BMC Neuroscience

Poster presentation

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Cell-field interaction arising from tissue inhomogeneity determines electric stimulation efficiency

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from Sixteenth Annual Computational Neuroscience Meeting: CNS*2007
Toronto, Canada. 7–12 July 2007

Published: 6 July 2007

BMC Neuroscience 2007, **8**(Suppl 2):P120 doi:10.1186/1471-2202-8-S2-P120

Background

Electrical stimulation of neuronal tissue has been widely used in laboratory research and in the treatment of neurological diseases such as Parkinson's disease, essential tremor and dystonia. During stimulation, cells are polarized by the electrically-induced transmembrane potential, and the electric field is re-distributed by the presence of the cell. Previous studies have separately studied each aspect of this interaction. The electrically-induced transmembrane potential has been computed by various modeling works with various cell shapes, cell-field orientations, and field designs. The electrical field distribution has also been extensively studied. How do cell-field interactions influence the efficiency of electrical stimulation? To answer this question, we have developed a simple spherical cell model under uniform DC electrical field stimulation.

Materials and methods

We computed the potentials in the extracellular medium, along the membrane (transmembrane potential) and the cytoplasm by solving Laplace's equation with appropriate boundary conditions. The electrical field distributions in all regions were calculated as $\vec{E} = -\nabla V$, where V is the potential.

Results

1. The membrane is regionally polarized by the electrical field.

2. The extracellular electrical field is perturbed by the presence of the cell. The transmembrane electrical field is amplified by the low-conductive membrane. The intracellular electrical field is partially shielded by the membrane.

3. Correlation between the transmembrane potential and the electrical field is a complex function of the cell geometrical and electrical properties, suggesting the two are not replaceable in considering the efficiency of electric stimulation.

Conclusion

1. The electrically evoked transmembrane potential not only depends on parameters that define the field, but also depend on the electrical properties of the tissue, suggesting that tissue inhomogeneity play a critical role for the efficiency of stimulation.

2. The model cell perturbs the extracellular electrical field, suggesting possible "secondary" effects from neighboring cells. The model cell also shields the intracellular electrical field, suggesting that the cell membrane plays a role in protecting internal organelles against electrical exposure.

3. The presence of complicated interactions between the cell and the electrical field suggest they should be considered simultaneously in future modeling work. Specifically, it is important to consider the reciprocal effects of the neuron to the extracellular field distribution.