A Cellular Automata Model for Dynamics and Control of Cardiac Arrhythmias

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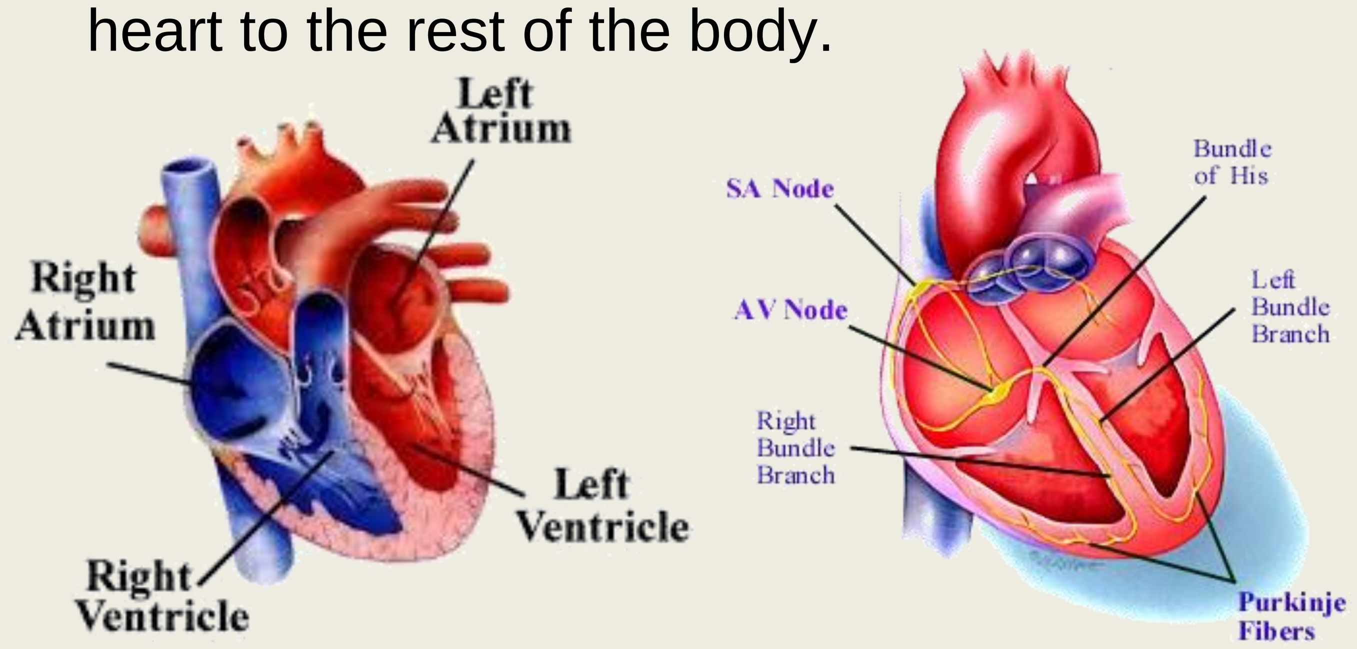
Task

Develop a cellular automata model to study the propagation of electrical waves in the heart, and use the model to explore cardiac arrhythmias and possible control algorithms to eliminate arrhythmias.

Background

Electrophysiology of the Heart:

- Four chambers: left atrium, right atrium, left ventricle, right ventricle
- Heartbeat driven by electrical signal from the right atrium, through the atrioventricular node, and into the ventricles via the His-Purkinje system (group of fibers).
- As signal passes through each chamber, the heart contracts, and heart is pumped from the heart to the rest of the body.



Cardiac Arrhythmias: disruptions in the heart's normal rhythm.

- Bradycardia: characterized by a heart rate under 60 BPM.
- Tachycardia: characterized by a heart rate over 100 BPM.
- AV Heart Block: the heart has a normal rhythm, but not all excitations go through the AV node (i.e. only 1 of 2 heartbeats in the atria produce a ventricular excitation).
- Ventricular Fibrillation: life-threatening arrhythmia in which many small waves propagate throughout the ventricles. Electrical waves are uncoordinated and cannot produce a contraction.
- Atrial Fibrillation: extremely rapid atrial rate. Many waves are present in the atria, compromising their ability to contract.

