Stokes' law.

We will determine v and α for electron transport in molecular chains too. Besides the assumption that the Wiener-Lévy process describes diffusion with deterministic motion we assume that the Bloch theorem may be used. Therefore, we will use the solid state theory of periodic structure as is described e.g. in [15]. The variance parameter is given by $\alpha = s^2/\Delta t$, where s is the length and Δt is the time interval of the elementary step. In our case s is the mean free path of electrons and $\alpha = sv = s\hbar|\boldsymbol{k}|m^*$, where m^* is the effective mass, and $|\boldsymbol{k}| = k = 2\pi\, g/(a\, G)$ is the absolute value of the reduced wave vector (a is period of the lattice, G is number of particles in the lattice, and g is an integer). The probability density of finding an electron at x is given by the sum [8]

$$f_e(x;t) = \frac{R}{A}\sum_k \frac{1}{\sqrt{2\pi\alpha t}} \exp\left(-\frac{\hbar^2 k^2}{2m^* k_B T}\right) \exp\left[\frac{(x-vt)^2}{2\alpha t}\right] \tag{2}$$

where A is the normalization factor and R stands for the decrease of probability by processes of trapping and recombination. We substituted the Boltzmann distribution for the Fermi-Dirac one. Velocity $v = \mu E$ where E is the intensity of the electric field and the electron mobility μ may be determined from the relation [8]

$$\mu = \frac{se}{2k_B TA}\sum_k \frac{\hbar k}{m^*} \exp\left(-\frac{\hbar^2 k^2}{2m^* k_B T}\right) \tag{3}$$

where e is elementary charge. The Einstein relation for the diffusion coefficient was used to derive Eq. (3) .

TRANSPORT OF MOLECULES AND CHARGES

Relation (1) is used to evaluate the probability density $f(x;t)$ of finding a particle at a distance x (in a small region of space along the axis x) at time t. The deterministic force acting on the particle may depend on the intensity of the electric field and on the charge of the particle, on the intensity and on gradient of the intensity of the electric field and on the dipole moment, and in the case of dielectrophoretic effect also on the polarizability of the particle. Fig. 1a shows $f(x;t)$ of a particle with a diameter Φ = 5nm as a function of x for time 0.1, 0.7, and 3 μs [16]. With no deterministic force (the dashed lines) the maximum value of the probability density remains at x = 0 but the curve $f(x;t)$ spreads with increasing time. Deterministic force shifts the curve in the direction of its action but the form of the curve does not

