Correlation-based Estimation of Activation Frequency in Intracardiac and ECG Signals During Atrial Fibrillation

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Abstract

Atrial Fibrillation (AF) is the most prevalent cardiac arrhythmia, affecting 2% of the population and having a significant impact on health and the economy. Despite advances in therapies, optimal treatment remains elusive due to variable success rates and subjective decision-making in ablation protocols. This study aimed to address these issues by non-invasively determining the modal Atrial Cycle Length (ACL) values in both atria of AF patients to improve ablation therapy.

Body Surface Potential Mapping (BSPM) and Intracardiac Electrograms (EGM) were recorded simultaneously in 22 patients, and different correlation-based methods were used to identify ACL. The results of the analysis indicated that correlation with five templates, achieved a relative error of 15% compared to the manual annotation. Furthermore, the custom metrics demonstrated a 1.2 ms difference and 97% agreement between the intra-atrial and surface recordings. Additionally, machine learning models predicted modal intra-ACL from surface data with a relative error of 7%. Clinically, estimating intra-ACL from surface measurements will enable rapid AF characterization to personalise therapy.

1. Introduction

Atrial fibrillation (AF) is the most prevalent cardiac arrhythmia worldwide, affecting millions of individuals due to its rapid and disorganised electrical activity in the atria [1]. Despite its high incidence, the precise mechanisms underlying the initiation and maintenance of AF remain controversial. Catheter ablation, particularly pulmonary vein isolation (PVI), represents a primary surgical intervention for AF, although its effectiveness varies between different forms of the arrhythmia [2]. To enhance the efficacy of treatment, the identification of regions with rapid atrial activation is critical. A key parameter for this is Atrial Cycle Length (ACL), which represents the interval between consecutive electrical activations in the atria measured in milliseconds. The identification of areas with the shortest ACLs allows clinicians to target them for ablation, potentially improving the efficacy of the treatment beyond that of PVI alone [3]. Moreover, the non-invasive identification of ACL values through surface signal analysis represents a promising approach to the management of AF [4]. However, FFT-derived methods, such as Dominant Frequencies, have complications for calculating ACL, mainly derived from the presence of harmonics [5]. In contrast, methods based on signal correlation are able to calculate the ACL value without these drawbacks [6]. These signals can be obtained non-invasively, generating accurate results even in the presence of noise [7].

The primary objective of this study is to develop a non-invasive method for ACL calculation based on signal correlation, using Body Surface Potential Mapping (BSPM) and intracardiac recordings. This method will be used to non-invasively estimate the modal value of the ACL for both atria. The study involves three key experiments: a comparison of an automated ACL calculation method with the manual gold standard, an assessment of the agreement between ACL values derived from Intracavitary Electrograms (EGM) and BSPM recordings, and the utilisation of Machine Learning (ML) models to predict modal intra-ACL from surface data.

2. Material and methods

2.1. Clinical database

Signals were recorded on N=22 patients using a dedicated Body Surface Potential Mapping (BSPM) system equipped with 52 electrodes and 6 standard ECG leads [4]. Simultaneously, Intracardiac Electrograms (EGM) were obtained using a basket catheter with 64 electrodes distributed across 8 splines (A-H), along with other intracardiac channels and a 12-lead ECG, all collected for subsequent analysis. All recordings were performed at Stanford Hospital during AF ablation cases.

57 EGM 1-minute recordings were obtained from the left atrium (LA) and 41 from the right atrium (RA).

Signal preprocessing encompassed four essential phases to prepare raw data for analysis. First, signal alignment was performed on BSPM and EGM signals recorded simultaneously, ensuring temporal accuracy through cross-correlation and synchronisation within a range of ±30 seconds. Second, a QRS complex removal algorithm was applied on intracardiac signals to eliminate artefacts caused by ventricular activity, enhancing the isolation of atrial activations by peak detection, smoothing, and subtraction from the original signal. Third, a band-pass filter (1-45 Hz) was applied to the signals to eliminate noise and interference. Finally, each signal was segmented into 6-second intervals to be used in the automated calculation of ACL.

2.2. Automatic ACL calculation methods

Two correlation-based methods were used to estimate the ACL in non-invasive and intracardiac signals. The first, autocorrelation-based method uses the classic autocorrelation estimator (Fig. 1.A). The ACL is determined from the time interval at the first local maximum, with a minimum threshold of 125 ms to reduce noise-related errors.

In the second method, multiple patterns from the signal were used to convolute the original signal by multiplying and summing corresponding points. Activations were identified as local maxima (>0.25 of correlation magnitude) with a blanking period of 100 ms, and ACL was determined as the median distance between activations (Fig 1.C). In this study, signals were convolved with patterns of 100 ms, using 5, 10, and 20 patterns.

