Automated Initiation of Fibrillatory Excitation in Monodomain Simulations

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Introduction

Atrial fibrillation is an arrhythmia of the atria, caused by chaotic electrical activity in the heart. Reentrant excitation occurs when an excitation wave repeatedly activates the same tissue area in a cyclic manner. In phase space, the point in the center of this reentrant wave has no defined value and is thus called phase singularity.

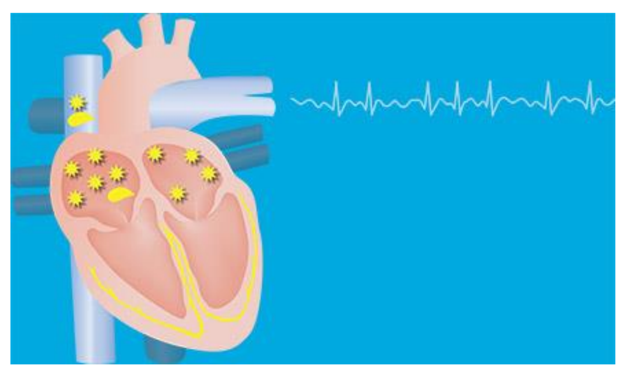


Figure 1: Electrical activity in fibrillating heart.

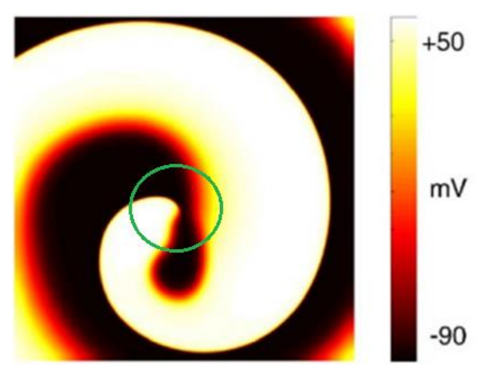


Figure 2: An activation map displaying a phase singularity.

Monodomain simulations replicate the propagation of a wavefront through cardiac tissue.

$$C_m \frac{\partial V_m}{\partial t} = \beta^{-1} \nabla \sigma \nabla V_m - I_{ion} + I_{stim}$$

Equation 1: Reaction-Diffusion equation for monodomain simulations

Existing programs achieve re-entry by manually searching for appropriate pacing protocols – an extremely time consuming process.

Goal

The goal of this project is to initiate a monodomain simulation of atrial fibrillation given one – or potentially multiple – phase singularity points as an input. The approach was described by Matene and Jacquemet in 2012.

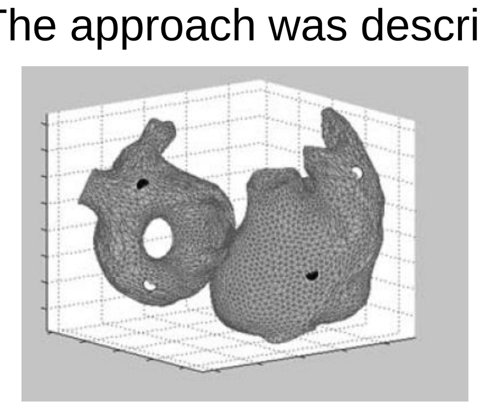


Figure 3: Subplot of Graphic User Interface in Mattlab implemented by Matene and Jacquemet (2012).

