Nonlinear Dynamics of Complex Biophysical Processes

André Erhardt (WIAS)

Mathematical and computational approaches have become essential tools in modern healthcare and quantitative biomedicine, providing a framework to understand, predict, and control complex biological processes. Many biophysical systems – ranging from cellular signaling and electrophysiology to tissue dynamics – are inherently nonlinear and involve multiple interacting time and spatial scales.

In this talk, I will discuss how nonlinear dynamical systems theory can be used to model and analyze complex biophysical processes, with a particular emphasis on electrophysiological phenomena. Starting from mathematical models of excitable cells described by systems of nonlinear differential equations, I will illustrate how multiscale interactions can give rise to rich dynamical behavior. Tools from bifurcation theory will be used to uncover mechanisms underlying transitions between physiological and pathological states.

As a representative example, I will highlight abnormal oscillatory dynamics arising from ion current interactions, such as early afterdepolarizations, which are linked to disease, pharmacological effects, and cellular stress and are believed to play a key role in the initiation of arrhythmias. Moving from the cellular to the tissue level, I will also discuss how collective dynamics and synchronization phenomena can emerge, including wave propagation and pattern formation, as observed in excitable media. Numerical simulations using modern open-source computational frameworks will be presented to illustrate these concepts.

Overall, the talk aims to demonstrate how nonlinear dynamics provides unifying principles for understanding complex behavior in biophysical systems across scales.