Morphological Transitions of Vesicles in AC Electric Fields

Rumiana Dimova 06.04.1971
1995: Diploma, Chemistry (Sofia University, Bulgaria), Major: Chemical Physics and Theoretical Chemistry, Thesis: Role of the Ionic-Correlation and the Hydration Surface Forces in the Stability of Thin Liquid Films
1997: Second MSc (Sofia University, Bulgaria) Thesis: Interactions between Model Membranes and Micron-Sized Particles
1999: PhD, Physical Chemistry (Bordeaux University, France) Thesis: Hydrodynamical Properties of Model Membranes Studied by Means of Optical Trapping Manipulation of Micron-Sized Particles
2000: Postdoc (Max Planck Institute of Colloids and Interfaces, Potsdam)
Since 2001: Group Leader (Max Planck Institute of Colloids and Interfaces, Potsdam)

Electromagnetic fields are widely generated by power transmission lines, home appliances and electronics for telecommunication. Thus, our bodies are always exposed to them. This raises the question: "How do biological cells react to electromagnetic fields?" Giant vesicles provide an excellent model system for the cell because their typical size (~10 µm) is of the same linear order and their fundamental structure presents a closed compartment encapsulated by a lipid bilayer membrane. The cell-size dimensions of giant vesicles allow us to observe them directly by optical microscopy. Furthermore, it is possible to systematically change the salinities of the internal and external solutions of the vesicles. Studies of giant vesicles exposed to alternating (AC) electric fields are a good start to clarify the interactions between biological cells and electromagnetic fields from the viewpoint of physics and chemistry **[1]**.

In AC electric fields, spherical vesicles can assume different shapes: spheres, prolate ellipsoids, and oblate ellipsoids. Recently, we reported the morphologies of the vesicles for a wide range of field frequencies **[1, 2]**. We found that the conductivities of the solutions had an important influence on the shapes of the vesicles and mapped those on a morphological diagram as a function of the field frequency and conductivity condition. The latter was characterized by the ratio of the conductivities of the internal vs. the external solutions: $x=\lambda_{in}/\lambda_{ex}$. On the basis of the experimental findings, we have theoretically clarified the mechanisms of the four types of morphological transitions discovered in the experiments **[3-5]**.

Experimentally Determined Morphological Transitions

Giant vesicles made of the conventional egg lecithin were prepared with different conductivity of the internal and external solutions, i.e. various conductivity ratios x. The vesicles were spheres in the absence of AC fields. They were subjected to AC fields systematically varying the field frequency ω. The vesicle deformation was visualized with phase contrast microscopy.

Fig. 1 shows the obtained morphological diagram of the vesicle shapes in AC fields. The vesicles are spheres at high frequency independent of the conductivity ratio x. When $x>1$, the spherical vesicles are deformed into prolates with decreasing frequency. The frequency of this transition is about 1-10 MHz, see transition 1 in **Fig. 1**. The vesicles remain prolate when decreasing the frequency further for $x>1$. On the other hand, when $x<1$, the spherical vesicles at high frequency change their shapes to oblates with decreasing frequency. The characteristic frequency of this transition is about 10 MHz (transition 2). The vesicles remain oblate in the frequency range from about 10 kHz to about 10 MHz. Note that for $x>1$, the vesicles are prolate in the same frequency range. Thus, there is a morphological transition at $x \cong 1$ from oblate to prolate in the course of increasing x while keeping the frequency constant (transition 3). When further decreasing the frequency, the oblate vesicles for $x<1$ change to prolates at the transition frequency of about 1 kHz (transition 4).

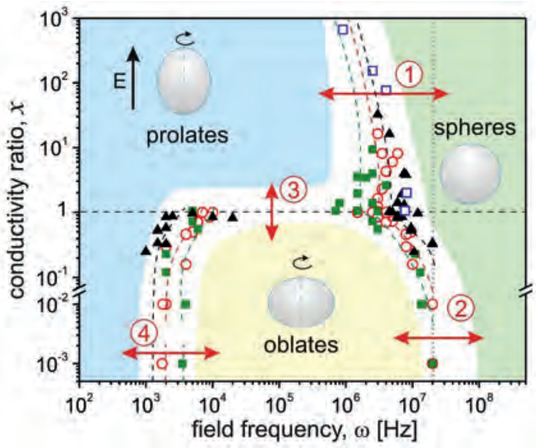

Fig. 1: Morphological diagram of giant vesicles in AC electric fields for a wide range of conductivity conditions and field frequencies. The conductivities of the internal solutions are fixed to 1.5 mS/m (filled squares), 6.5 mS/m (open circles), 13 mS/m (filled triangles), and 1000 mS/m (open squares). The broken lines are just a guide to the eye and the shaded areas indicate zones of specific morphology. The limit of the experimentally accessible frequency (2×10^7 Hz) is indicated by the dotted vertical line.

