Interaction of particles of biogenic origin with the electric field

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Received January 17, 2001

The problem of sampling, separating, and identifying biogenic particles in the upper atmospheric layers and in space is of great scientific interest and can be solved using high-frequency electric and magnetic fields. The goal of this paper is to solve direct and inverse problems of interaction of electric fields with biogenic particles. Solution of the direct problem yields the electric dipole moment and polarizability of particles, as well as the speed of particles in a liquid or in air in an external electric field within a broad range of frequencies. Solution of the inverse problem consists in determination of the structure and basic electric characteristics (conductivity and dielectric constant of cytoplasm and membrane) of biological particles from the measured speed of particles in a liquid or in air at different frequencies of the electric field applied.

Introduction

The problem of sampling, separating, and identifying particles of biogenic origin in the upper atmosphere and in space is of a considerable scientific interest and can be solved with the use of high-frequency electric and magnetic fields.[1,2]

In our previous paper[2] we have described a device for sampling biological particles in space that involves deceleration of particles by applying high-frequency electric and magnetic fields. In this paper, we solve the problem of detailed identification of sampled particles of biogenic origin based on their dielectrophoresis in a wide range of frequencies.

The aim of this paper was to solve the direct and inverse problems as applied to interaction of biogenic particles with the electric field. Solution of the direct problem yields the values of the dipole moment, polarizability coefficient, as well as the speed of particles' motion in a liquid or in air based on the known values of conductivity and dielectric constant of the cytoplasm and membrane. Solution of the inverse problem consists in determination of the basic electric characteristics (specific conductivity and dielectric constant of the cytoplasm and membrane) of biological particles from the measured speed of particles' motion in air and in a liquid at different frequencies of the electric field applied.

Interaction of particles with the electric field

A particle being in an inhomogeneous alternating electric field with the strength E acquires the dipole moment

$$d = \alpha\varepsilon_0 E = \alpha\varepsilon_0 E_0 \sin\omega t, \tag{1}$$

where α is the polarizability coefficient of the particle; ε_0 is the dielectric constant of vacuum; E_0 and ω are the amplitude of the field strength and the frequency of oscillations of the electric field. Because of the field inhomogeneity, the particle is driven by the force

$$\langle \mathbf{F} \rangle = \frac{1}{2}\nabla(dE_0) = \frac{1}{4}(\alpha\varepsilon_0 \nabla E_0^2). \tag{2}$$

Under the effect of this force, the particle in a liquid moves with the mean speed v, and the force of the electric field is balanced by the force of viscous friction F, which for a spherical particle is described by the Stokes equation:

$$F = 6\pi\eta R v, \tag{3}$$

where η is the viscosity of the liquid and R is the cell radius.

The values of the dipole moment and the force F depend on both the electric properties of the medium and properties of a biological particle, as well as on the frequency of the alternating electric field. In some frequency regions, biological particles move from the area with high field strength to the area with the low field strength, whereas in other regions the direction of the particle motion is opposite, and the set of equilibrium frequencies, i.e., the frequencies at which a biological particle holds still, is individual for every kind of particles.

For died microorganisms, as well as for non-biological particles, the dependence of the force on the frequency of the alternating electric field differs principally from this dependence for alive microorganisms. This principle forms the basis for devices separating and sorting biological particles.[2–4]

0235-6880/01/06–07 563-04 $02.00

Calculation of the dipole moment and the coefficient of polarizability for a cell of an arbitrary shape

A cell is usually considered as a spherical body of radius R (Fig. 1) with the dielectric constant of the cytoplasm ε_{cyt} and conductivity σ_{cyt}. The cell is covered by a homogeneous membrane of the thickness δ with the dielectric constant ε_{mem} and conductivity σ_{mem} and immersed in a liquid with the corresponding characteristics σ_{liq} and ε_{liq}. Using the definition of the complex dielectric constant $\varepsilon^* = \varepsilon + i\sigma/\omega$, where ω is the angular frequency of the electric field, we can obtain an analytical equation for the dipole moment of the cell.[6]

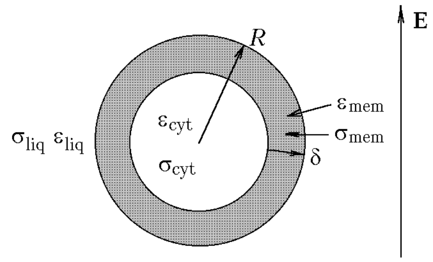

Fig. 1. Scheme and basic parameters of a cell that are taken into account at interaction with an alternating electric field.

