An Electrical Engineering Perspective of the Human Heart

Nicholas Krol

Advisors: Dr. Mohammad Imtiaz and Dr. In Soo Ahn

Bradley University

The Department of Electrical and Computer Engineering

Introduction

The purpose of this project is to aid medical professionals by helping them facilitate and understand heart function and dysfunction. To achieve this, we studied the human body from an electrical engineering perspective. The heart is an electrical organ that contracts in a specific and organized manner in order for blood to flow correctly through the body. These contractions are driven by propagating waves of depolarization, or current flow. Each excitable cell within the heart can be modeled by several nonlinear differential equations using the Hodgkin-Huxley mathematical model that won a Nobel Prize in 1963. By modeling an individual cell within Matlab, additional programs can simulate cables, 2D sheets and 3D figures of the electrical propagations in the heart.

Significance

Being able to simulate the electrical propagations in the heart can aid medical professionals in a handful of ways. Certain electrical heart disorders can be simulated with patient specific data from MRI or CT scans. With each patient's unique heart data, a 3D model can be generated and any abnormalities can be tested and studied in silico before surgeries are performed. These abnormalities include heart arrhythmias, long QT syndrome, physical heart abnormalities and more.

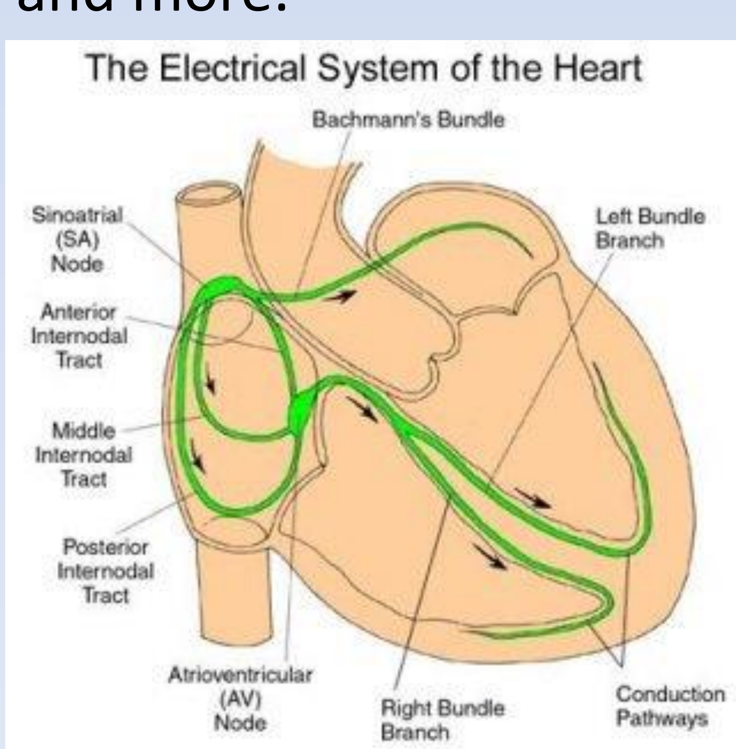

Figure 1: The Electrical System of the Heart

Methods

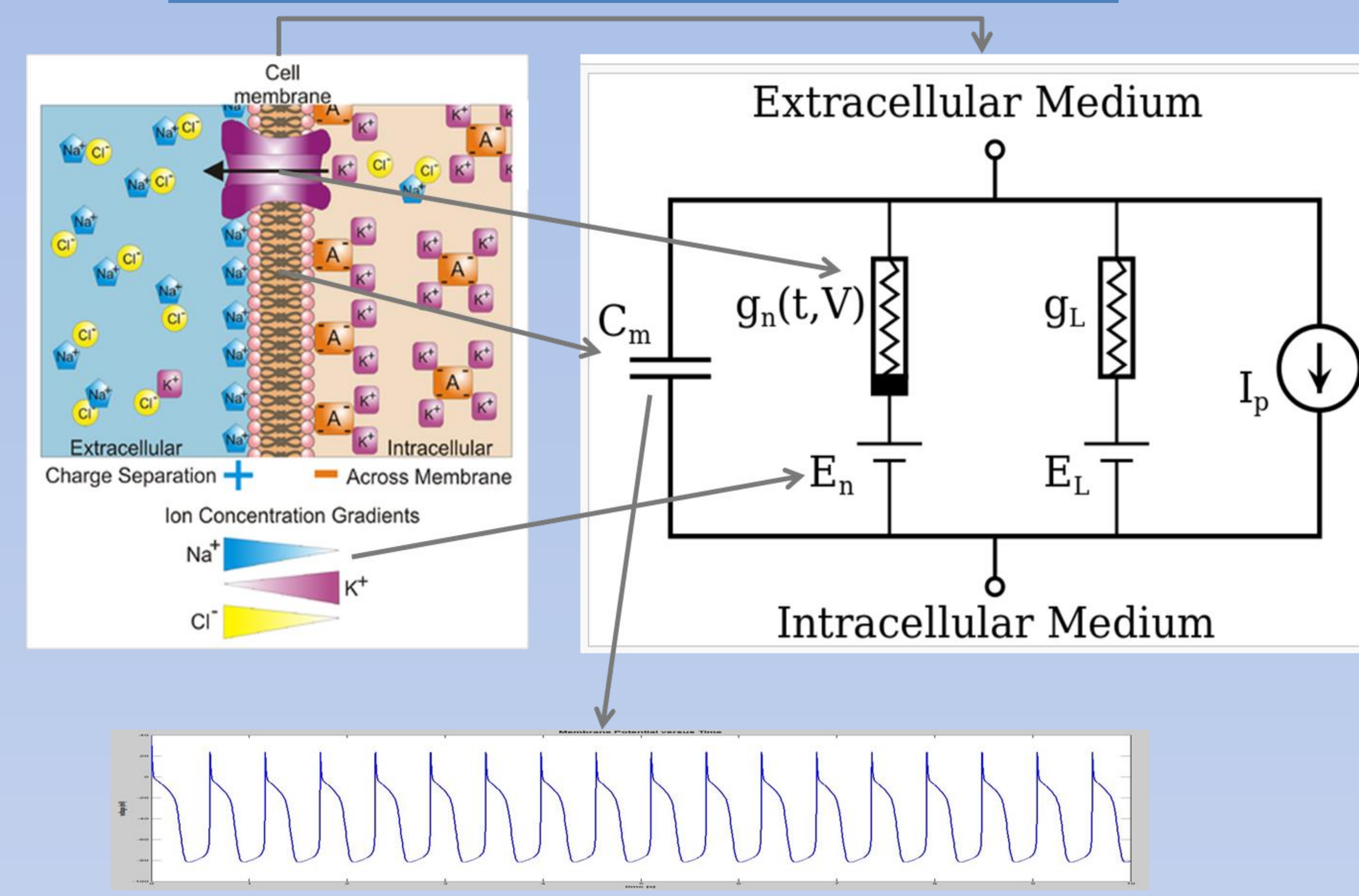

Figure 2: Cardiac Cell As An Electrical Circuit

The excitable cells in a human heart can be represented by an electrical circuit and each cell resembles a battery due to the ion concentrations. The cell membrane or lipid bilayer is modeled as a capacitor separating the extracellular and intracellular mediums. Each ion channel in the cell membrane is modeled as a variable resistor, varying due to the ion channel gates letting ions flow in or out of the cell which ultimately changes the membrane voltage potential and sends signals throughout the heart.

$$I = C_m \frac{dV_m}{dt} + \bar{g}_K n^4 (V_m - V_K) + \bar{g}_{Na} m^3 h (V_m - V_{Na}) + \bar{g}_l (V_m - V_l),$$

$$\frac{dn}{dt} = \alpha_n(V_m)(1-n) - \beta_n(V_m)n$$

$$\frac{dm}{dt} = \alpha_m(V_m)(1-m) - \beta_m(V_m)m$$

$$\frac{dh}{dt} = \alpha_h(V_m)(1-h) - \beta_h(V_m)h$$

Figure 3: Hodgkin-Huxley Equations

The nonlinear differential equations modeled by Alan Hodgkin and Andrew Huxley allow for the computerized simulation of excitable cells. This mathematical model approximates how action potentials are initiated and propagated in cells such as cardiac muscle cells which cause heart contractions.