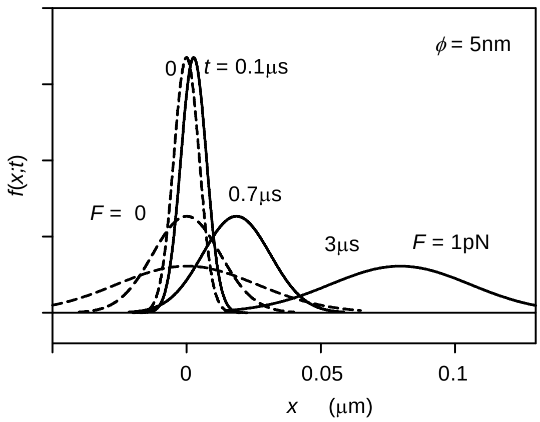

Fig. 1a

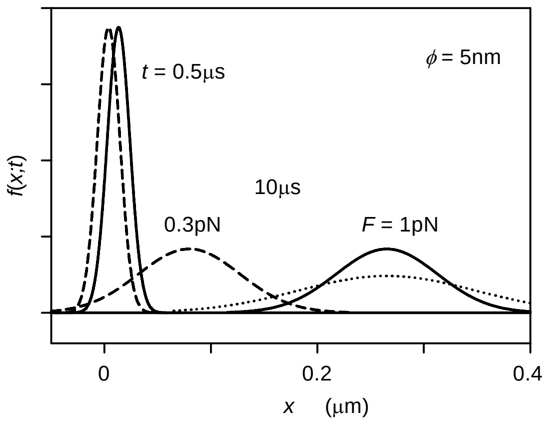

Fig. 1b

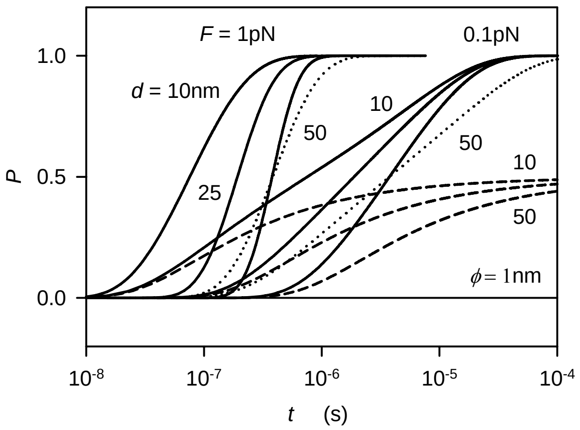

Fig. 2a

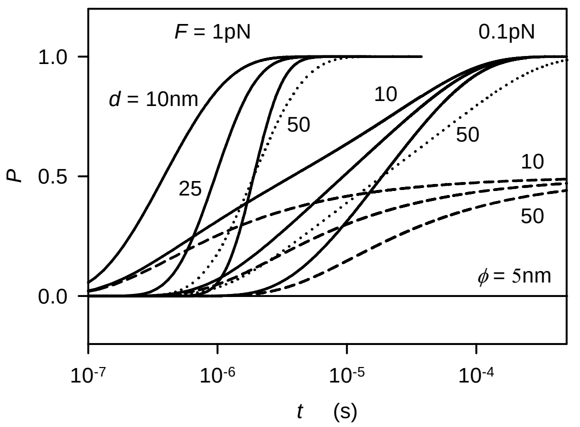

Fig. 2b

depend on the force. Fig. 1b shows the shift effect of the force 0.3 and 1 pN in the time 0.5 and 10 μs [16]. The solid and the dashed curves are evaluated for the variance parameter $\alpha_5 = 230$ nm^{2}s^{-1}. The dotted curve evaluated for $\alpha = \alpha_5$ shows the effect of the variance parameter on spreading of $f(x;t)$. Increased disturbances cause increased spreading. Figs. 2a, b show the probability that a particle will reach the target at a distance d of 10, 25, and 50 nm within the time t (P is a distribution function) [16]. The dashed and the solid curves are evaluated for thermal motion and for thermal motion together with a deterministic force, respectively. Diameter Φ of the particle is 1 nm, and the variance parameter α_1 is 1130 nm^{2}s^{-1} (a) and 5 nm and α_5 (b), respectively. The dotted lines are evaluated for the variance parameter $3\alpha_1$ (a) and $3\alpha_5$ (b) (the probabilities P in the range from 0.5 to 1 are smaller for greater α than those for smaller α).

Figs. 3a, b [8] show the probability P versus t that an electron will reach the target region at a distance 2, 5, 10, and 20 nm. The dashed lines and the solid lines denote probability P for thermal motion and for thermal motion together with a deterministic force. The electric field intensity is 10^6 (a) and 10^7 Vm^{-1} (b).

DISCUSSION AND CONCLUSIONS

Description of the mesoscopic processes in living matter is very likely neither quantum nor classical one. Processes in living matter result from combination of deterministic and of random components and both are very likely important for living functions. Randomness is a considerable part of any biological activity. The energy of thermal motion is many orders of magnitude greater than the energy exerted by deterministic forces but the random thermal motion is isotropic, not oriented to the target, and the required action has low probability. Nevertheless, thermal motion can help to overcome potential barriers. Coherent processes based on deterministic forces have high probability of required action regardless of the fact that their energy is small in comparison with the energy of thermal processes.

Changes of coherent component result in changes of probability of required action. Proportion of deterministic and of random processes may have an optimal value for biological functions. In the case of smaller probability the system is more liable to fluctuate under external disturbances (but the disturbances may be important in evolution). On the.

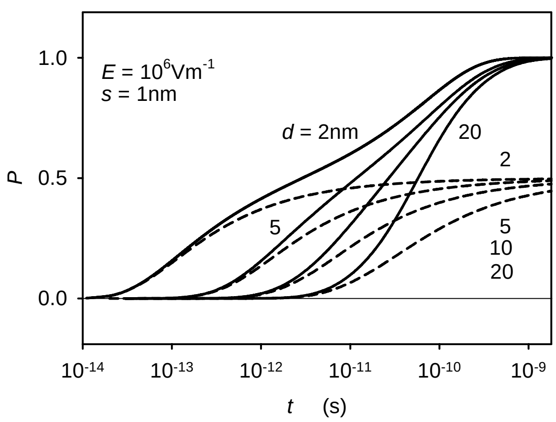

Fig. 3a

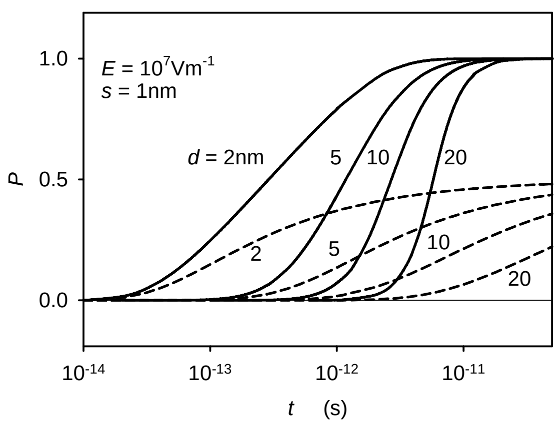

Fig. 3b

other hand the greater probability provides less errors in all processes. Exposure to external disturbances may increase the random component.

The majority of proteins in living matter are electrically polar. Microtubules are highly polar and form important functional structures in eucaryotic cells. Microtubules are excited by energy supply from hydrolysis of GTP to GDP (and very likely from motor proteins too) and may generate coherent electromagnetic field with strong electric component it their surroundings. The electric component may have dominant influence on directed transport in living matter.

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