Defining Re-entry

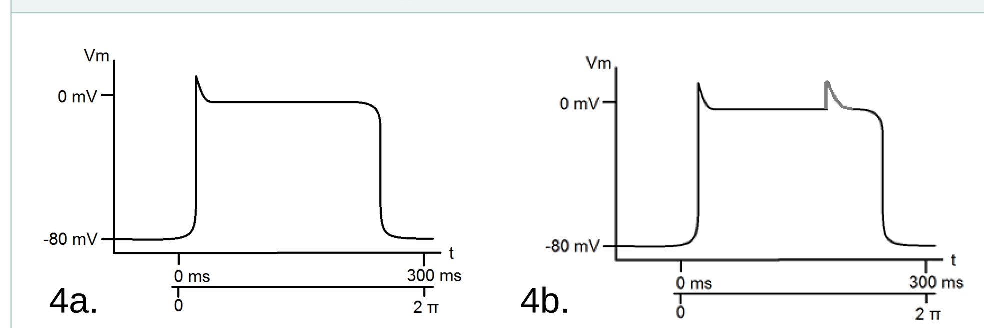


Figure 4: Diagrams displayed the stimulation of a cell. Subfigure 4a displays a typical spike in voltage followed by repolarization. Subfigure 4b shows the result of a stimulus during the ERP.

After a cell is stimulated, it exhibits an action potential is not susceptible for new stimuli during the effective refractory period (ERP). After complete repolarization, the cell is again excitable. Because re-entry is periodic, mathematically, the cycle length can be directly translated to phase values that range from 0 to 2π.

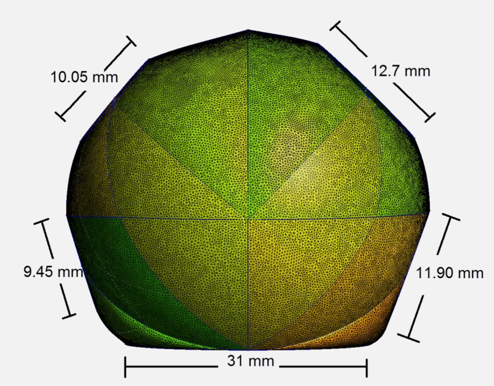
Workflow

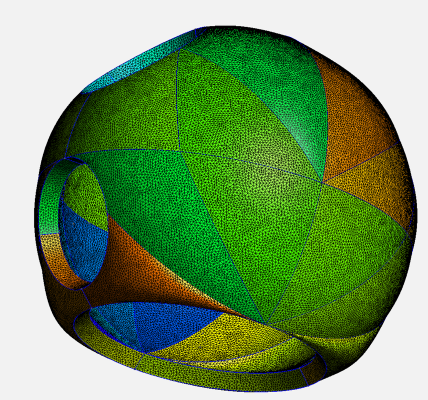
Create Geometry	Construct initial activation map	Conduct monodomain simulation
• Surface mesh • Volumetric mesh	• Construction of initial conditions • Laplace interpolation • Eikonal solver	• Initialize ODE variables according to position in cycle in single cell environment • Dynamic monodomain simulation

Implementation

Create Simplified Left Atrial Geometry

Surface Mesh	Volumetric Mesh
Figure 5: Triangular surface mesh with appropriate measurements for the mitral and pulmonary valves.	Figure 6: Tetrahedral surface mesh, scaled to form a 2 mm myocardial wall thickness.





Construct Initial Activation Map

Figure 7: The original application of the eikonal algorithm to solve for an initial activation map. Given an original phase map:
a) Random nodes and corresponding phase values are extracted.
b) Laplacian interpolation estimates an initial value.
c) The eikonal solver iteratively solves for activation map.

