Substrate Assessment of the Left Atrium in Persistent Atrial Fibrillation During Functional Mapping Using Machine Learning for Ablation Target Identification

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Abstract

Persistent atrial fibrillation (PsAF) is sustained by a complex and dynamic arrhythmogenic substrate that is not fully characterized by conventional sinus rhythm (SR) mapping nor by atrial fibrillation (AF) mapping, which is often dynamic and poorly reproducible. Functional mapping using short-coupled extrastimuli has been shown to unmask latent conduction abnormalities associated with fibrosis and slow conduction, which are critical for identifying ablation targets [3–5]. However, interpretation of electrogram (EGM) features across triple extra stimulation during functional mapping remains challenging and operator-dependent.

We propose a machine learning (ML) framework for automated classification of atrial substrate based on electrograms (EGMs) features derived from functional mapping. High-density electro-anatomical maps were acquired in PsAF patients undergoing short-coupled atrial extrastimuli (triple extra-stimulation protocol) paced from the coronary sinus [5]. For each mapping point, 13 features were extracted, capturing electrogram duration (SR, S1–S3), number of deflections (S1–S3), SR and stimulus delay (Δ), and peak-to-peak voltage (S1–S3). Sites were labeled as normal or abnormal substrate based on annotation by an expert electrophysiologist. To ensure robust generalization, a group-based cross-validation strategy was implemented, holding out two entire patient cases per fold (12 folds total). Models were trained within a pipeline including feature scaling and class balancing using SMOTE.

A total of 24 patients, including 4,808 mapping points (4307 normal, 501 abnormal; expert-labeled), were analyzed. Ensemble models achieved the best performance, with Gradient Boosting reaching an accuracy of 0.951, macro F1-score of 0.870, balanced accuracy of 0.877, and AUC of 0.958, followed by Random Forest (accuracy 0.950, AUC 0.961). These models achieved a balanced trade-off between sensitivity and specificity, with abnormal substrate recall up to 0.784 and specificity ~0.97. Linear models such as SVC showed higher sensitivity (recall up to 0.854) but reduced precision (~0.72), indicating over-detection of abnormal regions.

These results demonstrate that ML can reliably integrate functional EGM features to identify abnormal atrial substrate under strict patient-level validation. This approach enables objective and reproducible substrate characterization, reducing operator dependency and standardizing substrate identification, and has the potential to be utiçized for automated identification of ablation targets, improving patient-specific treatment strategies in PsAF.

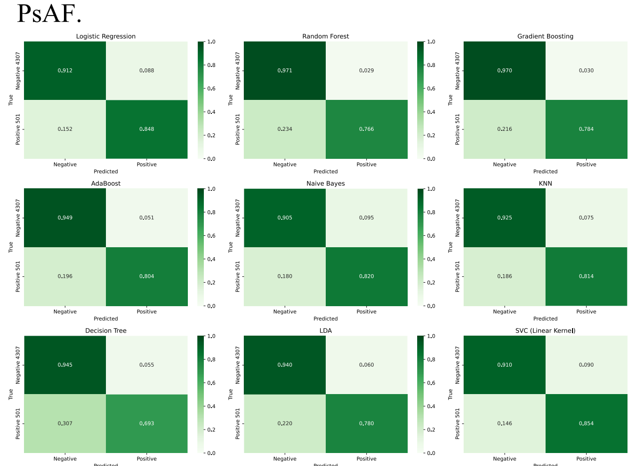

Figure 1. *Confusion matrices of all evaluated machine learning models under patient-level cross-validation (two-case holdout per fold). Values are normalized per class.*

References

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