The main chemical components of the plasma membrane are proteins and lipids, so the relative dielectric constant of the membrane is 2 to 4. The membrane is a good insulator; its conductivity is 0.5–50 μS/m (Ref. 5). The cytoplasm contains salt solutions and therefore it is a good conductor; its conductivity is 1–4 S/m. The relative dielectric constant of cytoplasm is roughly 60 to 80 (Ref. 5).

In the case of an arbitrary shape of the cell, the problem on determining the dipole moment has no analytical solution; therefore, we used numerical methods. The cell surface is approximated by a polyhedron with a large number of sides (up to 5000). Each side is characterized by a charge q_i with a constant density; the value of the charge is determined from the boundary conditions at the interfaces between the cytoplasm, membrane, and liquid:

$$\varepsilon^*_{\text{cyt}}\, E^*_{\perp\text{cyt}} = \varepsilon^*_{\text{mem}}\, E^*_{\perp\text{mem}}, \tag{4}$$

$$\varepsilon^*_{\text{mem}}\, E^*_{\perp\text{mem}} = \varepsilon^*_{\text{liq}}\, E^*_{\perp\text{liq}}. \tag{5}$$

The charges at each of the N sides are determined from a set of N linear equations relating the jump of the electric field strength with the charge density at the interface between the media with different dielectric constant:

$$\varepsilon^*_{\text{cyt}}(\mathbf{E}_0\, \mathbf{n}_i + \sum_{j\neq i}^{N} \mathbf{n}_i\, q_j\, \mathbf{m}_{ij} - 2\pi \frac{q_i}{S_i}) = \varepsilon^*_{\text{mem}}(\mathbf{E}_0\, \mathbf{n}_i + \sum_{j\neq i}^{N} \mathbf{n}_i\, q_j\, \mathbf{m}_{ij} + 2\pi \frac{q_i}{S_i}), \tag{6}$$

$$\varepsilon^*_{\text{mem}}(\mathbf{E}_0\, \mathbf{n}_i + \sum_{j\neq i}^{N} \mathbf{n}_i\, q_j\, \mathbf{m}_{ij} - 2\pi \frac{q_i}{S_i}) = \varepsilon^*_{\text{liq}}(\mathbf{E}_0\, \mathbf{n}_i + \sum_{j\neq i}^{N} \mathbf{n}_i\, q_j\, \mathbf{m}_{ij} + 2\pi \frac{q_i}{S_i}), \tag{7}$$

where $\mathbf{n}_i$ is the vector of normal to the ith side directed from the medium with ε^*_{1i} to the medium with ε^*_{2i}; $\mathbf{m}_{ij}$ is the strength of the electric field produced by the jth unit charge on the ith side; $\mathbf{E}_0$ is the amplitude of the strength of the external electric field; S_i is the area of the ith side, and unknown parameters are the side charges q_i. The obtained set of equations is solved by Gauss method.

The dipole moment of the cell is calculated as a sum of charges multiplied by the distance to the side center from an arbitrary fixed point. The obtained charge distribution allows us to determine the electric field strength and current in the cytoplasm, the membrane, and the liquid near the cell. Note also that Eqs. (6) and (7) can be used to determine electric fields for neutral and charged particles of a complex structure. The distribution of the electric field strength and current inside the cell and in the ambient medium at different frequencies is shown in Fig. 2.

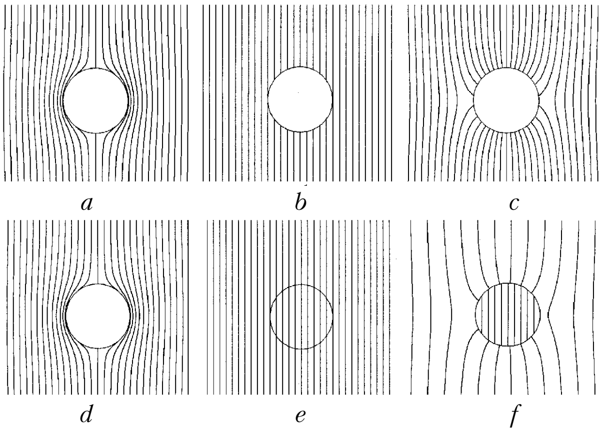

Fig. 2. Distribution of the electric field strength and current inside the cell and in the ambient medium: field and current at a low frequency (*a*, *d*), field and current at the equilibrium frequency (*b*, *e*), and field and current at a high frequency (*c*, *f*).

