Numerical Modeling of Nanopipettes for Electrophysiology and Imaging

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Abstract

Nanoscale pipettes allow for exciting extensions of traditional current- and voltage-clamping electrophysiology experiments. However, bulk electrodynamic properties begin to break down at nanoscale openings, introducing unusual effects that must be understood in order to properly evaluate experimental data. Moreover, nanoscale pipettes are difficult to reproducibly manufacture with high precision, and time-consuming to acutely characterize. Numerical modeling offers a solution to both drawbacks, as finite element simulations can accurately predict the electrodynamic properties of nanopipettes. In doing so, experiments with such devices can be more finely tuned to influence neurons as intended, and geometric device parameters can be inferred through simple system measurements.

The present work simultaneously solves the Poisson, Nernst-Planck, and Navier-Stokes equations using the electrostatics, transport of diluted species, and laminar flow physics modules in COMSOL 5.3 software. The simulations replicate the typical experiment of a nanoscale pipette entering a neuron, and are able to calculate pipette resistance and efflux, as well as ion concentration profiles, for current- and voltage-clamping situations. Thus, users can precisely understand how electrical constraints propagate through to the pipette-cell interface. Moreover, the pipette tip potential is accurately modeled as a function of pipette radius and cone angle, enabling deduction of geometric properties from easily measurable tip offsets. Finally, simulations are augmented to account for the influence of bath potential and approaching a charged surface on pipette dynamics.