A Digital Twin Framework with Synthetic Ablation and Electrogram Classification for Ablation Guidance

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Abstract

This work presents a digital twin framework designed to support radiofrequency (RF) ablation procedures by integrating synthetic electrophysiological simulations and machine learning (ML)-based electrogram (EGM) classification. The system uses in-silico modeling to aid clinicians in identifying arrhythmogenic substrates. The digital twin is implemented using cardiac data from Late Gadolinium Enhancement Magnetic Resonance Imaging (LGE-MRI) and the openCARP simulation platform, which models atrial tissue activity. EGMs are synthetically generated by navigating a virtual catheter across the atrial tissue surface. A supervised ML classifier is trained on these signals to classify potential ablation sites based on the EGM characteristics. Ablation is emulated by modifying tissue conductivity at selected points, governed by RF parameters. The system dynamically updates its electrophysiological state to reflect propagation changes due to lesion formation. The developed system aims to enable effective monitoring of the procedure using the classifier and an ablation quality index (AQI), providing visual results that assist clinicians in decision-making before, during, or after the ablation. This digital twin offers a versatile and reproducible platform for studying ablation strategies and training ML models on synthetic EGMs, holding potential for procedure planning and real-time clinical decision support.

1. Introduction

Cardiovascular diseases continue to be one of the leading causes of mortality and morbidity worldwide, accounting for approximately 30% of all annual deaths [1]. Atrial fibrillation (AF), in particular, is the most common sustained cardiac arrhythmia, affecting millions of people globally and significantly contributing to stroke, heart failure, and other serious complications [2]. Its prevalence is increasing due to an aging population and rising risk factors such as hypertension, obesity, and diabetes. The symptoms of AF vary widely, including palpitations, shortness of breath, fatigue, dizziness, and chest pain, significantly impacting patients' quality of life and imposing substantial economic burdens on healthcare systems.

In the context of ablation for AF, synthetic data can be employed to simulate the dynamic response of cardiac tissue during the ablation process and investigate the relationship between fibrotic patterns and re-entrant circuits in AF, providing insights into the arrhythmogenic substrate of the disease [3].

This work aims to develop and validate a digital twin framework that integrates synthetic and real cardiovascular data to simulate tissue ablation and support AF ablation procedures. This framework provides a visual tool for interactive simulations, combining an AQI based on catheter measurements and ML models for EGM classification. This is a promising tool to enhance procedure planning and guidance by identifying potential ablation areas, simulating the effects of tissue ablation based on conductivity changes, and quantifying ablation quality.

2. Methods

The proposed digital twin framework generates synthetic EGMs by simulating atrial electrophysiological behavior using openCARP [4], an open-source platform for cardiac electrophysiology simulations, and real patient anatomical information. This pipeline enables the replication of various atrial rhythm scenarios, including normal sinus rhythm and pathological conditions like persistent atrial fibrillation (AF). The system is designed with a graphical user interface (GUI) to facilitate user interaction and visualize the simulation process.

2.1. Application of Real Patient Data

Real patient data serves as the foundation for the digital twin framework. First, cardiac meshes derived from Late Gadolinium Enhancement Magnetic Resonance Imaging (LGE-MRI) provide the anatomical basis for synthetic data

generation through in-silico simulation of the heart. A dataset including 3D heart meshes from 100 AF patients, detailing fiber directions and fibrosis, obtained via MRI [5] is used. This anatomical data underpins the simulation of various tissue properties and catheter-tissue interactions during ablation procedures.

Real patient data provides the anatomical substrate for the digital twin. We use patient-specific atrial meshes with fiber orientation and fibrosis derived from LGE-MRI [5]. Fibrosis is quantified via the Image Intensity Ratio (IIR); cells with IIR ≥ 0.64 are assigned AF-remodeled Courtemanche properties [6], while the remainder retain normal properties, yielding spatially heterogeneous conduction. We vary fibrosis intensity and selected ionic parameters to modulate conduction velocity and wavefront fragmentation, producing diverse synthetic patients.

2.2. Simulation Protocol

Electrical propagation is simulated in openCARP using the Courtemanche atrial cell model [7], with AF remodeling applied in fibrotic regions as described above [6]. To induce persistent AF, we initialize the transmembrane potential in the Universal Atrial Coordinates (UAC) plane with eleven small Archimedean spirals of opposite chirality and map it back to the 3D mesh, generating stable rotor-driven activity and fractionated signals [6].

