1.0 Executive Summary
This document provides information on the purpose of the Left Atrial Model project and its specifications. Objectives and expectations are outlined, and an overview of the project management will provide guidelines for time.

2.0 Introduction and Background
The objective is to produce an electrophysiological model of an adult human left atrium. This model will be used to test mapping probe catheters used for locating cardiac arrhythmias against current technology used in practice. Dr. Chris Porterfield requested this model and other physicians or probe catheter manufacturers may also use this product in the future. Dr. Porterfield also discussed the possibility of future senior project groups using the model as a bench test for designing new catheter tips. The model will precisely simulate electrical behaviors of the heart in normal as well as arrhythmic conditions. Ideally, the model will be used to place an arrhythmia at a known location, and the mapping catheters will sense where the arrhythmia is located. The results from sensing the model will be compared to the results shown on the 3D mapping system to evaluate the precision of the catheter used in conjunction with the 3D mapping system.

Summaries of Customer Meetings
Week 1: 1/16/19 Dr. Porterfield specified that the shape of the atrial model should be generally related to actual heart anatomy, but that a simplified shape could be used to still meet his expectations. He also said that he has tried to obtain a model that is currently used by Abbott for the same purposes, but has not been successful because they are weary of sharing intellectual property. On the topic of related models, he said that most current models are used submerged in a saline bath but that a dry model would also be acceptable. It was also agreed upon that the model could be scaled larger than an actual heart as long as the electrode density would lend to be able to test for accuracy with a 9mm² accuracy. A team at University of Michigan has been working on creating a similar model using a conductive material instead of ballistics gel and was not successful with that material.

Week 2: 1/23/19 We showed Dr. Porterfield a rough 3D print of a heart to see if he was satisfied with the shape. We also showed him the gel so he could feel the material and provide any input. He said the gel was appropriate for the project.

Week 3: 1/30/19 We met Dr. Porterfield at the hospital to observe an ablation procedure. We were familiarized with the procedure itself, the mapping catheters, and the mapping system. Two members of the team also did dissection on a porcine heart to become familiar with cardiac anatomy.

Week 4: 2/6/19 We asked Dr. Porterfield if he could provide us with electrodes that are used for making EKG measurements. We also inquired as to who would be the target user for the device and Dr. Porterfield expressed that future senior project teams are likely to be the most frequent users of the finished product. It may be used in the development of mapping catheter
designs in the future. In regards to testing accuracy, we asked if someone could test our model against the mapping system used in the hospital. He said the model could be tested by him or one of his associates.

Week 5: 2/13/19 We talked about the scale of the model and presented our current design concepts. Dr. Porterfield expressed that a 2:1 scale model would be best for testing.

Discussion of Existing Designs
There are physical as well as CAD models of the human heart that are used for simulations, surgery practice, and academic use. Electrodes also exist for the purpose of mapping electrical activity on the surface of the brain and heart, but there is no documented in vitro model that combined the two to be electrophysiologically accurate. Most models used for this purpose are ex vivo models consisting of bovine or swine myocardium in a circulating bath [10]. A recent business intelligence study by Transparency Market Research has estimated that the global ET catheter ablation market will be worth US $2.74 billion by the end of 2026 [12]. Because of this competitive nature to be cutting edge in the electrophysiology field, there is not much information available about similar models that are being produced. Dr. Porterfield mentioned that a group working on a similar project was not successful using a conductive material to cast the shape of the heart, so it is more productive to begin prototyping using ballistics gel. Dr. Porterfield also mentioned that current in vitro heart models are commonly dunked in a saline bath before used for testing. Abbott has been contacted about the possibility of them sharing information about their model, but it is proprietary and cannot be shared. It’s known that some companies use porcine hearts in saline solution to simulate similar conditions. While there is not much information available about similar models, there are plenty of different mapping catheters that could be used in the model to evaluate their accuracy.