In the frequency region from 0 to 10^7 Hz, the field strength inside the cell is much lower than in the ambient medium, as is seen from Fig. 2 (field lines are absent inside the cell). Figure 2 demonstrates that the current traversing the cell increases with the increasing frequency of the electric field applied. This corresponds to the alternating direction of the force acting on the cell in the inhomogeneous field at these frequencies.

Results and discussion

Based on the solution of the direct problem – calculation of the electric characteristics of the cell with the known parameters, we consider the solution of the inverse problem – reconstruction of the cell parameters from the data of dielectrophoresis. For this purpose, we have developed specialized software for computing the dipole moment of a cell with an arbitrary shape of the surface taking into account the values of dielectric constant and conductivity of the cell and the ambient medium. The result obtained using this software is the dependence of the polarizability coefficient of a spherical cell on the frequency of the electric field.

Figure 3 shows a typical, for cells, dependence of the polarizability coefficient on the frequency of the alternating electric field applied. The entire frequency region is divided into five subranges, in which the dependence of the polarizability coefficient on the characteristics of the cytoplasm and membrane changes qualitatively.

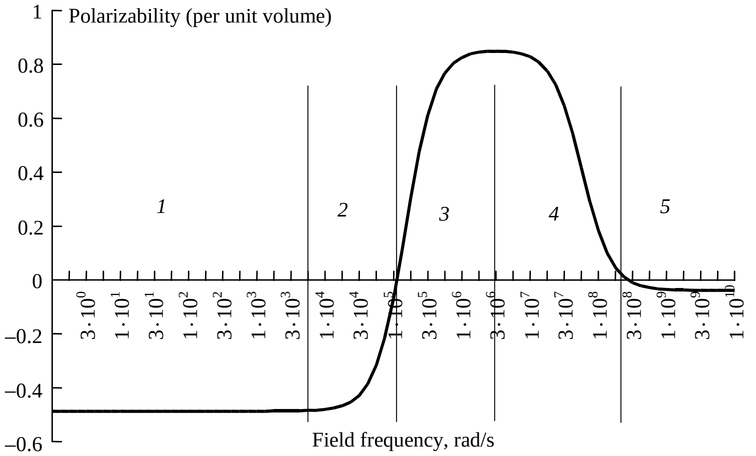

Fig. 3. Typical, for cells, dependence of the real part of polarizability on the frequency of alternating electric field. Cell parameters: $\sigma_{\text{mem}} = 5 \cdot 10^{-7}$ S/m, $\varepsilon_{\text{mem}} = 3\varepsilon_0$, $\sigma_{\text{cyt}} = 1.4$ S/m, $\varepsilon_{\text{cyt}} = 75\varepsilon_0$, $\delta = 7$ nm, $R = 3$ μm, $\varepsilon_{\text{liq}} = 81\varepsilon_0$, and $\sigma_{\text{liq}} = 0.017$ S/m.