A synthetic PentaRay catheter, controlled by the user, samples bipolar EGMs at atrial surface locations. Unipolar signals are computed as a weighted sum of transmembrane currents, and bipolar pairs are formed from adjacent electrodes, following prior work [8, 9].

The system integrates synthetic electroanatomic maps (EAMs) as well as real-world cardiovascular data extracted from LGE-MRI and ablation supporting systems into a cohesive simulation platform. This architecture combines computational electrophysiology, ML, and interactive visualization. It consists of two main components: a frontend and a backend engine. The backend manages the simulator based on openCARP and patient-derived anatomical data and supports custom stimulation protocols (e.g., sinoatrial node pacing or rotor-based initiation). ML models process EGM data to classify tissue regions and support decision-making. The overall interaction between user, frontend, and backend is summarized in Figure 1.

As illustrated in Figure 2, ablation effects are simulated by modifying the IIR-derived fibrosis map on the selected site(s) according to the chosen RF parameters. These edits are then used to update the initial condition, after which a new simulation is run. This loop enables iterative evaluation of lesion formation and its impact on electrical wave propagation.

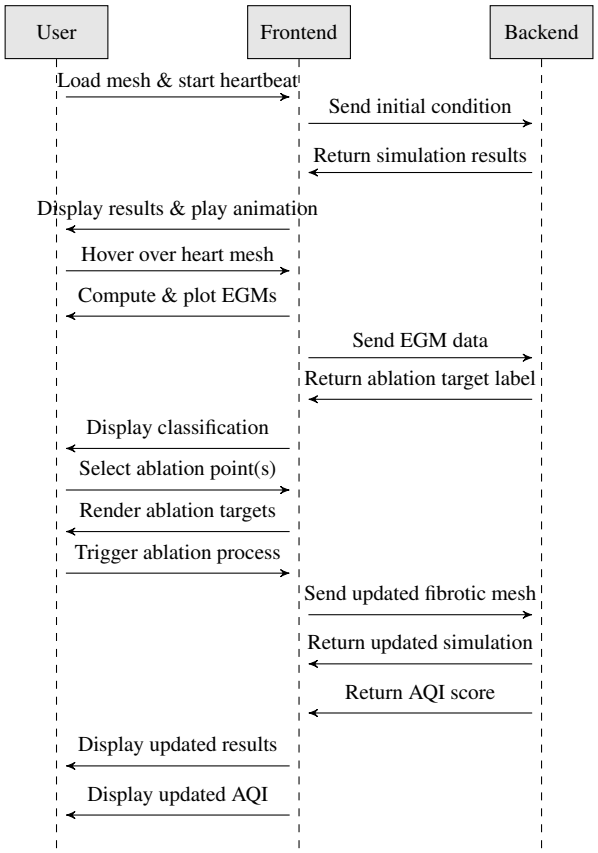


Figure 1: Unified Workflow of the Digital Twin System

2.3. AI-Driven Ablation Support

To further enhance the digital twin, ML models are integrated for EGM classification and ablation quality assessment. This section briefly outlines these components.

ML models are trained and employed as a binary classification problem to classify EGM samples that may correspond to potential ablation targets based on AF behavior [10]. This classification is performed in the backend (Figure 1), where signal processing techniques are used to detect arrhythmogenic patterns and return the classification results to the system.

In parallel, AQIs such as the force-time integral (FTI) [11] are being developed as quantitative metrics to evaluate lesion formation. These indices quantify parameters such as contact force, duration, and power, providing benchmarks for effective lesion formation [12–16]. Although still under development, their integration into the framework has the potential to improve procedural planning and guide personalized treatment strategies. Furthermore, statistical methods will be employed to evaluate correlations between AQIs and clinical outcomes, such as AF recurrence.