Table 1: Mapping Catheters that can be used in Left Atrial Model

<table>
<thead>
<tr>
<th>Catheter Name</th>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advisor HD Grid [1]</td>
<td>Abbott</td>
<td>Bi-directional high-density mapping catheter; 12 electrodes</td>
</tr>
<tr>
<td>Achieve Advance [9]</td>
<td>Medtronic</td>
<td>Circular loop with 8 evenly spaced electrodes for mapping electrical conduction between the left atrium and pulmonary veins</td>
</tr>
<tr>
<td>Intellamap Orion [5]</td>
<td>Boston Scientific</td>
<td>Bi-directional 180 degree curve “balloon”; 64 electrodes</td>
</tr>
<tr>
<td>Lasso eco [4]</td>
<td>Biosense Webster</td>
<td>Deflectable catheter consists of a 4.5 Fr circular spine on its distal tip, with platinum</td>
</tr>
</tbody>
</table>
electrodes that can be used for simulation and recording; 10 or 20 electrodes

**Related Patents**

**Table 2: Relevant Patents to the Left Atrial Model**

<table>
<thead>
<tr>
<th>US Patent No. (s)</th>
<th>Patent Name</th>
<th>Applicant</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,136,829</td>
<td>Systems and methods for using <em>electrophysiology</em> properties for classifying arrhythmia sources</td>
<td>St. Jude Medical, Cardiology Division, Inc.</td>
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<tr>
<td>6,233,476; 6,556,695; 7,365,745; 7,774,051; 7,825,925; 7,855,707; 7,894,871; 7,988,639; 8,038,625; 8,130,221; 8,229,545; 8,253,725; 8,352,019; 8,364,253; 8,454,538; 8,454,589; 8,647,284; 8,805,490; 8,849,393; 9,026,196; 9,078,591; 9,111,175; 9,113,807; 9,137,611; 9,159,162; 9,198,601; 9,204,927; 9,237,920; 9,392,973; 9,339,325; 9,486,152; 9,549,689; 9,560,988; 9,585,586; 9,591,990; 9,597,036; 9,610,027; 9,956,049</td>
<td>Multiple names (All patents for EnSite Precision Cardiac Mapping System owned by Abbott)</td>
<td>Multiple Owned by Abbott</td>
</tr>
<tr>
<td>9,950,141</td>
<td>Dual braid reinforcement deflectable device (sheath or catheter)</td>
<td>St. Jude Medical, Atrial Fibrillation Division, Inc.</td>
</tr>
<tr>
<td>10,143,374</td>
<td>Systems, devices, components and methods for detecting the locations of sources of cardiac rhythm disorders in a patient's heart</td>
<td>Ablacon Inc.</td>
</tr>
<tr>
<td>10,149,626</td>
<td>Methods and systems for mapping and ablation of cardiac arrhythmias comprising atrial flutter</td>
<td>American Medical Technologies, LLC</td>
</tr>
</tbody>
</table>
Relevant Technical Literature
As of 2001, it was estimated that approximately 2.3 million US adults have atrial fibrillation (AFib), and that number is expected to increase to more than 5.6 million by the year 2050 [8]. In itself, AFib is not dangerous, but the complications that arise from it can be lethal. The atria of the heart have appendages that provide a perfect nook for clots to form when the heart is in AFib, which can then travel from the heart and lead to stroke [2]. Currently, the most common technique for treating atrial fibrillation is catheter ablation, but studies have shown that 1 in 8 patients may require a repeat ablation within 1 year, and up to 40% of patients will require a repeat ablation within 5 years [3,8]. As any medical procedure, ablations may place a large financial burden on patients ranging from $16,278 to $21,294, so it is desirable to complete the first procedure as thoroughly as possible [7]. An ablation procedure is performed by first threading catheters from the jugular and femoral veins to the heart, and then continues with 3D mapping of the heart using specialized mapping catheters [3]. These catheters come in different shapes with different electrode orientations that the physician will use at their discretion. The accuracy of these mapping catheters is integral to the success of the procedure because it determines the resolution of the 3D map that is produced. Currently, physicians do not have an easily accessible way to test the accuracy of the catheters that they can choose between before using it in a surgical setting. The companies that are selling these products will market improved accuracy, but the physicians are not provided with a method to test these claims outside of a patient. It is very important for a physician to be confident in a new tool before using it in surgery.

Applicable Industry Regulations
Since this is an in vitro model and is not designed to come into contact with biological systems, it is not considered a medical device. This greatly reduces the amount of codes and standards that the model itself must meet. However, the Class 2 or Class 3 ablation catheters that will be used are already FDA compliant.

