

Electrostatic Force in Furrowing of Biological Cells

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abstract—Previously, I have proposed that electrostatic repulsion between the negatively charged free ends (FEs) of polar microtubules furnished the driving force for pole separation and cytokinesis in primitive biological cells. The present work shows that given the charge at the FEs of astral microtubules (AMTs) adjacent to the cell equatorial cortex (EC) and layered water associated with the charge it is possible to describe an electrostatic component to the positioning of the cell division plane during cytokinesis. After establishing persistent electrostatic contact with the EC, force exerted by the FEs of AMTs interacting with positive charge induced on the EC could determine the division plane and initiate furrowing as the poles of the cell separate and pull the AMTs poleward.

0.1 INTRODUCTION

Primitive eukaryotic cells had to divide prior to the evolution of very many biological mechanisms, and it is reasonable to assume that basic physics and chemistry played dominant roles in both mitosis (nuclear division) and cytokinesis (cytoplasmic division). It is proposed here that electrostatic force played a major role in the dynamics of cytokinesis in primitive cells, and that the fundamental solutions to the problem of cell division that were found by primitive cells may persist in modern eukaryotic cells.

In the cytoplasmic medium (cytosol) electrostatic fields are subject to strong attenuation by screening with oppositely charged ions, and decrease rapidly over a distance of several Debye lengths. The Debye length within cells is typically of order 1 nm [1], and since cells of interest in the present work (i.e. eukaryotic) can be taken to have dimensions between 10–30 μm , one would be tempted to conclude that electrostatic force would not be a major factor in the dynamics of furrow formation in biological cells. However, the presence of microtubules (MTs) changes the picture completely. MTs can be thought of as intermediaries that extend the reach of the electrostatic interaction over cellular distances, making this potent force available to cells in spite of their ionic nature.

Microtubules are 25 nm diameter cylindrical structures comprised generally of 13 *protofilaments*, each consisting of tubulin dimer subunits, 8 nm in length, aligned lengthwise parallel to the MT axis. The protofilaments (PFs) are bound laterally to form a sheet that closes to form a cylindrical MT. Neighboring dimers along PFs exhibit a small offset of approximately 0.92 nm from PF to PF. This offset will be approximated as 1 nm in the calculations in subsequent sections. A number of investigations have focused on the electrostatic properties of MT dimer subunits [2-5]. Studies [6,7] have shown that the net charge depends strongly on pH. Dipole moments have been calculated to be as large as 1800 Debye (D). In experiments carried out at nearly physiological conditions, the dipole moment has been determined to be 36 D [8].

It is reasonable to assume that the electric dipole nature of dimer subunits greatly assists in their self-assembly into MTs. In particular, over the short distances consistent with counter-ion (Debye) shielding, their dipolar nature would allow them to be attracted to, and align around, any net charge distribution within cells. This may account for the efficient self-assembly of the asters during prophase, when MT polymerization and microtubule organizing center nucleation is favored because of the higher intracellular pH (pH_i) at this time [9, 10]. Thus we may envision that electrostatic fields organize and align the electric dipole dimer subunits, thereby facilitating their assembly into the MTs that form the aster [11, 12]. The attraction between oppositely charged ends of the dipolar subunits takes place over the short distances allowed by counter-ion screening. This self-assembly may be further assisted by significantly reduced counter-ion screening due to layered water adhering to the net charge of the dipolar subunits. Such water layering to charged proteins has long been theorized [13, 14], and has been confirmed by experiment [15]. This layering would also operate between charged protofilament free ends (PFEs) and cellular structures.

An electrostatic component to the biochemistry of the MTs in the assembling asters is consistent with experimental observations of pH effects on MT assembly [9], as well as the sensitivity of MT stability to calcium ion concentrations [16, 17]. The mutual electrostatic repulsion of the negatively charged MT free ends distal to the centrosomes in assembling asters could provide the driving force for their poleward migration in the forming spindle [11].

