The Inverse Problem of Phase Singularity Distribution: An Eikonal Approach

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Phase singularity analysis provides a tool to quantify the complex spatiotemporal behavior observed in electrophysiological models of cardiac arrhythmia. The associated inverse problem consists in constructing an initial condition for a reaction-diffusion system with a given spatial distribution of anatomical/functional reentries. We aim to tackle this problem by solving an eikonal-diffusion equation that generates phase maps.

The eikonal-diffusion was extended to handle anatomical/functional reentries and wavefront collisions. Boundary conditions on activation times were used to specify pathways of reentry. A dedicated finite-element-based method was developed to solve this equation on a triangular mesh. The resulting phase maps served to construct an initial condition for a propagation model through a mapping between phase and cell state. Cardiac propagation was then simulated from this initial condition in the monodomain framework. Evolution of phase singularities was tracked.

Our approach was applied to initiate reentries in an atrial model. Anatomical and functional reentrant circuits were placed at 24 different locations in the atria. For each reentrant circuit, the eikonal-diffusion equation was solved on a coarse triangular mesh representing the epicardium and a phase map was reconstructed. Monodomain simulations (Courtemanche model; L-type calcium current reduced by 75%) were run on a finer 3D mesh after interpolation of the initial condition. In two cases, the reentry self-terminated within 3 s. In the other cases, the phase singularity meandered in the vicinity of the desired location specified in the eikonal problem.

The results suggest that this tool could help in the development of dedicated models aimed at better understanding clinical case reports, as well as in the creation of a library of different forms of simulated arrhythmias.