Figure 1.A shows a 3-second segment of two EGM signals and the results of applying autocorrelation. For EGM #1, autocorrelation accurately identifies the ACL value at 207 ms (Figure 1.A). However, for EGM #2, it fails, giving an incorrect ACL of 336 ms (Figure 1.B). In contrast, the multiple pattern correlation method yields an ACL of 235 ms, closely approximating the actual value (Figure 1.C), effectively addressing issues of beat-to-beat variations that can cause errors in autocorrelation.

2.3. Design of machine learning models

The database creation process entailed the extraction of the 99 valid epochs from N = 22 patients, resulting in 872 segments of simultaneous 64-intracardiac and 58 surface ACLs. In order to provide a label representing the global atrial activation rate, the mode of the ACL values across 64 intracardiac electrodes was used, reflecting the general ACL value on each atrium. The database was split by patients: 12 patients were used for training, and validation was performed with the remaining 10 patients (8 with LA data and 6 with RA data). This split resulted in 320 segments for LA training and 262 for RA training, and 179 segments for LA and 111 for RA validation.

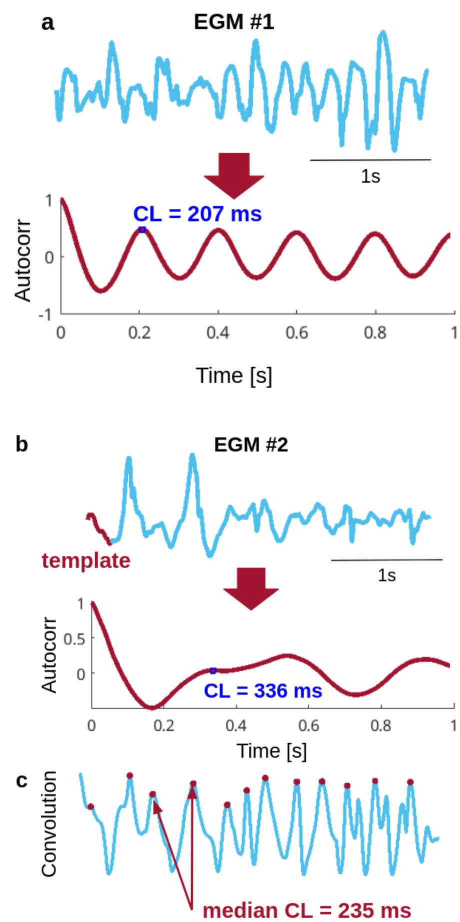

Figure 1. Correlation-base methods for automatic ACL calculation. A) Successful application of the autocorrelation method. B) Case where the autocorrelation method fails to identify the correct ACL and C) multiple patterns method accurately calculates ACL.

Machine learning models were trained with part of the surface channels, selecting the 14 most representative electrodes ACL estimation in LA and 20 electrodes for RA, which were selected based on mean squared error calculations between the electrodes ACL and the label. A 'manual' model was developed whose prediction consisted of the median of the selected BSPM electrodes. This model served as a baseline for evaluating the performance of more complex machine learning algorithms. For the more advanced models, the hyperparameters were optimised using the grid search method. This involved systematically testing all possible combinations of hyperparameters and selecting the combination that minimised the error. The models included linear regression, regression trees (min leaf size, LA: 45, RA: 23), Support Vector Regression (SVR) (kernel and scale, LA: Gaussian 3, RA: Gaussian 13), K-Nearest Neighbors (KNN) (k value, LA: 2, RA: 2), and random forest (leaf size and number of trees, LA: 28 and 13, RA: 22 and 7). These models were trained and validated using the same selected electrodes.

3. Results

3.1. Comparison with manual annotation

To evaluate the methods for automatic ACL calculation, a gold standard benchmark was established to provide a quantitative comparison of the results. For that purpose, 96 EGM signals (4 patients, 12 electrodes, 6 seconds) were visually reviewed and their ACL estimated by counting the number of electrical activations per second. Figure 2 presents the relative error of the 4 evaluated automatic ACL measurements compared to manually annotated results. The autocorrelation-based method exhibited a median relative error of 31% with a variability of ±16%, significantly higher compared to convolution-based methods. Convolution-based methods, particularly using 5 patterns, demonstrated superior performance with a median relative error below 15%. This finding underscores the effectiveness of the convolution approach in achieving more accurate ACL calculations compared to the manual annotation.

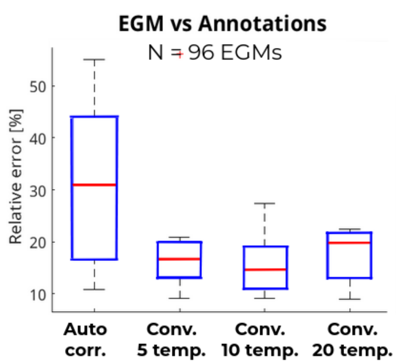

Figure 2. Relative error of automatic methods for ACL against manual-annotated ACL.