Microtubules continually assemble and disassemble, so the turnover of tubulin is ongoing. The characteristics of MT lengthening (polymerization) and shortening (depolymerization) follow a pattern known as "dynamic instability": that is, at any given instant some of the MTs are growing, while others are undergoing rapid breakdown. In general, the rate at which MTs undergo net assembly – or disassembly – varies with mitotic stage; for example, during prophase the rates of MT polymerization and depolymerization change quite dramatically [18].

The charge on the *plus* free ends of MTs is negative. (According to existing convention, these ends are designated "plus" because of their more rapid growth, there being no reference to charge in the use of this nomenclature.) The negative charge on the plus ends of astral microtubules (AMTs) adjacent to the cell equatorial cortex (EC) would induce positive charge on the EC leading to an attractive force between the free ends of AMTs and the EC. An *ab initio* calculation of the maximum tension force exerted by a MT interacting with induced charge on mitotic structures that agrees with experimental results has been given else-

where [19]. A similar calculation of the magnitude of the maximum (tension) force exerted by AMTs on the EC due to induced charge will be given below.

0.2 INDUCED CHARGE ON THE EQUATORIAL CORTEX

As mentioned above, net negative charge at the ends of MTs can induce charge on the cell cortex. The magnitude of the induced charge and the conditions under which charge induction can occur will be discussed next.

A standard derivation from electrostatics [20] shows that a point charge q at a perpendicular distance x from a planar boundary between two dielectric materials of permittivity ϵ_1 and ϵ_2 will induce a polarization charge density $\sigma(x, s)$ (C/m²) at the interface given by

$$\sigma(x, s) = \frac{qx}{2\pi k_1 (s^2 + x^2)^{3/2}} \left(\frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + \epsilon_2} \right), \quad (1)$$

where q is embedded in dielectric medium 1 of dielectric constant k_1 and σ is the charge per unit area on the interface at a perpendicular distance s from a line connecting q and its image charge in dielectric medium 2. In the context of the present work, ϵ_1 is the permittivity of the cytosol (essentially cytoplasmic water) at a PFE where a charge q is located and ϵ_2 is the permittivity of the dielectric medium (medium 2) within which the image charge is induced, the EC. A nearly planar geometry is assumed for the EC interface because it is much greater in extent than the diameter of a PFE on which the charge q is located.

Microtubule polymerization occurring at PFEs with distances of 8 to 11 nm from the cortex could add 8 nm electric dipolar tubulin dimers, resulting in PFEs at distances of 0 to 3 nm from the interface between the cytosol and the EC. This range of distances is significant for the present calculation because 1.5 nm may be taken as the thickness of the layered water adsorbed to each charged surface [14, 21]. Thus, as charged surfaces approach within 3 nm, counter-ion screening could be virtually eliminated in the spaces between charged PFEs and the charged EC.

The magnitude of the induced charge density on the EC due to an astral microtubule (AMT) with its nearest PFEs at distances of 1, 2, and 3 nm from the EC will now be calculated. From (1), $\sigma(x, 0)$ ($=\sigma(x)$) at the interface between the cytosol and a point directly adjacent to the charge at a PFE is

$$\sigma(x) = \frac{q}{2\pi k_1 x^2} \left(\frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + \epsilon_2} \right), \quad (2)$$

where ϵ_1 is the permittivity of layered cellular water at a PFE and ϵ_2 is the permittivity of the EC.

It is well established in electrochemistry [22] that the permittivity of the first few water layers outside a charged surface is an order of magnitude smaller than that of the bulk phase. The effective permittivity of water as a function of distance from a charged surface has been determined by atomic force microscopy [23] to increase monotonically from 4–6 ϵ_0 at the interface to 78 ϵ_0 at a distance of 25 nm from the interface. The values of the dielectric constants $k_1(x)$ at distances of 1, 2, 3, and 4 nm from a charged surface were measured to be 9, 21, 40, and 60, respectively. The experiment was carried out with mica, which is known to have