Results

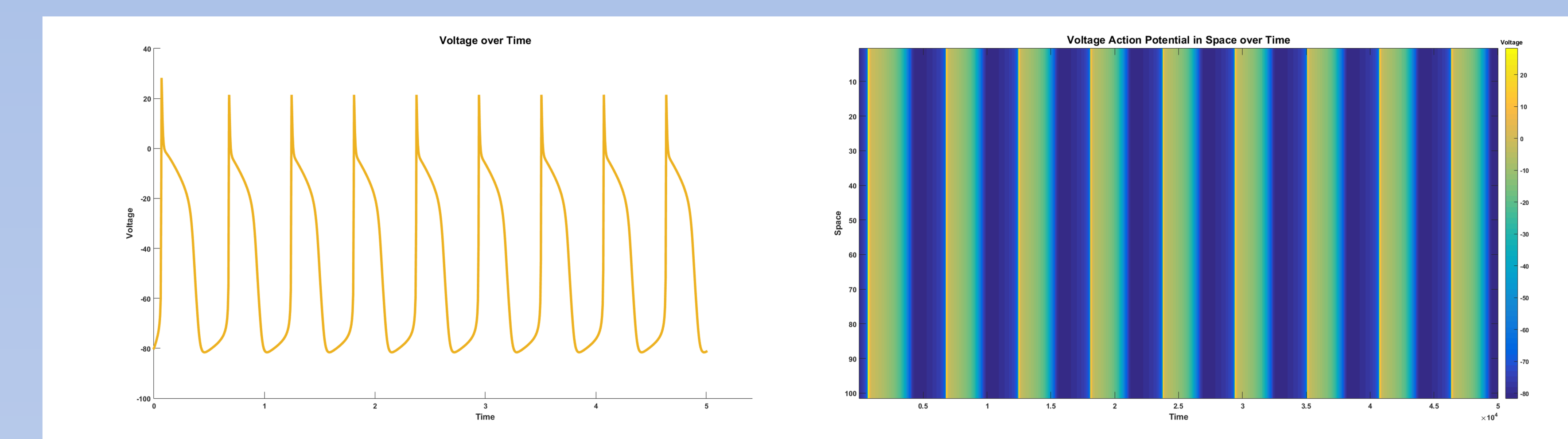

Figure 4: Action Potential and Colormap Plots

From the Matlab simulations using the Hodgkin-Huxley equations, an approximated action potential can be generated to show the influx and outflow of ions. The plots on the left show the action potential over time similar to what would be seen in an electrocardiogram (EKG). The graphs on the right portray a colormap of the action potentials through a one-dimensional system down the y-axis. The difference between the top and bottom figures are a change in capacitance (or cell membrane size). Numerous variables can be modified in order to simulate different issues within the heart.