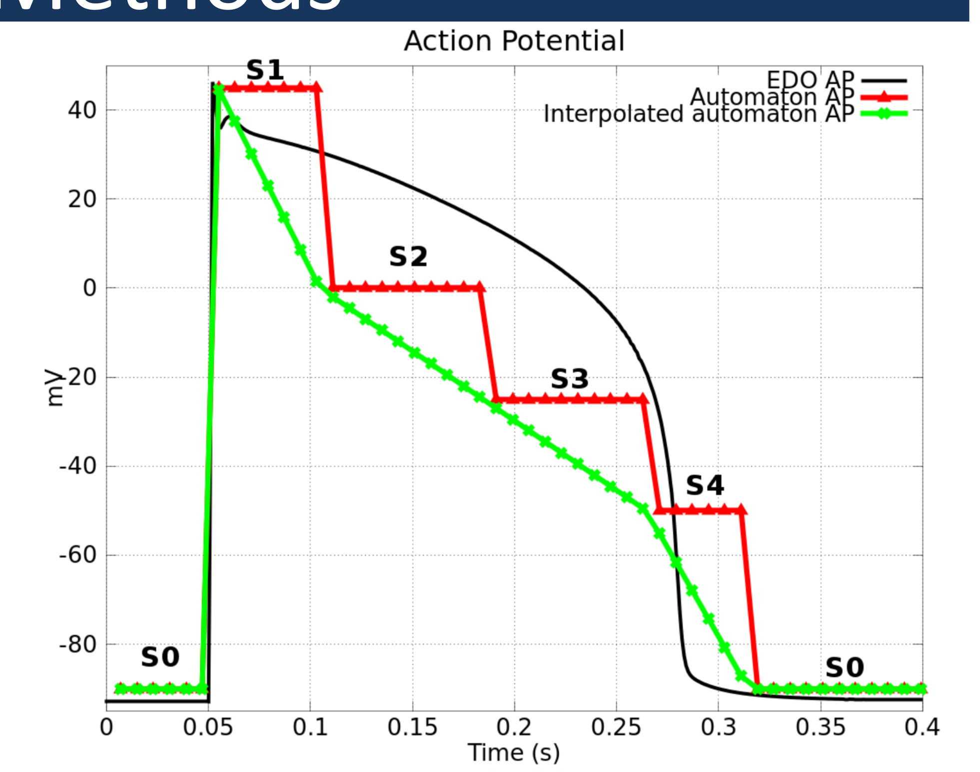
Research Steps

1. Study the Mathematica model created by students who previously contributed to this project.
2. Use MATLAB to recreate the Mathematica simulation.
3. Translate MATLAB code into C so it can run on GPU.
4. Implement various control mechanisms to remedy arrhythmias.

Methods

Four states:

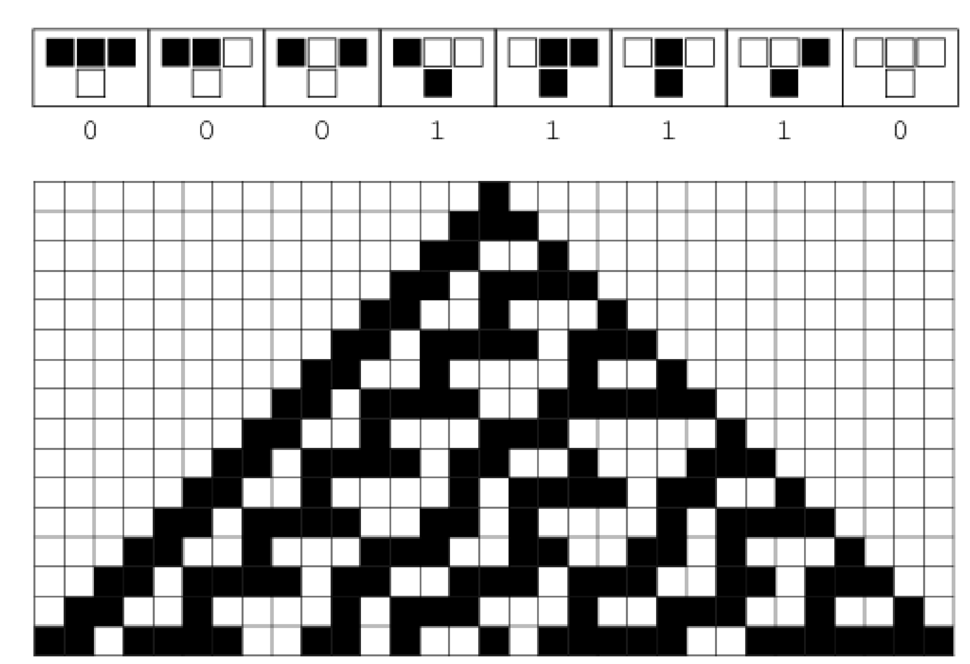
- S0 = Resting
- S1 & S2 = Excited
- S3 = Absolute Refractory
- S4 = Relative Refractory



