Substrate-Specific Simulations of Atrial Fibrillation Reproducing Electrophysiological Clinical Markers

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Abstract

Digital Twins able to reproduce patient-specific electrical patterns during atrial fibrillation (AF) could help to identify the optimal therapy. Calibration of atrial simulation parameters is mandatory to reproduce observed clinical markers such as cycle length (CL) or conduction velocity (CV).

A realistic 3D atrial anatomy including fiber orientation, conduction anisotropy and ion channel heterogeneities across atrial regions was built to simulate AF patterns. Functional reentries were simulated under different degrees of electrical remodeling and tissue diffusion (healthy to chronic AF), then CV and CL were measured at different atrial regions.

The heterogeneous model allowed to simulate differences in transmembrane potential curves as reported in bibliography. As expected, CV at atrial regions increases with increasing diffusion, whereas CL decreases with electrical remodeling, from healthy to chronic AF substrate.

Electrical remodeling and diffusion factors can be used to calibrate AF models to clinically measured CV and CL markers. This will permit Digital Twins to reproduce the patient-specific electrophysiological patterns simulating AF progression and test potential therapies.

2. Materials and Methods

2.1. Heterogeneous atrial model

The 3D model of human atri shown in Figure 1a was used, which includes fiber orientation and atri division into different regions [3]: right atrium (RA), left atrium (LA), sinoatrial node (SAN), crista terminalis (CT), pectinate muscles (PM), Bachmann bundle (BB), right atrial appendage (RAA), left atrial appendage (LAA), inferior vena cava (IVC), superior vena cava (SVC), cavotricuspid isthmus (CTI), mitral valve (MV), tricuspid valve (TV), pulmonary veins (PV) and fossa ovalis (FO).

Differences between atrial regions at cellular scales were included in the model. Based on the work of Krueger [3], anisotropy was included as variations in the transverse and longitudinal diffusion values of each region as shown in Table 1. In addition, we included a specific cellular model for each atrial region based on previous experimental [4,5] and simulation studies [6-10]. Using Koivumäki’s model [11] as a basis, we modified the conductivities of 5 ionic currents: \( I_{K_s} \), \( I_{CaL} \), \( I_{K1} \), \( I_{K1} \) and \( I_{K1} \) as shown in Table 2. Tissue propagation was based on the
monodomain model and solved with a dt of 10 µs on a custom-made GPU solver [12].

2.2. Heterogeneous model simulations

After stabilizing the heterogeneous atrial model following a pacing protocol at 5 Hz for 4 seconds, reentrant activity was generated in the left atrial septum using an S1-S2 protocol. Two sets of simulations were performed: i) varying the diffusion percentages (25%, 50%, 75% and 100%) together with a 125% remodeling; and ii) varying the remodeling percentages (25%, 50%, 75%, 100% and 125%) with a 25% diffusion. Note that a remodeling percentage of 0% and a diffusion percentage of 100% represents healthy atrial conditions. Increasing the remodeling percentage implies progressing from healthy to chronic AF (cAF), for a remodeling of 100%, and long-standing AF when exceeding this percentage. To create the FAc model, the following currents were modified from Koivumäki’s model in all regions of the atrium: SERCA expression (-16%), PLB to SERCA ratio (+18%), SLN to SERCA ratio (-40%), maximal $I_{\text{NCX}}$ (+50%), sensitivity of RyR to $[\text{Ca}^{2+}]_{\text{SR}}$ (+100%), conductance of $I_{\text{CaL}}$ (-59%), conductance of $I_{\text{to}}$ (-44%), conductance of $I_{\text{Kr}}$ (-22%) and conductance of $I_{\text{K1}}$ (+100%). For the 25%, 50% and 75% remodeling models, the values of the modified currents were obtained as a linear interpolation between the healthy case and the cAF model, while the currents of the 125% remodeling model were calculated by linearly extrapolating.

2.3. Measurement of cycle length and conduction velocity

Seven points covering the surface of both atria were selected to measure clinical markers: LA, MV, PV, CT and RAA and two in RA wall. These points, represented in Figure 2a, were used to measure CL and CV using 2s of each simulation after the functional reentry was stabilized.
The CL was obtained from the transmembrane potential curve of each of these 7 points by averaging the time between consecutive activations (fig 2c).