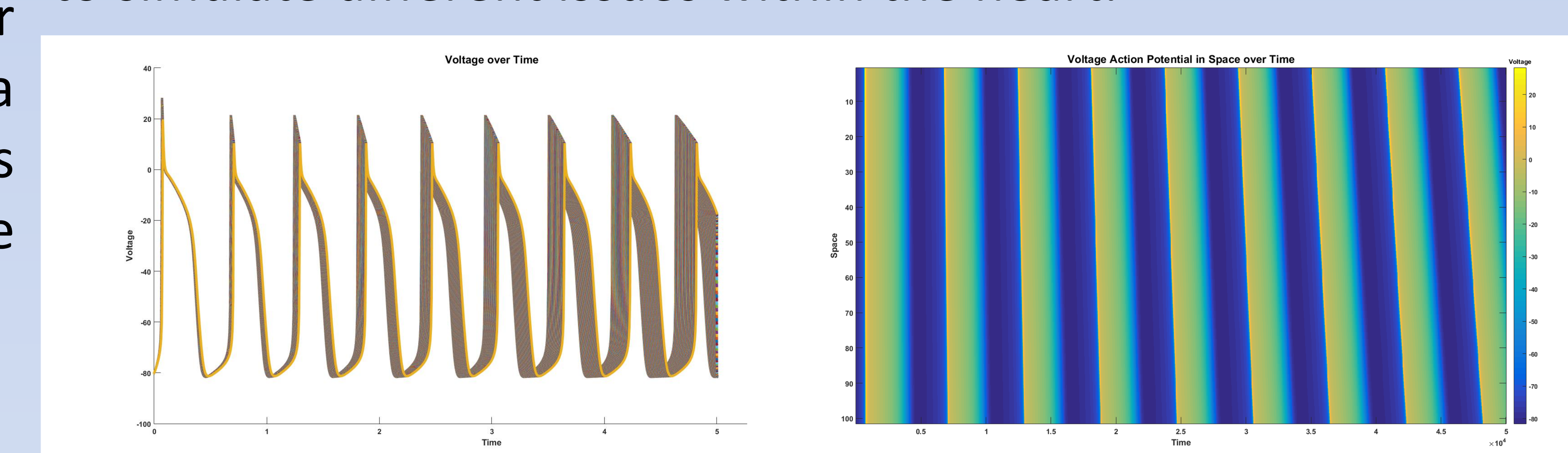

Figure 5: Increasing Capacitance Plots

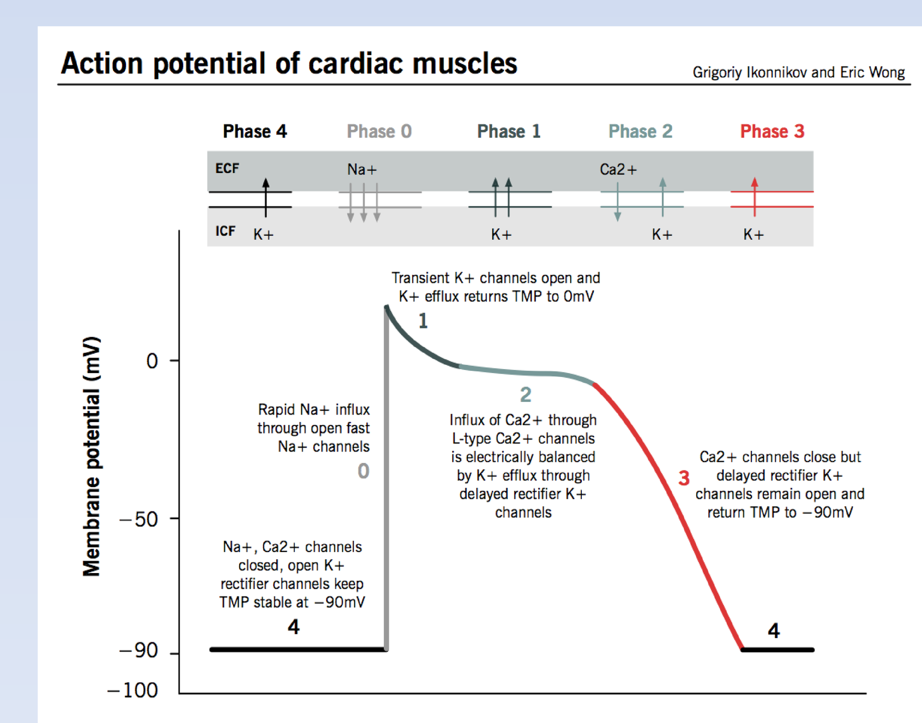

Figure 6: Phases of Action Potential

This figure describes each stage of the action potential in a cardiac muscle cell. The flow of ions cause the cell to act like a battery and is able to send current throughout the muscle in order to send signals.