In Silico Framework for Estimation of Atrial Septal Ectopic Beats: a Combination of Mathematical Models, Electrocardiographic Imaging, and Support Vector Machines

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Abstract

Electrocardiographic Imaging (ECGI) allows the estimation of cardiac electrical propagation on the epicardium, but it does not accurately reflect septal ectopic activations. This study introduces a novel framework merging mathematical simulations, ECGI, and Support Vector Machine (SVM) models to enhance localization within septal regions.

We conducted 17,220 cellular automata simulations of atrial ectopic beats across the epicardial surface and within the atrial septum. Geometries for cardiac and torso models were generated from statistical shape models, and ECGI was computed for the simulations. Local activation time (LAT) maps were computed, and a novel framework with SVM models was developed to identify septal ectopic beats. We compared the earliest activation sites (EAS) of LAT maps detected by ECGI with those selected by our framework to identify the most similar simulation.

SVM models achieved an accuracy of 99.58% in classifying septal and non-septal beats and 94.29% of accuracy in identifying left and right septal ectopic beats. Furthermore, our approach reduced EAS location error from 2.3±1.03 cm (ECGI alone) to 0.46 ± 0.24 cm.

This study demonstrates the potential of integrating simulations, ECGI, and machine learning to advance cardiac arrhythmia diagnosis overcoming ECGI's limitations in estimating septal wall activity.

1. Introduction

Electrocardiographic Imaging (ECGI) serves as a valuable tool for assessing the propagation pattern of cardiac electrical activity [1]. In particular, the estimation of Local Activation Times (LAT) from ECGI signals facilitates the identification of focal and reentrant patterns that are characteristic of ectopic beats originated in patients with supraventricular arrhythmias. The accurate determination of LATs and the detection of the earliest activation site (EAS) is crucial in identifying the locations that are arrhythmogenic, a critical step in guiding ablation therapy for patients afflicted with atrial arrhythmias.

Traditionally, ECGI has been formulated to calculate epicardial potentials [1, 2], or a combination of endocardial and epicardial potentials [3]. Consequently, conventional ECGI methodologies encounter limitations in accurately estimating the electrical activity of atrial septal walls [4]. Albeit beats originated in the atrial septum can be identified observing the epicardial propagation, they are not able to show the EAS of the beat.

To address these challenges, cardiac mathematical modelling offers the capability to simulate diverse activation patterns of focal atrial activity [5]. Simulations enable us to explore various scenarios of ectopic beat generation and propagation within the atria, including those originating from septal regions.

In this context, we propose a framework that integrates a comprehensive database of focal ectopic beats of atrial activity with ECGI and machine learning techniques. This integrated approach combines the strengths of each component: mathematical models provide a gold standard of the activation pattern, ECGI offers a non-invasive estimation of cardiac electrical activity, and machine learning facilitates the automated analysis and classification of ectopic beats. By this combined approach, we aim to enhance the identification of the origin of septal ectopic beats within the atria and reduce the error in the localization of their origin.

2. Material and methods

2.1. Data generation and processing

A total of 17,220 simulations of atrial ectopic beats were performed using cellular automata models of the atria [5]. Among these, 16,800 simulations with ectopic beats originating at a random location in the epicardial surface

of the atria, while 420 simulations had the origin located within the atrial septum (210 in the left atrial septum and 210 in the right atrial septum). Forty-two distinct cardiac geometries derived from a statistical shape model comprising 4,000 nodes were used for EGM [6] and ECGI computations. The use of a statistical shape model allows us to ensure a one-to-one correspondence of all nodes between instances. Torso geometries were generated from a statistical shape model of the human torso, resulting in a total of 17,220 unique torso instances. These geometries included 128 nodes to emulate the distribution of electrodes in ACORYS mapping system (Corify Care SL).

Cardiac meshes were positioned centrally within each torso instance and randomly displaced within physiologically relevant ranges of ±3.5 cm along each axis and rotated within the range of ±20° in the x and z axes and ±45° in the y axis.

The forward problem utilized the boundary element method to generate Body Surface Potential Mapping (BSPM) signals from each simulated beat. Gaussian noise with SNRs ranging from 0 to 20 dBs was added to simulate real-world conditions. A low-pass filter with a cutoff frequency of 40Hz was applied to BSPM signals to reduce noise. The inverse problem was solved using zero-order Tikhonov regularization and L-curve optimization to estimate the underlying cardiac electrical activity from measured BSPM signals [7].

2.2. Estimation of EAS of septal beats

To estimate the EAS in atrial ectopic beats, local activation time maps were computed for each EGM and ECGI signals coming from the simulations. The minimum LAT location was identified as the EAS of the beat. The estimation error of EAS localization was quantified as the Euclidean distance between the stimulation point of the simulation and the minimum LAT of the ECGI signals.

To estimate of the EAS on septal ectopic beats, that ECGI cannot estimate properly, a novel framework was developed to estimate the origin of propagation (see Fig. 1). LATs from the 17,220 simulations were used to train a support vector machine (SVM) model for classifying beats based in their origin propagation, whether it is at the atrial septum or not. A linear SVM model with 10-fold cross-validation was trained using 14,350 simulations for the training subset and 2,870 simulations for the test subset.