To measure the CV, 4 points were selected at 5 mm surrounding each of the 7 measurement points (fig 2b). A planar wave conduction was fit by least-squares to the respective activation instants, from which the propagation direction and CV were extracted. Finally, the CV was obtained as the average value of all activations.

![Figure 2](image)

**Figure 2.** a) Points to measure CL and CV. b) Detail of 4 points used to measure CV. c) Transmembrane potential to determine CL.

### 3. Results

#### 3.1. Electrophysiological model evaluation

The atrial model reproduced differences in transmembrane potential curves across different regions (fig 1b), obtained for a pacing simulation at 2 Hz for healthy conditions. LA tissue showed an action potential duration (APD\(_{90}\)) of 232 ms, whereas the atrioventricular rings, TV and MV, presented the shortest action potentials with APD\(_{90}\) of 210 ms and 206 ms, respectively. In contrast, the CT had the longest APD\(_{90}\) (256 ms), and the PVs presented an earlier repolarization but longer APD\(_{90}\).

Figure 1c shows the local activation map for the pacing simulation from the SAN at 2 Hz, where the entire atrium takes 114 ms to depolarize. The effect of anisotropy can be observed as a faster conduction zone corresponding with the CT that causes a triangular profile in the isochrones.

#### 3.2. Conduction velocity fitting

![Figure 3](image)

**Figure 3.** CV for 125% electrical remodeling.

#### 3.3. Cycle length fitting

Figure 4a, which represents the values measured at the 7 points of the atrium in the simulations with 25% diffusion. At points in the LA, PV and MV regions the CL decreased with increasing remodeling. For example, at the LA point a CL of 229.71 ms was measured for 25% remodeling and 172.40 ms for 125%. Note that, from 25% to 75% remodeling the conduction ratio from LA to RA was approximately 4:3 (fig 4b), where for every 4 cycles of potential at the LA 3 cycles are conducted to the RA. For 100% remodeling conduction to the right atrium was reduced to a ratio of 2:1 (fig 4c), causing an increase in CL.

### 4. Discussion and Conclusions

This study demonstrates that detailed simulations of the atrial substrate, including fiber direction, ionic heterogeneity and electrical remodeling, can reproduce clinical markers as CV and CL in ranges observed in clinical practice. Calibration curves were obtained at 7 atrial regions able to link clinically measurable markers, CV and CL, as a function of the parameters used to perform simulations: electrical remodeling and diffusion. It has been observed that CV increases with increasing diffusion percentage, covering the range from 231.68 mm/s to 584.49 mm/s in the LA, and from 100 to 900 mm/s in the whole atria. Conversely, increasing the electrical remodeling resulted in a decrease in CL, from 229.71 to 172.40 ms in the LA, and ranging from 160 to 350 ms across both chambers.

The detailed atrial model with anisotropy and substrate heterogeneities was used to measure the CV in presence of chronic AF substrate. Different conduction velocities were obtained for each atrial region, observing variations also reported in bibliography [2].
Regarding the measurements on the TP curve, the lowest APD$_{90}$ was obtained in the TV and MV (206 ms and 210 ms, respectively) and the highest in the CT (256 ms). These results agree with those obtained in experimental studies [4]. In addition, a decrease in amplitude (from 102.31 mV to 87.86 mV) were obtained in the PVs, as measured in [5].

This study shows a single CV calibration curve for a single value of 125% remodeling, as well as a CL curve for 25% diffusion. It is necessary to extend these calibration tables to fit CL and CV for any substrate condition, in order to cover all potential clinical situations. This study focuses on the arrhythmic condition on the LA, as it is known the relevance of this region in AF maintenance. However, other AF maintenance mechanisms, such as multiple waves or micro-reentries, and other dominant regions should be considered.

The results obtained in this investigation demonstrate diffusion and electrical remodeling can be adapted on computational models to reproduce the CL and CV values measured in patients. This will allow the creation of Digital Twins by adapting the percentage of remodeling and diffusion of the simulations performed to the ranges corresponding to the clinical markers measured in the patient. Even sweeps of simulations can be performed to reproduce the temporal dynamism of the markers. In this way, it will be possible to reproduce not only the anatomy but also the specific AF phenotype of each patient, to identify the specific mechanisms of AF and predict the efficacy of each therapy.

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References


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