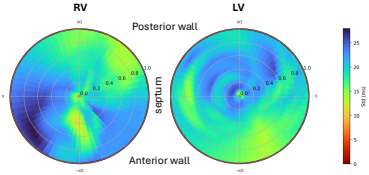
Families of Equivalent Ventricular Activation Patterns Inferred from the 12-Lead ECG

Guadalupe García-Isla, Sandra Perez-Herrero, Elena Zappon, Javier Saiz, Gernot Plank, Jorge Sánchez

Center for Research and Investigation in Bioegineering (Ci2B),
Universitat Politècnica de València
Valencia, Spain

Non-invasive inference of ventricular activation from surface ECG is a key step in cardiac digital twinning. It is known that multiple activation patterns can reproduce a patient's ECG with equivalent accuracy, yet the solution space remains unexplored. In this work we study this problem by identifying distinct clusters of ECG-equivalent activation patterns.

Over 2,744 high-quality solutions (Pearson's CC > 0.94) were generated by inferring the locations and activation times of 7 His–Purkinje root nodes from a patient's clinical 12-lead ECG. This was performed using an optimization pipeline with 5 initialization seeds using an eikonal model and lead-field ECG formulation. For each solution, an endocardial local activation times (LAT) map was obtained and rasterised to a 64x64x2 image in universal ventricular coordinate (UVC) space, with separate channels for the left ventricle (LV) and right ventricle (RV). A self-supervised DeepCluster pipeline was applied to the LAT images: a 4-layer convolutional neural network with 128-d embedding was trained over 3 rounds of KMeans pseudo-label assignment and supervised fine-tuning with data augmentation for regularization. Final L2-normalised embeddings were clustered with KMeans. Six distinct clusters were identified (silhouette=0.532), all showing comparable mean±SD ECG CC values (0.952 ± 0.01), yet each corresponding to a different LAT distribution in UVC space. Highest variation between clusters focused on basal RV free wall and posterior LV (Figure 1). The identified set of cluster centroids may provide a more complete representation of a single patient's ventricular activation pattern than any single inferred solution.



STD LAT on UVC for RV and LV endocardium of cluster centroids.

Clustering of endocardial LAT maps revealed distinct families of activation patterns, all reproducing the patient's ECG with equivalent fidelity. Characterizing this solution multiplicity is an important step toward uncertainty-aware cardiac digital twinning. Caution should be taken against treating any single inferred root node configuration as a unique physiological ground truth.