Theoretically Predicted Shape Deformations

The conductivities and the field frequency determine the conduction currents and displacement currents through the system, respectively. We have studied the mechanisms of the morphological transitions from the point of view of the current flow through the system. The developed approach extends a previous model (Winterhalter and Helfrich, J. Coll. Interf. Sci. 122, 1987) to include the effect of asymmetric conductivity conditions and the frequency dependence of the conductivity **[3-5]**. Analytical expressions of the transition frequency were derived **[4]**. The theoretically calculated morphological diagram, plotted in **Fig. 2**, agrees well with the experimental observations as shown in **Fig. 1**.

In the low frequency regime, the shapes of the vesicles are prolate independent of x. Lipid membranes are insulators, and both conduction currents and displacement currents flowing across the membranes are negligible in the low frequency regime ($\omega<1$ kHz). As a result, the electric fields are tangential to the surface of the vesicles and do not penetrate into the vesicle interior but avoid the high impedance membrane. Maxwell stresses arise from the tangential electric fields and squeeze the vesicles at the equator: the vesicles are deformed into prolates.

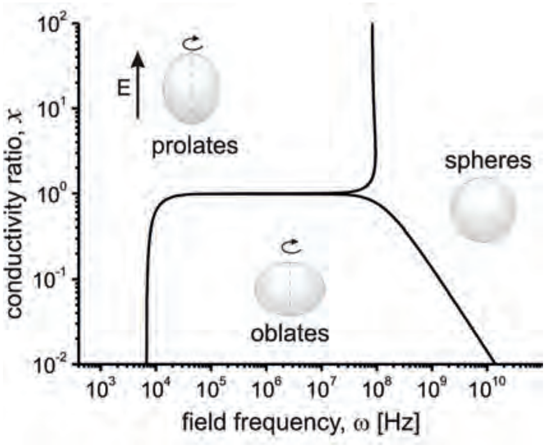

Fig. 2: The morphological diagram of vesicles in AC electric fields predicted theoretically. The calculation was carried out for vesicles with radius 20 µm. The membrane was assumed to have thickness of 4 nm and bending stiffness of 2×10^{-19} J. The conductivity of the internal solutions is 6.5 mS/m [4].

With increasing frequency, the displacement currents across the membrane grow together with the component of the electric field normal to the vesicle surface. In the intermediate frequency regime, this normal component generates shear Maxwell stresses. The latter compete with the Maxwell stresses, which deform the vesicles into prolates in the low frequency regime. The shear Maxwell stresses arising from the normal electric fields are the origin of the prolate-oblate transition 4 in **Fig. 1**.

In the intermediate frequency regime, electric charges accumulate at the interfaces of the vesicles because of the normal electric fields. The electric charge density and the corresponding net charges across the membrane depend on the conductivity condition. Within the continuum theory, these charges arise from the discontinuity of the permittivities across the interfaces and represent local accumulation of cations and anions at these interfaces. **Fig. 3** gives schematic snapshots of the electric charge distributions. They experience forces by the tangent electric fields denoted as f in **Fig. 3**. This force acts parallel to the tangent electric fields to deform the vesicles into prolates when $x>1$, and perpendicular to the tangent electric fields to deform the vesicles into oblates when $x<1$. The flip of polarity of the electric charges at $x \sim 1$ provides the mechanism of transition 3 in **Fig. 1**.

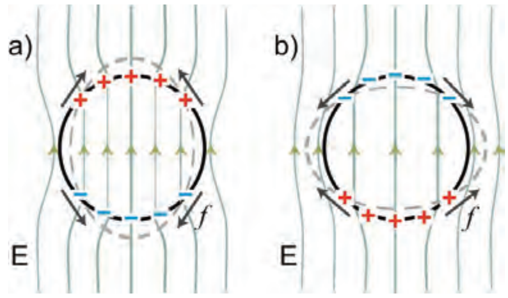

Fig. 3: At intermediate frequencies, electric charges accumulate at the vesicle interfaces. Due to the difference in the conductivity conditions, the net charges across the membrane (illustrated with pluses and minuses) differ depending on the value of x. The force applied to the charges by the tangential electric fields (f) deforms the vesicles (a) into prolates for x>1 and (b) oblates for x<1, which leads to transition 2 in Fig. 1.

In the high frequency regime, the shapes of the vesicles are spherical independent of x. The time required to charge the vesicles is characterized by the Maxwell-Wagner charging time. For higher frequency, the net electric charges across the membrane interface decay with the field frequency, and at frequencies larger than the inverse Maxwell-Wagner charging time, the electric charges cannot follow the oscillation of the electric fields. This changes the shapes of the vesicles from prolate ($x>1$) or oblate ($x<1$) to spherical, see transition 1 and 2 in **Fig. 1**.

In summary, the distributions of the electric fields by the displacement currents and the electric charges accumulated by the Maxwell-Wagner mechanisms play important roles in the morphological transitions of vesicles in AC electric fields.

R. Dimova, S. Aranda, T. Yamamoto, P. Vlahovska
rumiana.dimova@mpikg.mpg.de

References:

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