An additional SVM model was trained to classify septal beats based on if they were originated from the left or right atrium. The septal activation dataset was divided into 350 simulations for the training subset and 70 simulations for the test subset. A 10-fold cross-validation was employed during training.

Confusion matrices and Receiver Operating Characteristic (ROC) curves were generated for both SVM models. Performance metrics including accuracy, precision, recall, and F1-score were computed to evaluate the efficacy of the models.

Finally, following the beat classification by SVM, the LAT maps computed from ECGI signals of septal beats from the test dataset were correlated with all the simulations in our training set. For instance, LAT maps of beats classified using the SVM as originating from the left septal wall were correlated with all the LAT maps from left septal origins in out training set. The stimulation site for the simulation with the highest CC with the beat under test was defined as the EAS of the ECGI map. Subsequently, the Euclidean distance between the predicted EAS and the stimulation point of the beat under test was computed and compared to the error obtained solely using ECGI.

2. Results

The results of our study reveal significant differences in the localization error of EAS with LAT maps estimated with ECGI between septal and non-septal simulations. Specifically, the mean error in the location of the EAS using ECGI was 1.21±0.98 cm for non-septal beats, compared to 2.31±1.03 cm for septal simulations, which illustrates the limitations of ECGI in the detection of

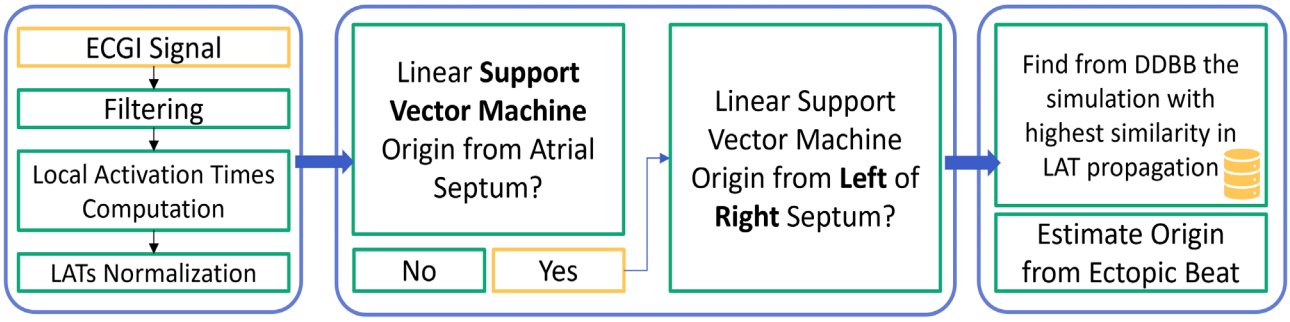

Fig. 1. Framework for the identification of the origin of propagation of septal ectopic beats.

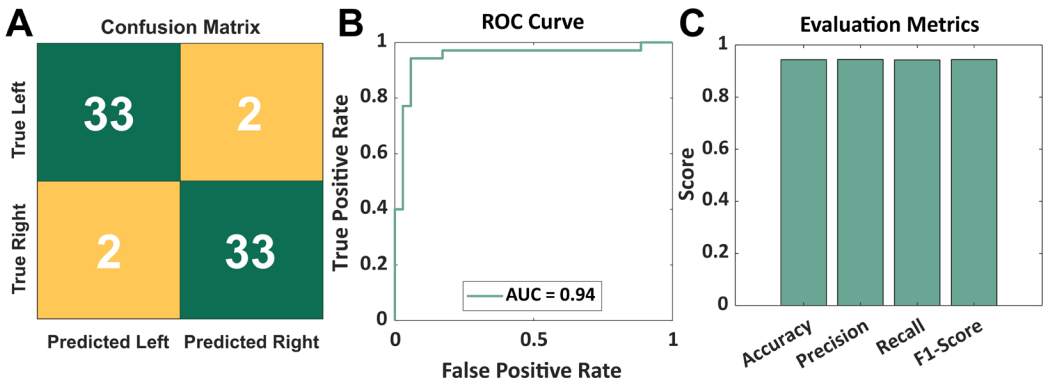

Fig. 2. Results of the trained SVM classifier for identifying the atrium (left vs. right) in septal ectopic beats. A. Confusion matrix, B. Receiver Operating Characteristic Curve and C. Performance Metrics.

activity in the septum.

On the other hand, our SVM models demonstrated remarkable performance in classifying ectopic beat origins. The first SVM achieved an accuracy of 99.58% in distinguishing beats with the EAS in the atrial septum from non-septal EAS beats. Besides, the second SVM accurately differentiated between beats with the EAS in the left vs. right septum, with a test subset accuracy of 94.29%. Graphical representation of the second SVM's results is provided in Fig. 2, showcasing better identification of right septal ectopic beats, with an area under the curve of 0.94. The SVM model exhibited excellent recall and F1-score values (0.94), underscoring their high classification accuracy. In contrast, EAS detection of beats with septal origin using ECGI-alone yielded a considerably lower accuracy of 23.57% in correctly identifying the originating atrium. This highlights the superior performance of our SVM-based approach in accurately localizing ectopic beat origins.