Cellular Automata:

- A two-dimensional grid of cells
- Each cell changes state based on specific rules, usually determined by the states of neighboring cells

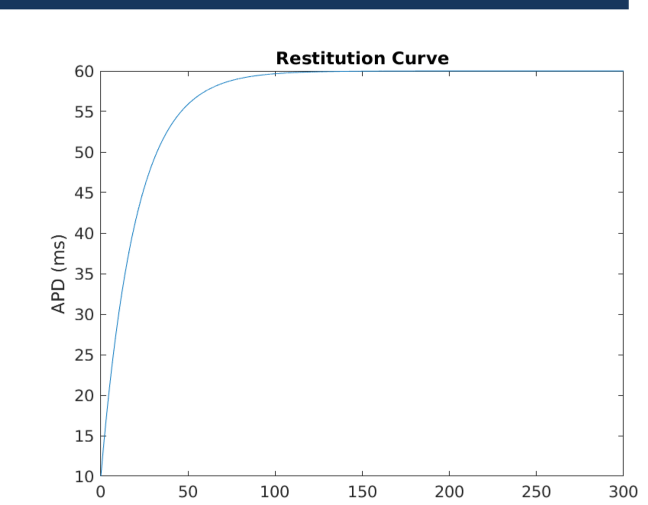
rule 30



Graphs

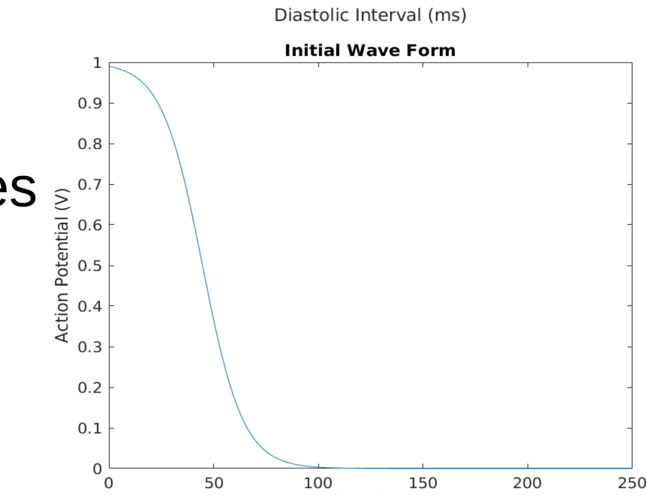
Restitution curve

- Describes the relationship between the diastolic interval and action potential duration
- $f(D_n) = A_{max} - A_0 e^{-Dn/\tau}$
- $f(D_n) = 60 - 50e^{-Dn/20}$
- Unstable for $f'(D_n) > |1|$