3.0 Customer Requirements and Design Specifications

3.1 IFU
The Left Atrial Model is an electrophysiological model of the left atrium of the heart intended for use by clinicians or future senior project groups that are designing catheters. The device provides a way to simulate arrhythmias on a flat bench test in order to test probe catheters that are used in cardiac ablations. The modeled arrhythmia location is intended to be compared with results from the probe used in a current mapping system in order to determine probe accuracy. This will allow physicians to make an informed decision on which catheters to use in their procedures, or will allow senior project groups to verify their prototype designs.

3.2 Product Design Specifications
The design must be precise within 9mm², comparable to heart tissue, safe, easy to use, and produce repeatable results. The precision will be determined by the spacing of electrodes and the homogeneity of the conductive gel. The gel’s stiffness and conductivity determine how similar it is to native tissue. Safety and ease of use depend on design of the user interface and
voltage output. The repeatability is reliant on the lifespan of the product, electrode density, and electrode half-cell potential.

<table>
<thead>
<tr>
<th>Customer Requirement</th>
<th>Engineering Metric</th>
<th>Specification</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar to magnitude of heart signal</td>
<td>Electrode voltage</td>
<td>5-7 mV</td>
<td>Range of normal to irregular voltage in endocardium</td>
</tr>
<tr>
<td>Accurate</td>
<td>Electrode spacing</td>
<td>1 electrode per 12 mm²</td>
<td>Catheter tip is 3 mm in diameter, model does not need to be more accurate than how much tissue will need to be ablated anyways</td>
</tr>
<tr>
<td>Repeetable</td>
<td>Electrode lifespan</td>
<td>&gt; 500 cycles</td>
<td>Model needs to function with similar results for repeated tests</td>
</tr>
<tr>
<td>Able to simulate early firing node and atrial fibrillation</td>
<td>Time delay between regular fire and early fire</td>
<td>450 ms</td>
<td>Model will simulate healthy tissue, an early firing node, and tissue in AFib</td>
</tr>
</tbody>
</table>

### 3.3 House of Quality
The criteria used in the House of Quality below are as follows: precise, comparable to heart tissue, safe, repeatable results, and easy to use. This analysis shows that electrode density is the most important engineering characteristic at about 23% weight, with half-cell potential and scale close behind, around 17% and 16%.
4.0 Stage Gate Process

4.1 Concept Review

Three concepts were considered:

1. **Inorganic Ballistics Gel with Saline Solution**

   This concept involves a mold made of ballistic gel (Humimic Gelatin #1) that is embedded with electrodes and covered in saline solution. Electrical signals are generated by a grass stimulator and then sent to the mold through wires with electrodes connected at the end. The signals travel from the electrodes across the model with the help of the conductive saline solution on the surface. There will be circuits and an electrical control system such as an Arduino to power and control the electrodes, and these can be manipulated to model different conduction patterns.

   ![Diagram of Inorganic Ballistics Gel with Saline Solution]

   Humimic Gel

2. **Organic Gel made Conductive with Salt**

   This concept is similar to Concept 1, but the mold material is organic gel instead of inorganic. Organic gel allows us to manipulate the conductivity of the whole model, and make it more similar to endocardial/myocardial tissue. The gel itself would conduct the signals throughout the model instead of relying on the saline solution. The main challenge with this concept is determining the appropriate salt to gel ratio since that's
what dictates the resistivity/conductivity of the model. This concept also relies heavily on electrical control systems in order to simulate necessary electrophysiological features of a healthy and arrhythmic cardiac cycles.

3. **Non-conductive Model with Electrode Mesh**

A dense electrode mesh would be connected to the surface of a 3D printed PLA model of the atrium, represented by an oval. This concept does not involve the use of any gel, thus the electrode density must compensate for the lack of conductivity in the surrounding material. The model is not elastic and would not have the same stiffness or tissue compliance as native cardiac tissue. This concept does not involve any testing in terms of surface conductivity but relies on dense circuitry. Programming this model would be more involved than programming one with fewer electrodes. The cost of this concept is also far higher than the other concepts due to the $200 electrode mesh.

4.2 Design Freeze

Concept 2 was deemed the most appropriate out of the three options. Concept 1 was eliminated because the saline solution would not provide enough control of the electrical pathway, and Concept 3 was eliminated because of the high cost and the labor-intensive programming that would be required.

