An Efficient Approach for Eikonal-Based Cardiac Activation Site Localization

Ingmar F Lercher, Elena Zappon, Matthias Gsell, Thomas Pock, Gernot Plank

Graz University of Technology / Medical University of Graz
Graz, Austria

Cardiac digital twins of human electrophysiology — digital replicas of patient hearts that reproduce clinical observations — hold significant promise for clinical applications enabling precision therapy. In this study, we address two key factors limiting their practical utility: insufficient computational efficiency for rapid prediction and challenges in calibrating models to patient data with adequate fidelity.

Current approaches to functional cardiac digital twinning commonly employ reaction–Eikonal models to enable accurate and computationally efficient prediction of electrical excitation wavefront propagation and the electrical state of the heart. These models are typically combined with leadfield formulations to generate biophysically consistent ECG predictions. A major remaining challenge is the solution of the associated inverse problem — estimating the location and timing of the earliest activation sites from body-surface ECG recordings. Recent gradient-based methods, such as GEASI and geodesic backpropagation, remain computationally and memory demanding, limiting their applicability to clinical-resolution meshes.

We derive a formulation for the backward pass that significantly reduces the memory overhead and is agnostic to the eikonal solver, requiring only the converged arrival times and the stencil weight matrix. Combined with a novel adaptive Frank–Wolfe solver this achieves low per-iteration cost on clinical-resolution meshes.

A preliminary validation on a biventricular mesh (1.7 M elements) with 12-lead ECG recordings showed that the closed-form backward pass was 4.0× faster than the automatic differentiation baseline (215 ms vs. 861 ms), reducing total iteration time from 2.10 s to 1.26 s on a 12 GB consumer GPU. GPU memory remained constant at 9.5 GB regardless of iteration count. A GPU-accelerated FIM reduced the forward eikonal solve by 9× (0.44 s vs. 4.0 s on CPU). On an RTX PRO 6000, total iteration time dropped to 0.6 s.

The constant memory footprint enables gradient-based localization of earliest activation sites on clinical-resolution meshes using consumer hardware.