3.2. Concordance of non-invasive and intracardiac ACL estimation

To evaluate the concordance between simultaneous BSPM and EGM recordings, automatic ACL values were compared in simultaneous recordings (2 patients, 2 60-seconds epochs, 2560 EGM / 1920 ECG signals). The percentage of intracardiac ACLs that matched non-invasive ECG ACLs within a deviation window of less than 5 ms was assessed using each automatic method (called count similar metric), whose results are shown in Figure 3. Results showed that the convolution-based method with 5 patterns achieved the highest agreement between EGM and ECG ACLs (97% with a variability of ±5%), compared to the autocorrelation method (91% with a variability of ±8%) and the use of more patterns. These findings reinforce the previous results that highlighted the accuracy of the 5-pattern convolution method for automatic ACL calculation.

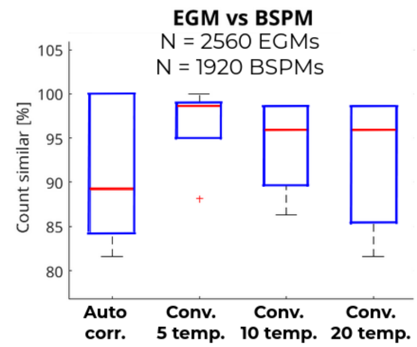

Figure 3. Similarity of ACL between non-invasive and intracardiac recordings obtained for each method.

3.3. Training of machine learning models

All models were trained with the configurations indicated in section 2.4 and their predictions were compared against the actual simultaneous label (intracardiac modal ACL). The basal model predictions, based on the median surface ACL, achieved a 12% error for LA and a 9% error for RA in validation. Among the various models, SVR stands out, achieving an 11% error for LA (slightly better than the manual model) and a 10.5% error for RA (slightly worse). The metrics for the other models can be observed in Figure 4, 4.A for LA models and 4.B for RA models.

4. Discussion

This project successfully developed an automated method for calculating ACL using a five-pattern correlation. A machine learning approach was used to predict intra ACL from BSPM data with high accuracy, improving personalised therapy planning for AF patients. Despite the project's success, several limitations were identified. The small sample size of 22 patients limits the generalizability of results, and the lack of detailed clinical history and the absence of a previous gold standard for ACL calculation may introduce biases. The model's inability to predict multiple ACL modes in bimodal atriums and the need for extensive preprocessing also present challenges. Future research should focus on expanding the database to improve result generalisation, developing models capable of dual ACL predictions, and enhancing regional ACL prediction capabilities. These improvements could provide a more comprehensive understanding of atrial activity and further enhance clinical treatment planning for AF.

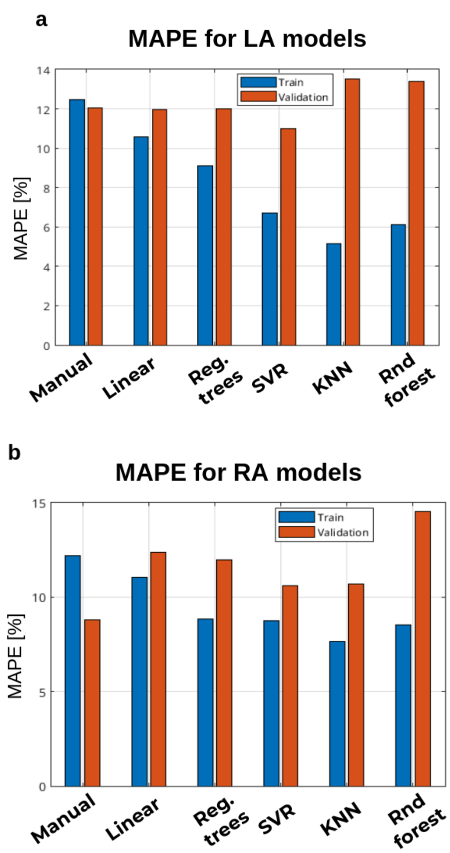

Figure 4. Relative error obtained for each machine model. A) Results obtained for LA models and B) Results obtained for RA models.

5. Conclusion

During this project, an automated method was successfully developed and validated to calculate the ACL using correlation with five patterns. This method achieved a percentage error of 15% when compared to the stabilised gold standard. The study also evaluated the concordance between non-invasive BSPM and invasive EGM recordings. Two custom metrics demonstrated that the five pattern correlation method effectively captured the relationship between the two types of recordings, showing a 1.2 ms difference and 97% similarity.

A database of 872 samples was created, enabling the training and validation of machine learning models to predict the modal ACL in the atrium using exclusively BSPM data. The SVR and manual models were the most effective in capturing the relationship between surface ACL and intra ACL mode. SVR's ability to handle non-linear relationships contributed to its superior performance, with an error of 11% in validation data for both atria. Also, the manual approach, despite its simplicity, was also accurate in prediction.

Acknowledgments

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