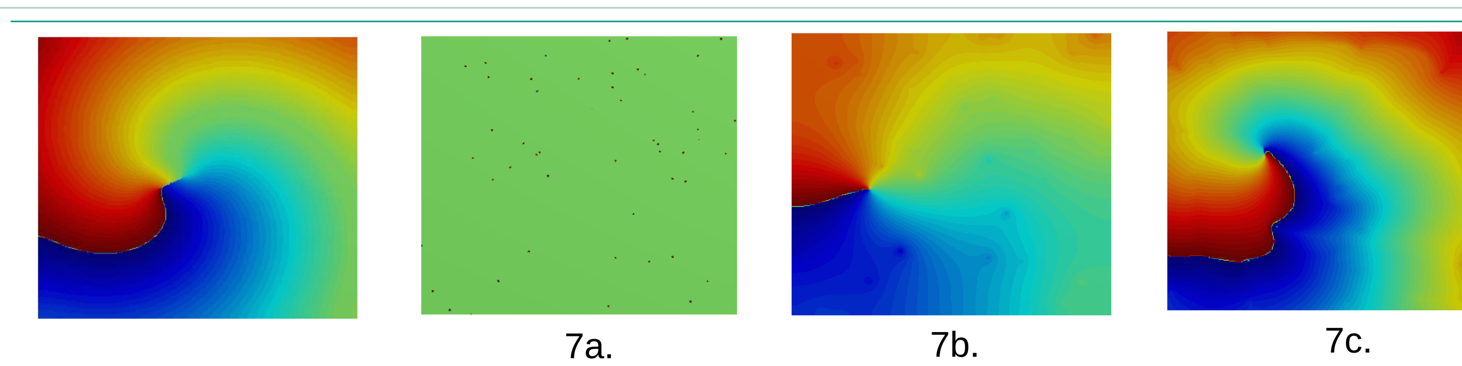
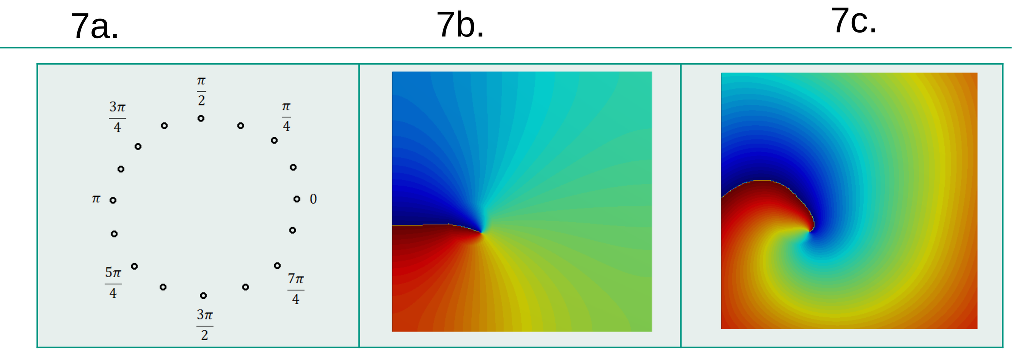


Figure 8: Process modified to be independent of an initial phase map: A circle of phase values are assigned to seeds around a phase singularity.



Conduct Monodomain Simulation

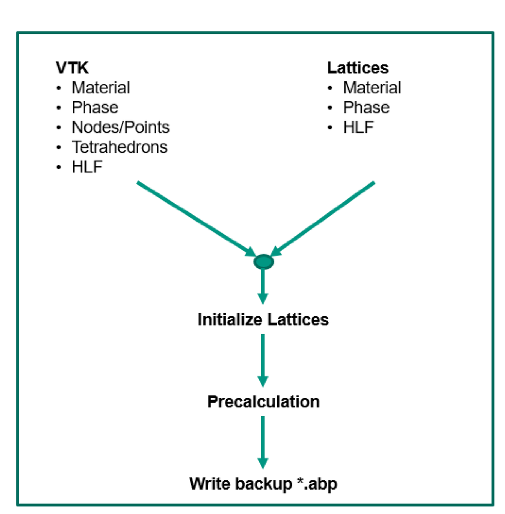


Figure 9: Incorporation of VTK structures into precalculation with initializeXCLT.

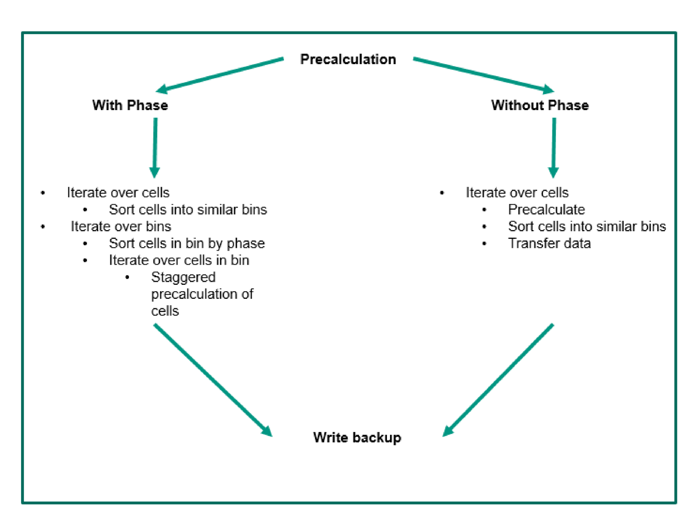


Figure 10: Precalculation process factoring phase values.