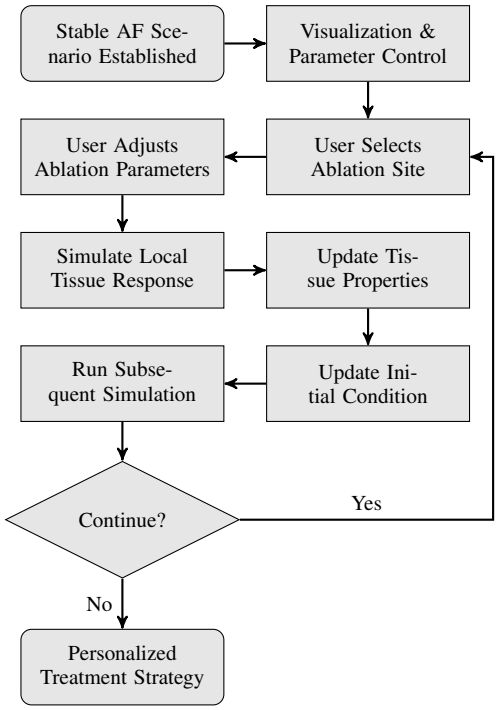
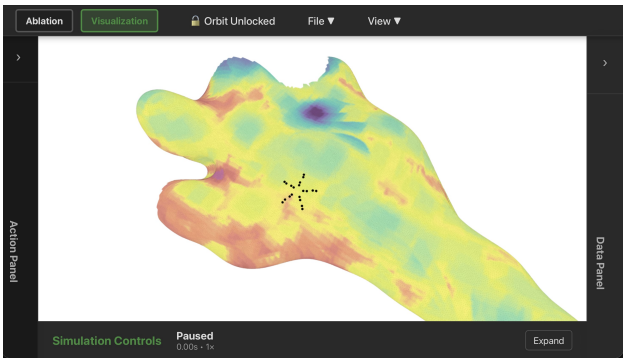
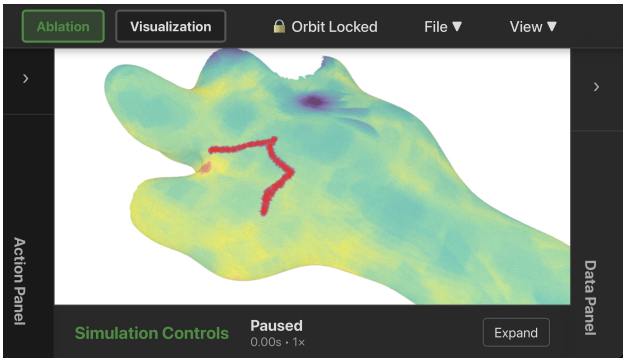


Figure 2: Flowchart of ablation simulation in the digital twin framework.



(a)



(b)

Figure 3: Software user interface with a) during EGM visualization and b) during ablation simulation

3. Results

Initial efforts have focused on creating a functional software interface and a synthetic generation framework, which are now operational in their first version, providing a foundation for further integration. As shown in Figure 3, a first iteration of the software interface and synthetic generation framework is working.

The framework simulates dynamic electrical activity under different stimulation conditions, including organized propagation for sinus rhythm and chaotic rotor formation and reentry patterns for persistent AF, leveraging techniques from the literature.

4. Discussion

The developed digital twin framework provides a reproducible method for simulating ablation procedures under controlled conditions. By integrating patient-derived anatomical information with advanced electrophysiological modeling in openCARP and an EGM acquisition process considering catheter-tissue contact, the framework allows the simulation of personalized cardiac activity. The interactive GUI allows users to visually select ablation sites and adjust simulation parameters, providing immediate feedback on electrical propagation changes due to lesion formation, which is critical for personalized treatment strategies.

The current operational state of the software interface and synthetic generation framework demonstrates a foundational step towards a comprehensive solution for ablation guidance. This platform offers a non-invasive, controllable, and reproducible environment to test hypotheses in cardiac ablation, aiding clinicians in decision-making before, during, or after the procedure. The ability to create ”git-like” branches of ablation strategies further enhances its utility as a planning and training tool. Moreover, the system integrates ML-based EGM classification and AQI, providing additional computational support for evaluating ablation strategies and simulating procedural outcomes.

5. Conclusion

In this work, we present a digital twin framework for ablation procedures. The proposed system includes an EGM classifier designed to identify ablation targets and foresees the inclusion of a module to compute an AQI.

Despite these advancements, the framework has areas for further development. Future work will prioritize validation and refinement of the framework, particularly through simulating and comparing Pulmonary Vein Isola-

tion (PVI) strategies to redreinforce clinical applicability. In the simulator, circumferential lesions around the pulmonary veins will be modeled, and subsequent simulations will assess the isolation. These synthetic outcomes will be compared against published PVI criteria.

Overall, the developed system, with its software interface and synthetic generation capabilities, represents a functional platform for studying ablation strategies and training ML models on synthetic EGMs. It holds potential for advancing procedural planning, guiding real-time clinical decisions, and enhancing physician training for AF ablation.

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