Numerical Model of Induced Transmembrane Voltage for Cell Electroporation using COMSOL Multiphysics®

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INTRODUCTION

Electroporation is a widely used technique where the application of an external electric field of specific strength and duration induces electrical breakdown of the cell membrane and creates hydrophilic, water-filled, transient pores across the lipid bilayer membrane. Microfluidic devices are used to carry out single-cell electroporation with high accuracy and greater cell viability (1).The proper understanding of the electric field distribution and cell membrane permeabilization are key factors during the design of such platforms. In this work, we present a cell electroporation model of an isolated biological cell to compare the induced transmembrane voltage (ITV) before and after electroporation. The cell membrane was defined as a contact boundary condition in one model and a full-fidelity model with a physical thickness in another using COMSOL Multiphysics 5.4.

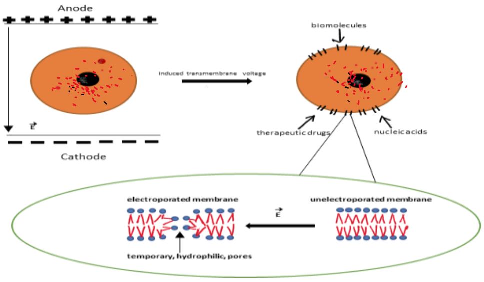


Figure 1: Electroporation and its many applications.

COMPUTATIONAL METHODS

Geometry: The spherical cell was drawn to scale with membrane thickness of 5nm and cellular radius of 5mm. The electroporated model was defined with the use of Work Plane and Booleans and Partition application nodes in COMSOL.

Physics: Electric current node in the AC/DC module and Laplace's equation were used to calculate the induced transmembrane voltage.

$$\nabla^2 \emptyset = 0; \;(3)$$

$$\text{ITV} = 1.5ER\cos\theta \frac{3\frac{d}{R}\sigma_i\sigma_e}{(\sigma_m+2\sigma_e)(\sigma_m+0.5\sigma_i)-(1-3\frac{d}{R})(\sigma_e-\sigma_m)(\sigma_i-\sigma_m)};\;(2)$$

$\emptyset$: electric potential; ∇^2: Laplacian operator; **E:** external electric field; **R:** radius; **d**: thickness; σ: electrical conductivity; **i:** intercellular region; **e:** extracellular region; **m:** cell membrane

Mesh: The two models were meshed with extremely fine customized mesh for better results. The cell membrane was meshed with a free tetrahedral mesh for the contact impedance model and a free quad mesh for the other.

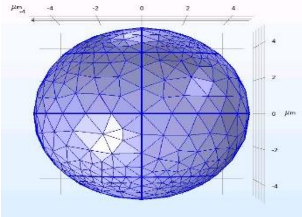


Figure 2: Boundary condition model with customized mesh.

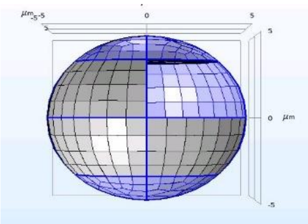


Figure 3: Full-fidelity model with customized mesh.

RESULTS

The following results were obtained through postprocessing in COMSOL and MATLAB to compare ITV values before and after the cell electroporates.

Before Electroporation

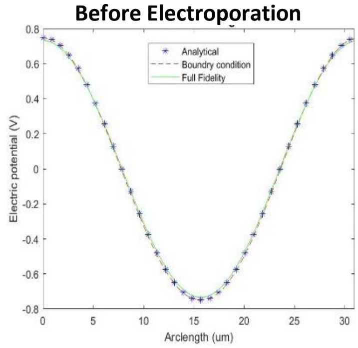


Figure 4: ITV comparison along the arclength before the cell electroporates.

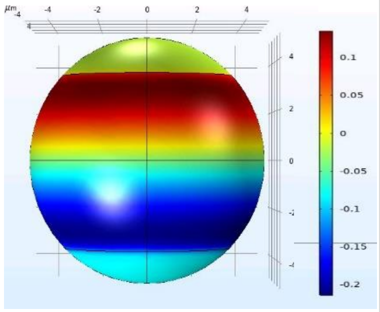


Figure 5: ITV plot after cell electroporation indicating the drop in electric potential around the poles.

After Electroporation

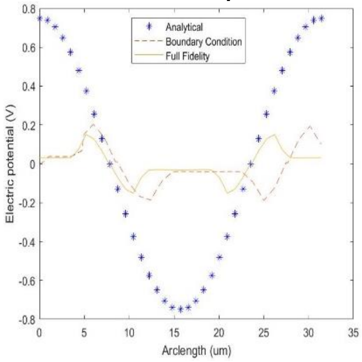


Figure 6: ITV comparison along arclength after the cell electroporates.

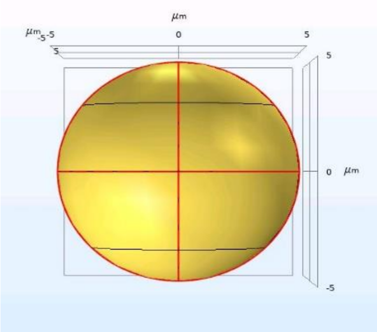
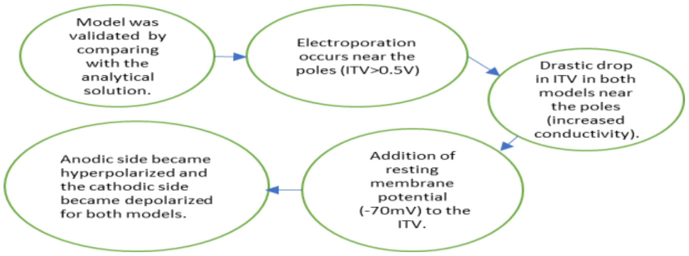


Figure 7: Polarization with the addition of resting membrane potential to ITV.

CONCLUSION



Thus, the two different approaches for defining the cell membrane produces comparable values of total transmembrane voltages before and after electroporation, with only differences in their meshing and material-defining techniques.

FUTURE DIRECTION

Further studies are directed to investigate how placing the cell in a constrained geometry such as a microfluidic electroporation device affects the electric field distribution and ITV as a design tool for such a device being developed in our laboratory.

RUTGERS

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