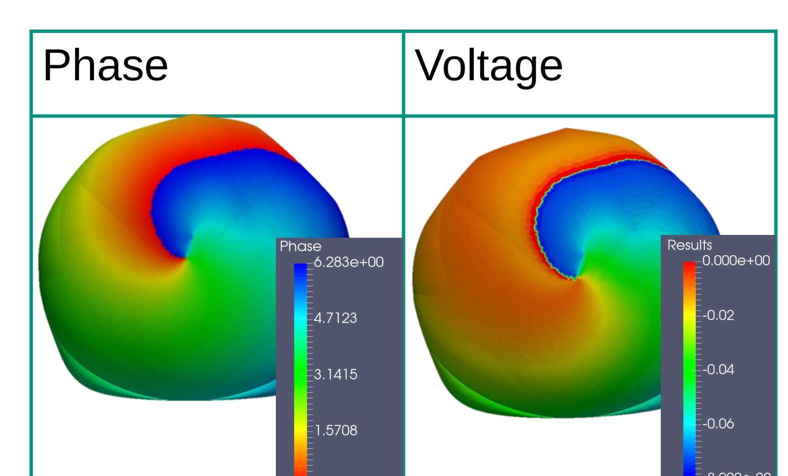


Figure 11: Translation of phase values to voltage after precalculation.

Precalculation allows all cell state variables within the mondomain equation to be satisfied, in addition to the phase value. For this particular simulation, the standard Courtemanche cell material was used.

Results

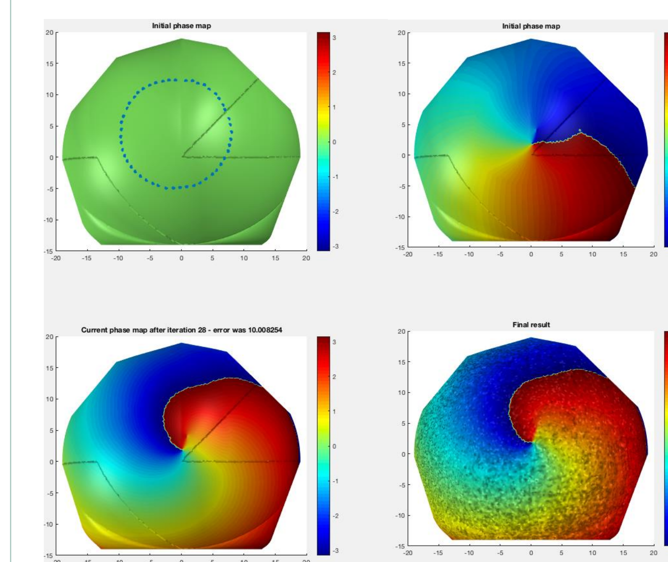


Figure 12: Screenshot of the Matlab interface to create initial phase map once the user sets a single point of phase singularity on a 3D model of the left atrium.

