A Real-Time Solver for Simulating Cardiac Arrhythmias

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Introduction: Simulations of cardiac arrhythmias are generally based on the bi- or mono-domain reaction-diffusion model, which has offered important insight into mechanisms underlying the formation and maintenance of arrhythmias. A major drawback of this approach are the vast computational costs due to the requirements on spatio-temporal discretization, which often preclude their application in industrial or clinical applications where tighter constraints regarding available time frames are imposed. Recently, we reported on a novel reaction-eikonal modeling approach that overcomes these limitations by lifting the spatial discretization constraints of reaction-diffusion models. However, this approach is not suitable for studying arrhythmia induction and maintenance mechanisms as relevant underlying key features are not captured.

Objectives: This motivates the development of a novel EP solver based on the eikonal equation that is able to simulate arrhythmia induction and maintenance with real-time performance.

Methods: An efficient moving horizon eikonal-based EP solver was developed and coupled to a finite state machine to control the velocity term in the eikonal equation based on salient electrophysiological properties that govern arrhythmia mechanisms. Specifically, the action potential and conduction velocity restitution properties were taken into account.

Results and Conclusion: The novel solver was verified and validated against a ground-truth bidomain simulation under a normal-paced activation pattern and yielded a root mean squared error of only 0.27 ms with a computational speedup of $\sim$$6500$. Furthermore, the ability to induce a reentrant activation pattern under a classic S1-S2 pacing protocol was demonstrated. The induced spiral wave behaved qualitatively similar to a spiral wave induced in a matching bidomain simulation, with some differences in behavior near the filament of the rotor due to a lack of diffusion effects. With the performance achieved, the solver was able to simulate arrhythmias at the organ scale in real-time, using only desktop computing resources.