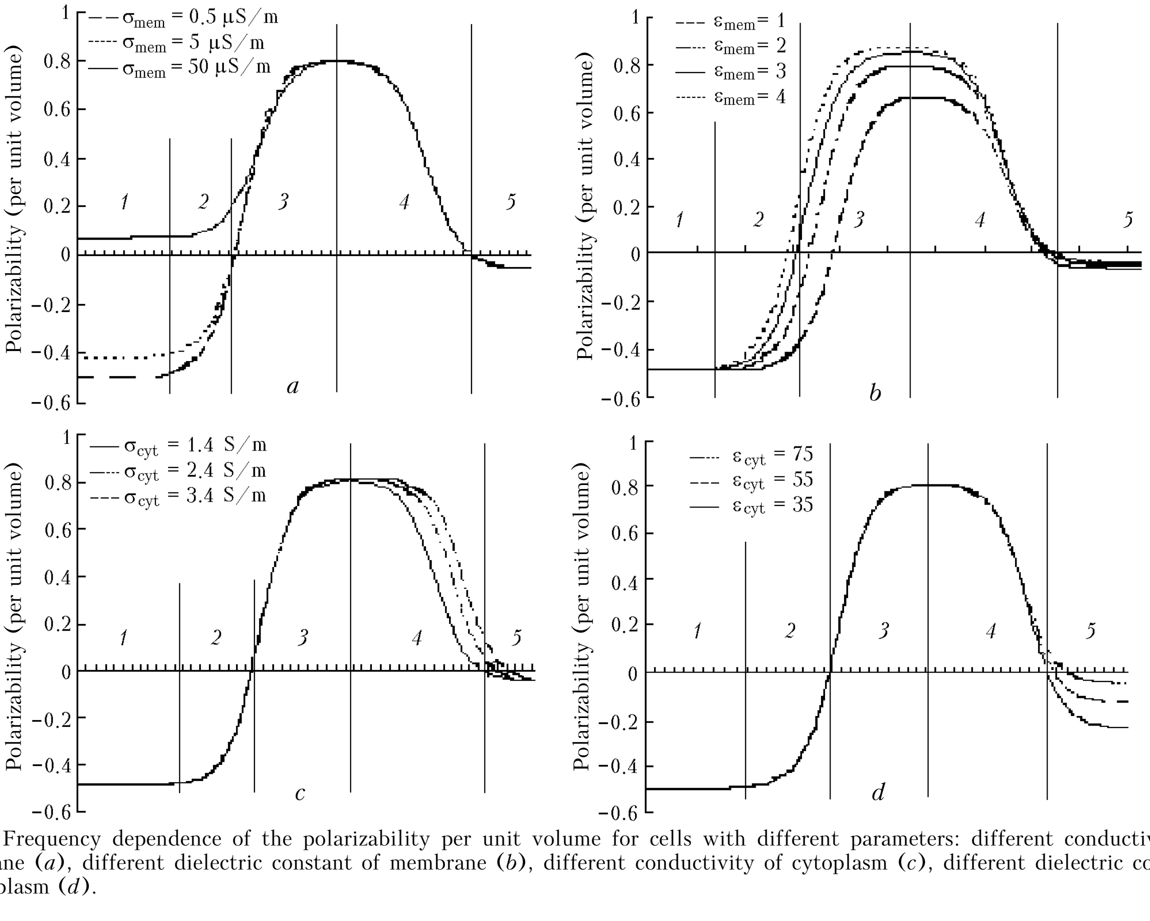

Fig. 4. Frequency dependence of the polarizability per unit volume for cells with different parameters: different conductivity of membrane (*a*), different dielectric constant of membrane (*b*), different conductivity of cytoplasm (*c*), different dielectric constant of cytoplasm (*d*).

Figure 4*a* shows the dependence of the coefficient of cell polarizability per unit volume on the membrane conductivity and the frequency of the electric field. The polarizability coefficient changes most widely in the first frequency region. Figure 4*b* shows the frequency dependence of the polarizability coefficient per unit volume for cells with different dielectric constant of the membrane. It is seen from this plot that the variations of the polarizability coefficient are maximum in the second and third frequency regions, and the variations of the membrane dielectric constant can be judged from these variations of the polarizability coefficient. Figure 4*c* shows the frequency dependence of the polarizability coefficient per unit volume for cells with different cytoplasm conductivity. Variations of this parameter cause variations of the polarizability coefficient in the fourth frequency region. Figure 4*d* shows the frequency dependence of the polarizability per unit volume for cells with different dielectric constant of cytoplasm. Variations of the cytoplasm dielectric constant manifest themselves in variations of the polarizability coefficient in the fifth frequency region. The maximum variations of the polarizability coefficient at variations of the characteristics of different cell elements in different frequency regions are tabulated below.

Table. Maximum variations of the cell polarizability coefficient per unit volume at variations of characteristics of different cell elements in different frequency regions

Characteristic	Cell polarizability coefficient per unit volume				
Frequency region	1st	2nd	3rd	4th	5th
Variation of membrane conductivity σ_{mem}, 0.5–50 μS/m	+0.6				
Variation of membrane dielectric constant ε_{mem}, (1–4)		+0.4	+0.8		
Variation of cytoplasm conductivity σ_{cyt}, 1.4–3.4 S/m				+0.4	
Variation of cytoplasm dielectric constant ε_{cyt}, (35–75)					+0.3

It is seen from the Table that variations of characteristics of the cell elements can be determined from variations of the cell polarizability coefficient in different frequency regions.

Based on the experimental data on interaction of particles with electric fields, we have compiled a library of video images of motion of various microorganisms and cells in the electric field in a wide range of frequencies at continuous and periodic exposure to the field. Processing of video images allows testing the solutions of the direct and inverse problems. In the experiments, we succeeded in determination of the first and second equilibrium frequencies (in the regions of 50–500 kHz and 50–300 MHz, respectively). Variations of the cytoplasm characteristics significantly change the position of the second equilibrium frequency. These variations may be connected with propagation of viruses in a cell or transition of cells into the spore form.

Conclusions

It is shown that the values of dielectric constant and conductivity of the cell cytoplasm and membrane can be determined separately from measuring the cell polarizability in the frequency region from 0 to 10^9 Hz.

The software is developed for determining electric characteristics of charged and neutral particles of an arbitrary shape in direct and alternating electric fields in air or a liquid.

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