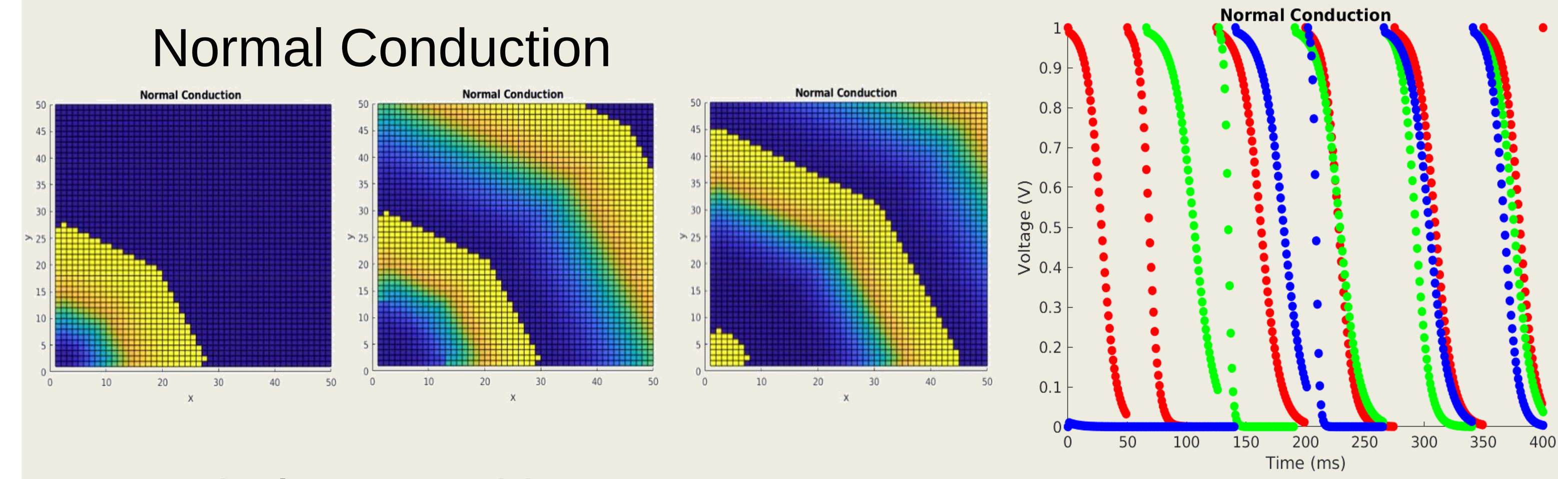
Initial wave form

- Describes the voltage of a heart cell after being stimulated as time passes
- $f(A,t) = e^{-t/T(A)} / (c+e^{-t/T(A)})$
- $T(A) = A / (\ln(0.9) - \ln(0.1^*c))$
- $T(66) \approx 9.7025$
- $f(t) = e^{-t/9.7025} / (0.01+e^{-t/9.7025})$