4.3 Design Review

For the design review, the model was discussed and reviewed to ensure validity of rationale behind the circuit design decisions. The voltage value and timing were the two most important factors to be implemented into the model, and were discussed with advisors.

5.0 Description of Final Prototype Design

5.1 Overview

The final prototype design includes an Arduino driving sixteen electrodes which are embedded in a ballistics gel layer. The Arduino is programmed to simulate propagation of current in the heart by stimulating each electrode in series, where each individual electrode outputs a
rectangular pulse. Two PCBs include two quad op amps each, which attenuate the Arduino’s 3.3V outputs to 7mV, per Dr. Porterfield’s specifications. The circuit includes a button which allows the user to switch the Arduino output between healthy propagation, arrhythmia, and atrial fibrillation (AFib) modes. The arrhythmic mode includes a small current which stems from a misfiring electrode, and the AFib mode causes electrodes to fire in a nonsense pattern, as cardiac cells do in the human heart.

5.2 Design Justification
The final design outputs the appropriate voltage, can model healthy, arrhythmic, and fibrillating tissue with a change of the button.

5.3 Analysis

5.4 Cost Breakdown

<table>
<thead>
<tr>
<th>Item Description</th>
<th>ASIN/Product Number</th>
<th>Vendor</th>
<th>Unit</th>
<th>Quantity</th>
<th>Cost</th>
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<tr>
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<td>Humimic Medical</td>
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<td>$52.32</td>
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<td>30391-023</td>
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</tr>
<tr>
<td>Deionized water</td>
<td>15230-147</td>
<td>Thermo Fisher Scientific</td>
<td>1 L</td>
<td>1</td>
<td>$23.22</td>
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<td>PLA 3D printed mold</td>
<td>Ultimaker NFC PLA - Blue</td>
<td>Dynamism</td>
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<td>Printed Circuit Board</td>
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<td>Bay Area Circuits</td>
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<td>$104.11</td>
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<td>$6.49</td>
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</tr>
</tbody>
</table>
Quad Operational Amplifier

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Supplier</th>
<th>Quantity</th>
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</tr>
</thead>
<tbody>
<tr>
<td>5735</td>
<td>Texas Instruments</td>
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<tr>
<td>eBay DUE R3 Board</td>
<td>eBay</td>
<td>1</td>
<td>$21.51</td>
</tr>
</tbody>
</table>

5.5 Safety Considerations

Design hazards include hot materials, sharp edges, and corrosion. Ballistics gel must be heated in order to melt. This presents possible danger due to the use of a hot plate and the pouring of hot liquid. This was considered during the manufacturing process. Hot materials are also used during the manufacturing of the PCB; all electronic components must be soldered to the board, causing burn risk as well as exposure to lead. All personnel involved in the soldering process were instructed in the use of a soldering iron beforehand, and care was taken to reduce exposure to lead by washing hands after soldering or touching the PCB. Electronic components and their housings may have sharp edges and could be dangerous to those handling the device, and thus must also be considered during design. Sharp edges must be
filed down. Shock will be prevented by minimizing exposed electronic components. Batteries will also be inspected before use in order to eliminate the danger of shock. A full hazard checklist can be found in Section 10.4: Appendix D.

6.0 Prototype Development

6.1 Model Analyses
Our model was designed after physiology of left atrium of human heart. This means, assuming that electrical signals are initiated in the Sinoatrial node of the heart and as time progresses, such signals travel down the atrium and toward the apex of the heart. This is what a regular heartbeat would look like. During AFib, signals do not necessarily follow the pattern described above.

In patients who suffer from Atrial Fibrillation, due to faulty tissue in the atria, signals get generated randomly and out of order. They may vary in voltage from regular signals or may have irregular timing patterns as well as locations.

This model is designed to simulate regular as well as irregular timing and location of electrical signals in human's left atrium.

6.2 Evolution of Prototypes
Prototype 1:
Initially, Humimic ballistics gel was mixed with sodium chloride to serve as the conductive gel catheter interface. This gel was tested using a multimeter and four AAA batteries as a power source. The conductivity of the gel was far too low to achieve the desired current propagation.

Prototype 2:
Porcine gel was used in a layer on top of a ballistics gel layer. The porcine gel was mixed with sodium chloride in order to enhance its conductive properties. The ballistics gel was cut into a rectangle, then aluminum foil was used to create a makeshift mold that the porcine gel was poured into. An Arduino was used to drive one electrode, which was used with one ground electrode to test the conductivity of the gel. Porcine gel’s electrical properties were extremely inconsistent.

