Non-Invasive Action Potential Estimation and Atrial Substrate Characterization from Body Surface Potential Mapping using Deep Learning

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Background. Deceleration zones arising from fibrotic atrial remodeling are key drivers of atrial fibrillation and primary targets for catheter ablation, yet their non-invasive characterization remains an open challenge. Electrocardiographic Imaging (ECGI) based on Tikhonov regularization is limited by the ill-posed inverse problem and signal over-smoothing. This study introduces an enhanced deep learning framework to estimate atrial action potentials and identify deceleration zones directly from body surface potential mapping (BSPM), without requiring cardiac geometry.

Methods. A database of 8,820 simulations was generated using a cellular automata model across 28 atrial geometries (14 male, 14 female) incorporating slow conduction substrates of varying extent and severity. Realistic Wasserstein Generative Adversarial Network generated noise was added to BSPM signals at multiple SNR levels. An asymmetric 3D-CNN autoencoder with attention-based Gated Recurrent Unit layers and a combined loss function was trained to estimate APs from 4D BSPM tensors including electrode connectivity masks. Local Activation Time (LAT) maps and conduction velocity (CV) maps were derived from the estimated APs for comparison against Tikhonov-based ECGI.

Results. The proposed method achieved accurate action potential reconstruction (Fig. 1A) and statistically significant improvements over ECGI (Fig. 1B) across LAT and CV maps (paired t-test, $p < 0.01$), translating into an 11.8 percentage-point gain in overall deceleration zone detection, rising to 19.5 percentage-point for single deceleration zone cases.

Conclusion. These results demonstrate the potential of geometry-free non-invasive cardiac mapping for atrial substrate characterization, representing a step towards improved identification of arrhythmogenic substrate for ablation guidance.

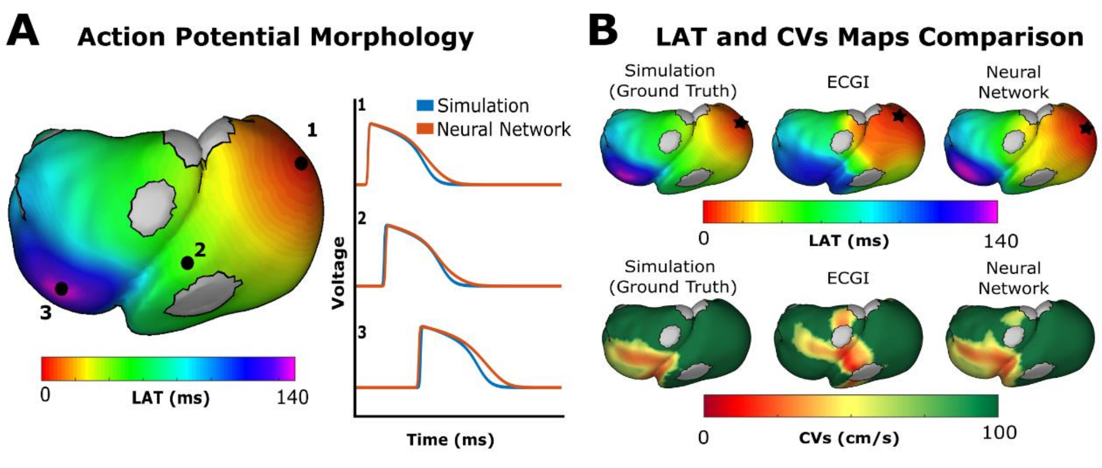

Figure 1. (A) AP morphology comparison for different nodes between the simulation and the estimation obtained with the neural network. (B) Maps comparison between a selected simulation, ECGI and neural network estimation.