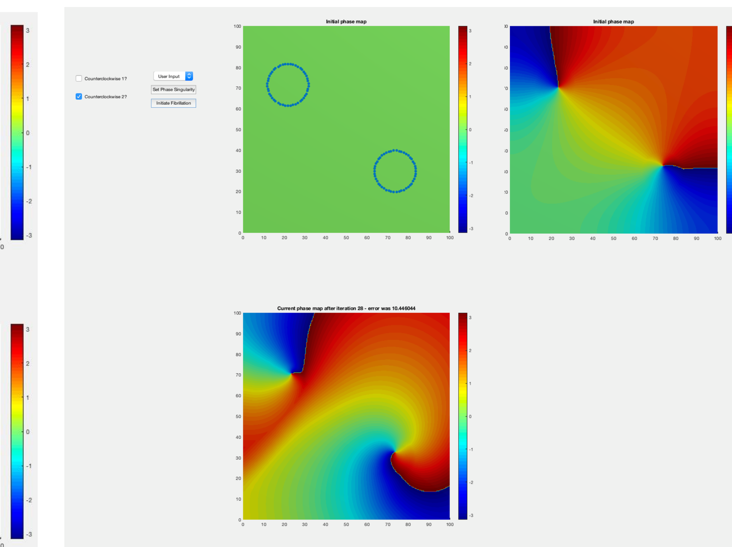


Figure 13: Screenshot of the Matlab interface and the placement of multiple phase singularities with assigned chirality.

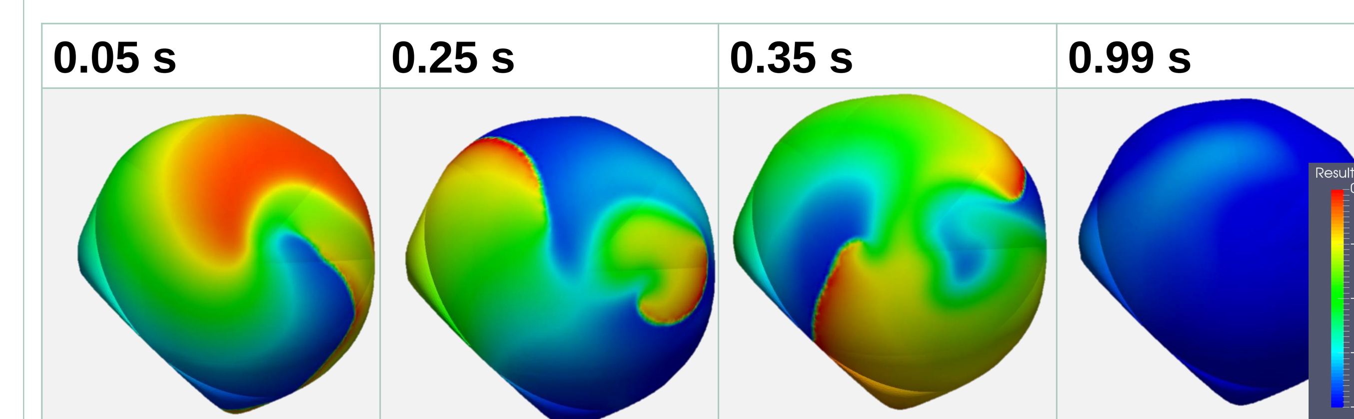


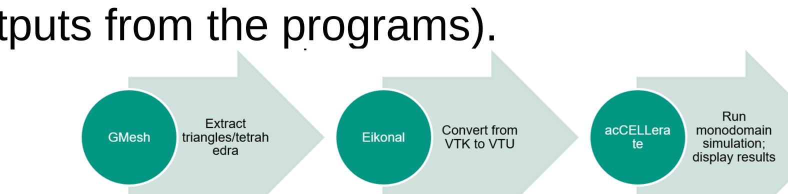
Figure 14: Screenshots of the resulting monodomain simulation at multiple timestamps.

Conclusions

A monodomain simulation was successfully conducted given one phase singularity on a model of the left atrium. A Matlab user interface was implemented that has two main functionalities: 1) The user may import a 2D or 3D mesh of choice and 2) the user may set one or multiple phase singularities. In addition, the KIT tool initializeXCLT was modified to handle VTK files and phase values in order to prepare for the monodomain simulation.

Future Improvements:

- Streamlining the steps into one single process (combining inputs/outputs from the programs).



- Random distribution of a given number of phase singularities on a 3D surface.

Acknowledgments

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