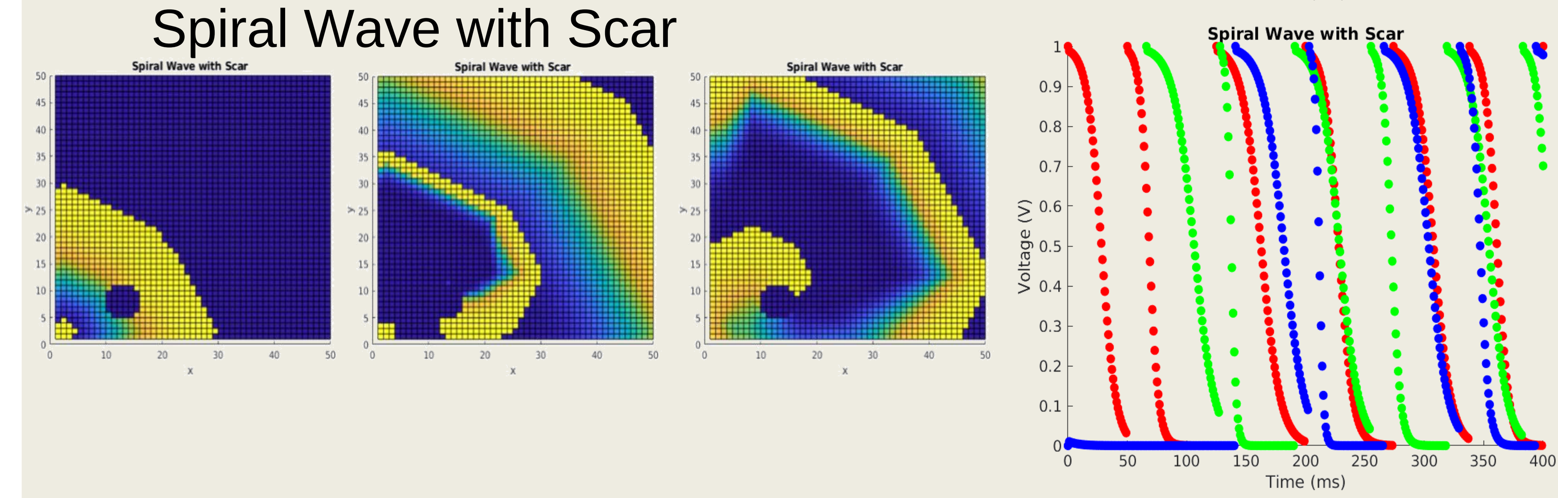


Cellular Automata Models

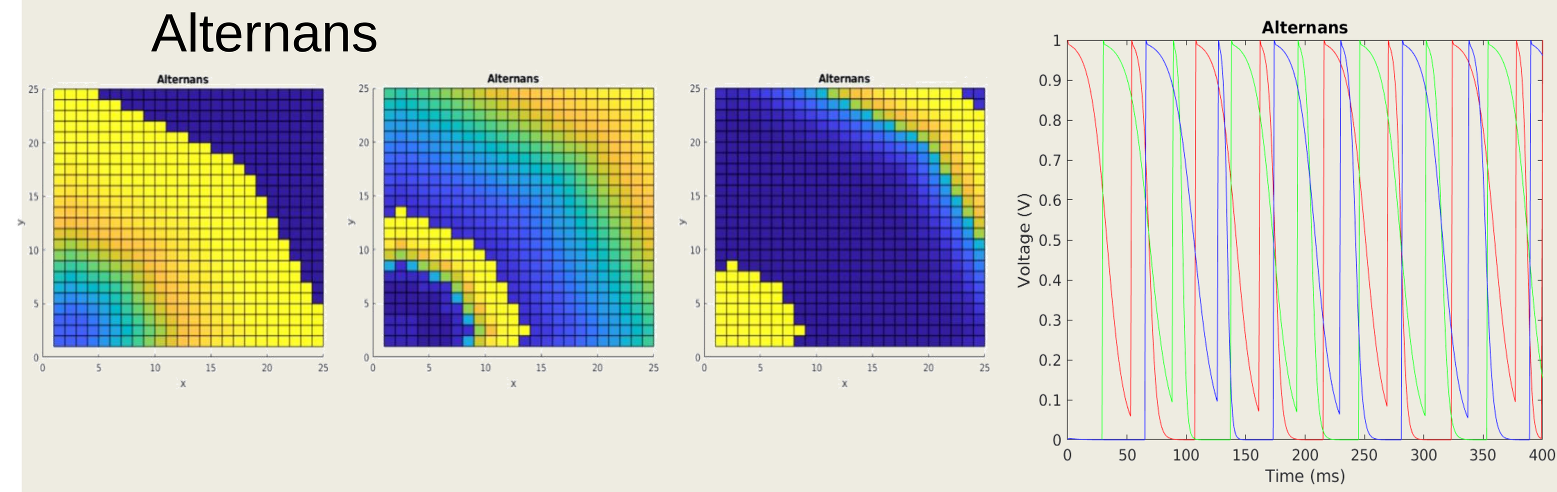
Normal Conduction



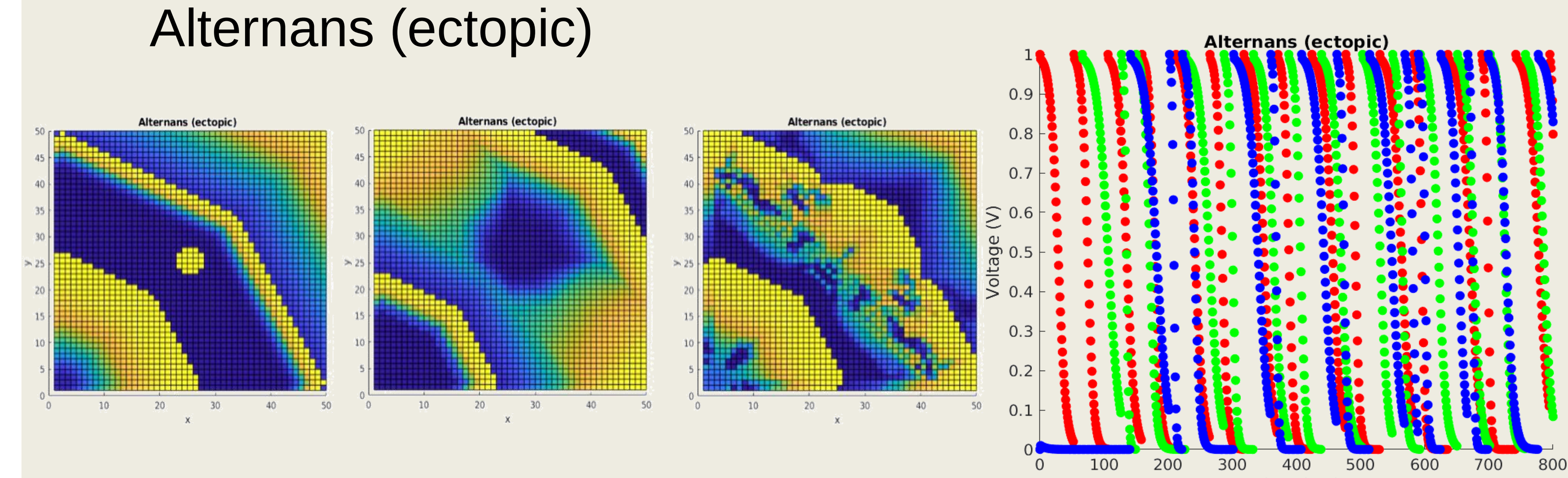
Spiral Wave with Scar



Alternans



Alternans (ectopic)



Future Work

1. Translate MATLAB code into C code
2. Extend the simulation to 3D tissue
3. Implement simulation on GPU to produce larger models
4. Control mechanisms

Acknowledgements

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