Prototype 3:
Porcine heart tissue was used with the same Arduino setup as the previous porcine gel sample. The heart tissue was tested without the presence of saline. The porcine heart tissue did not

Prototype 4:
A polyethylene gel recipe was used which includes agar, sodium azide, polyethylene powder, sodium chloride, and DI water. This gel was placed on top of a ballistics gel layer, like the previous prototype model. The ballistics gel was cut into a rectangular shape, then the Arduino was programmed to output a healthy propagation wave, or to simulate atrial fibrillation. In order to switch between the two, the board had to be reprogrammed using a computer with
the Arduino IDE. ±15V pins from an Elvis board were used to power the op-amp rails. The gel was not homogeneous and never set entirely.

Prototype 5:

The same polyethylene gel recipe was used, though sodium azide and polyethylene powder were eliminated. Additionally, the agarose gel was boiled during manufacturing, which increased consistency and helped with mixing. This gel was poured into a petri dish to set, and was also tested still in this circular Petri dish mold. A button was added to the breadboard and to the Arduino code, which allows the user to switch between healthy propagation and atrial fibrillation. Four 9V batteries were used to power the op amp rails. The agarose gel’s electrical properties were not sufficiently consistent.

Prototype 6:

The ballistics gel layer is housed inside of a 3D printed mold which includes a slot for a 40-pin header at the bottom of it. The female side of the header is at the underside, which allows for connections to the Arduino output circuit. The male pins are exposed out the top of the ballistics gel. A PCB of the Arduino output circuit was made, not including the button. A function generator was used to power the op amp rails, due to insufficient battery voltage.

### 7.0 IQ/OQ/PQ

**Installation Qualification (IQ):**

**Electrode Assembly**

**Electrode connection to control system**

**Gel conductivity:** 3.0-6.25 mS/cm

**Gel stiffness**

**Control system**

---

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Part Number</th>
<th>Link</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

**Operation Qualification (OQ):**

Voltage Range: 5-7 mV  
Electrode Lifespan: 1000 cycles  
Precision: < 9 mm² electrode density  
Timing: Early firing node should fire

OQ: Have the defined specifications been met? Does your test plan and resultant data mitigate risks and ensure that the performance requirements (i.e. performance / engineering metrics) are achieved? • Protocols and reports should be easy to follow with statistically defined success criteria clearly articulated
7.1 Design of Experiments
Materials testing is performed using electrical equipment found in on-campus labs. Voltage and conductivity was tested using function generators and multimeters.

Table 4: Design of Experiments of Left Atrial Model

<table>
<thead>
<tr>
<th>Engineering Metric</th>
<th>Specification</th>
<th>Test Method</th>
<th>Test Apparatus Location</th>
<th>Apparatus Experience/Training</th>
<th>Sample Size</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 9 mm² precision</td>
<td>Model electrode density</td>
<td>Compare arrhythmia detection to known location from programming</td>
<td>Coastal Cardiology</td>
<td>Training on EnSite or other mapping system</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>5-7 mV supplied to electrodes</td>
<td>Voltage</td>
<td>Multimeter measurements</td>
<td>EE lab on campus</td>
<td>Previous use of multimeter</td>
<td>all electrodes (200)</td>
<td>95</td>
</tr>
<tr>
<td>70 cm/s ± 50 cm/s</td>
<td>Conduction velocity of healthy and arrhythmic tissue</td>
<td>Compare Ensite pattern to known pattern from programming</td>
<td>Coastal Cardiology</td>
<td>Training on EnSite or other mapping system</td>
<td>5</td>
<td>70</td>
</tr>
<tr>
<td>&gt; 500 cycles</td>
<td>Electrode Life</td>
<td>Test single electrode output with multimeter every 100 cycles</td>
<td>BMED 420 Lab Eng IV</td>
<td>Programming electrodes</td>
<td>16</td>
<td>90</td>
</tr>
</tbody>
</table>

7.2 Verification and Validation
Voltage Range:

**Spatial Voltage Test**
1. Header is placed into gel sample
2. One pin of header is supplied with 6.9 mV
3. Another pin is grounded across the sample
4. Voltage measurements are taken every 0.1” across the header
5. Data is graphed in Excel to find mathematical model

