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Simulation of Astrocytic Calcium Dynamics in Lattice Light Sheet Microscopy Images

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ABSTRACT
Astrocytes regulate neuronal information processing through a variety of spatio-temporal calcium signals. Advances in calcium imaging started to reveal astrocytic activities, but the complexity of the recorded data strongly call for computational analysis tools. Their development is hindered by the lack of reliable annotations that are essential for their evaluation and for the design of learning-based methods. To overcome the labeling problem, we present a framework to simulate realistic astrocytic calcium signals in 3D+time lattice light sheet microscopy (LLSM) images by closely modeling calcium kinetics in real astrocytes.

METHOD
Simulation of Calcium Puffs
- Simulation model (monoscale):
  \[ p(x) = \begin{cases} \gamma^2 (1 - \frac{x^2}{\Delta^2}) & \text{if } x \in A, \\ 0 & \text{otherwise.} \end{cases} \]
- Determination of \( A \): set of points belonging to astrocyte
- \( \Delta \): temporal resolution
- \( \gamma \): number of IP points in a cluster

Simulation of Calcium Waves
- Simulation model (microscale):
  \[ f(x,t) = \sum_{i=1}^{N} \int (\nabla f_i(x,t)) \cdot \nabla (\gamma^2 (1 - \frac{x^2}{\Delta^2})) \delta(x-x_i) \]
- Determination of \( x_i \): set of IP points belonging to astrocyte

- Brownian motion:
  \[ f(x,t) = f(x,t) + \beta \cdot \delta x(t) \]
- \( \beta \): maximum intensity
- \( \delta x(t) \): Ornstein-Uhlenbeck diffusion

RESULTS
- Generation of 3D+time LLSM images depicting astrocytic activity: First simulator of its kind
- Driven by a calcium kinetic model that we adapted from nanoscale to microscale
- Image background made of realistic astrocytic ramifications
- Simulation of experimental conditions of LLSM acquisitions (e.g., noise and blur)
- Implementation as an ImageJ plugin with parameters and user interface

CONCLUSIONS
- Variety of synthetic datasets that realistically represents the complexity of experimental data
- Helpful to develop computerized learning-based methods to analyze astrocytic calcium signals in 3D+time images

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