Following the development of our classification framework, we proceeded to assess the accuracy of ectopic beat localization in the test subset of simulations. The EAS determined from LAT maps computed over ECGI signals exhibited a mean error of 2.3±1.03 cm. Subsequently, we applied the trained SVM model to the test subset, correlating LAT values with those from septal simulations of the corresponding identified atrium. The simulation with the highest correlation was selected, and its stimulation point was assumed as the estimated EAS for the test subset ECGI LAT maps. The resulting Euclidean distances from the gold standard were then computed, revealing a significant reduction in EAS detection error to 0.46±0.24 cm. These findings are depicted in Fig. 3.

An illustration demonstrating the efficacy of our method is shown in Fig. 4. Panels A and B display the LAT maps obtained from the original test simulation and ECGI, respectively. The white point in both panels represents the EAS. Upon application of our framework, Panel C presents the simulation from our database that exhibits the highest correlation with the ECGI, closely resembling it.

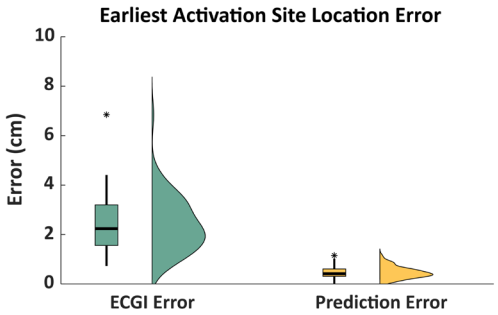

Fig. 3. Euclidean error in the localization of EAS of septal ectopic beats using ECGI-alone (green) and using ECGI combined with SVM and mathematical simulations (yellow).

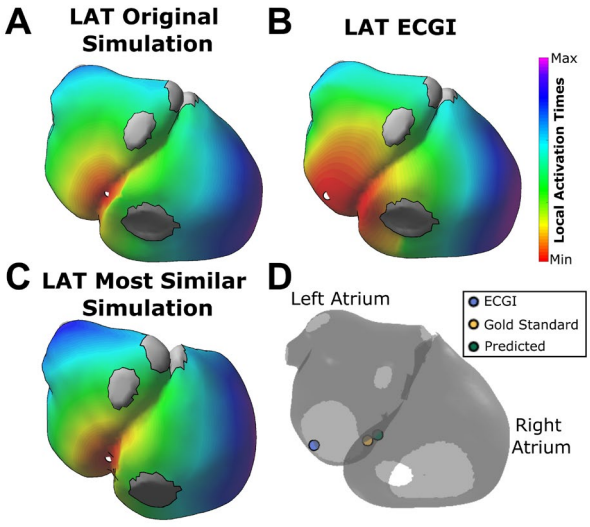

Fig. 4. Example of an improvement on the EAS detection of a simulation of a septal ectopic beat. Local activation time (LAT) maps of the original simulation, the ECGI and the most similar simulation from the dataset of left atrial septum ectopic, estimated with SVM. White dots represent the EAS. D. Representation of the EAS estimated by ECGI, the predicted after applying the developed framework and the gold standard.

In Panel D, the EAS estimated by ECGI (blue), the gold standard (yellow), and the predicted EAS (green) are shown. Notably, the predicted EAS significantly improves upon the EAS detected solely by ECGI, reducing the Euclidean distance to 0.35cm. This exemplifies the enhanced accuracy and precision achieved by our approach in localizing ectopic beats.

4. Discussion

In the present study, we have observed that while ECGI demonstrates the ability to predict the propagation pattern of ectopic beats and their origin, it encounters challenges in accurately detecting septal ectopic beats. This limitation highlights the need for complementary approaches to improve the performance of ECGI in septal ectopic detection.

Our proposed framework, which integrates SVM and mathematical modelling with ECGI, has demonstrated notable advancements in overcoming this limitation. By incorporating machine learning techniques and mathematical models, our framework enhances the identification of EAS particularly within the septal regions.

Furthermore, the developed framework has the potential to contribute to the selection and development of cardiac digital twins, facilitating personalized medicine approaches by a better identification of their EAS. By accurately identifying focal sources during ablation procedures, our framework may aid in reducing intervention times and improving outcomes for patients with supraventricular arrhythmias such as atrial fibrillation.

Looking ahead, future work should focus on validating our framework in clinical settings and more complex simulations. Extending the validation to patient data will provide crucial insights into the real-world applicability and efficacy of our approach.

4. Conclusion

The combination of mathematical simulations with ECGI is a powerful tool for finding the origin for atrial ectopic beats with the EAS in the septum. In addition, our proposed classification algorithms facilitate the identification of the atrial chamber. Furthermore, our framework exhibits superior performance in localizing the origin of ectopic beats compared to traditional ECGI methodologies that cannot estimate activity in the septum, achieving a reduction in localization error of 0.46 ± 0.24 cm.

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Conflict of Interest

A.M. Climent and M.S. Guillem are co-founders and stakeholders of Corify Care S.L. R. Molero and C. Fambuena receive honoraria form Corify Care S.L.

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