Real-Time End-to-End Purkinje Tree Generation and Fully Coupled Electrophysiology

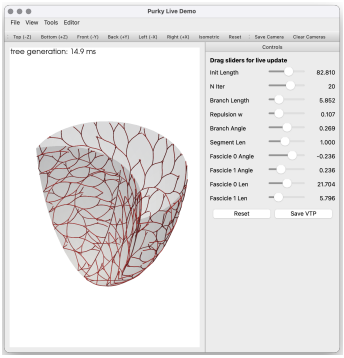
Simone Pezzuto, Efraín Magaña, Francisco Sahli Costabal

Department of Mathematics, University of Trento
Trento, Italy

Background. Calibration of cardiac electrophysiology models is computationally expensive, with significant cost arising from anatomical model setup and simulation of activation and electrograms. Eikonal-based models can substantially accelerate computations compared to monodomain models; however, end-to-end pipelines still require several seconds per run. While fast, such runtimes remain prohibitive for calibration workflows requiring hundreds of thousands of samples. A key bottleneck is the generation of the Purkinje network and its integration into the forward model. Here, we address this limitation.

Methods. We reformulate a fractal-based Purkinje tree generator on a planar domain via conformal mapping of the endocardial surface, accounting for the induced metric distortion. For electrophysiology, we propose a mixed-dimensional eikonal model in which the Purkinje tree and 3-D myocardium are solved simultaneously. At each iteration, the Purkinje activation is updated and coupled to the tissue. The method flexibly assigns Purkinje–muscle junctions (not restricted to mesh vertices) and supports both ortho- and antidromic propagation. Surface ECGs are computed using a lead-field approach. The solver is implemented in JAX, enabling a fully differentiable pipeline.

Results. Generation of a Purkinje tree for a human heart takes less than 15 ms on a modern single CPU core, enabling real-time interaction. We provide a simple GUI for generation and visualization (see Figure). Solving the eikonal equation on the Purkinje tree requires less than 3 ms on average, adding negligible overhead to the 3-D solver.



Conclusions. We present a real-time, end-to-end electrophysiology pipeline, implemented and benchmarked. The proposed approach can substantially accelerate calibration workflows.