**Timing Test**
1. Header is placed into conductive gel sample
2. `afib.ino` code is uploaded to DUE board, controlling 16 electrodes
3. Another electrode is grounded at the end of the sample per MPI
4. Oscilloscope measurements are taken at point A between electrodes 11 and 12, and point B between electrodes 8 and 9.
5. Record one loop of simulated afib and upload oscilloscope data to computer
6. Use cursors to ensure that point A peaks twice and point B peaks once

Electrode Lifespan:

Repeated Cycles Test

1. ‘propagate_button16.ino’ code is uploaded to DUE board, controlling 16 electrodes
2. Voltage output is measured on each electrode
3. The code is run until each electrode has fired 500 times
4. Voltage output is measured again on each electrode
5. The voltage measurements are compared and evaluated

Precision:

Spatial Resolution Test**

1. Headers are placed into the 3D printed mold
2. Jump wires are plugged into the header at the bottom of the mold (equally spaced with 4 slots between each wire)
3. The ground wire is plugged in at the end of each header, 3 slots from the last firing electrode
4. Each pin is manufactured to be 0.1” apart, but will be verified by using a ruler

**Ablation catheter tip is 3 mm in diameter. The entire tip of the catheter heats up during the ablation, so there is no need to be more precise than the tip itself. This precision can be achieved by choosing the correct electrode density. Since the electrodes are embedded in a conductive gel, the electrodes do not need to be spaced
### 7.3 Manufacturing Process Instructions

<table>
<thead>
<tr>
<th>Step</th>
<th>Instructions</th>
<th>Photo(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Melt 103g of Humimic ballistics gel in a glass beaker on a hot plate at 150°C until it has completely liquified</td>
<td><img src="image1.jpg" alt="Image" /></td>
</tr>
<tr>
<td>2</td>
<td>Fix two 40 pin M-F headers in the slots of the 3D printed mold with the M pins pointing up &amp; the F pins flush with the bottom of the mold; place the assembly in a glass dish</td>
<td><img src="image2.jpg" alt="Image" /></td>
</tr>
<tr>
<td>3</td>
<td>Pour the Humimic ballistics gel into the 3D printed mold, avoiding the header pins and evenly distributing the gel</td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
<tr>
<td>4</td>
<td>Allow ballistics gel to cool completely and remove any gel that may be stuck to the pins</td>
<td><img src="image4.jpg" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Measure out 2 g of agar powder, 0.5 g of NaCl, 100 mL of deionized water and combine in one beaker</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Heat the mixture on a hot plate to 95°C</td>
<td></td>
</tr>
<tr>
<td>Step</td>
<td>Instruction</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Cover the beaker with a layer of aluminum foil and mix with a magnetic stir bar at 800 rpm until the flakes of agar are dissolved and the mixture is homogeneous (about 10 minutes)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pour the agarose gel into the mold, covering the Humimic gel and embedding the header pins</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Refrigerate the gels for 15 minutes to allow the agarose gel to set</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Outsource PCB manufacturing using Eagle board file ‘sr proj 2 quad op amps cap.brd’</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Solder all components to the PCB per the PCB schematic</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Connect 16 jumper wires to the headers and solder the other ends to the PCB output pads per PCB board schematic (8 wires per header, 4 gaps are placed between each wire, with the first wire plugged into the outermost slot)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Connect 2 jumper wires (1 per header) to the outermost slot on the other side of the header as a ground. (There should be 3 gaps between this ground and the nearest wire)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Plug the other ends of the 2 ground wires into the ground plate on the small breadboard</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Wire the button and 3 indicator LEDs on a breadboard per the button schematic</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Program the DUE R3 outputs: use Arduino file ‘propagate_button16.ino’</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Wire corresponding PCB inputs to DUE R3 Board digital I/O ports per PCB board schematic</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Ensure op amps rails are powered by 18V supplies and DUE R3 board is powered via USB connection</td>
<td></td>
</tr>
</tbody>
</table>

7.4 Divergence Between Final Design and Final Functional Prototype
<table>
<thead>
<tr>
<th>MPI step</th>
<th>Deviation from MPI</th>
<th>Completed By</th>
<th>Signature</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Humimic gel was melted in microwave at full power for 7 minutes, stirring halfway</td>
<td>Sarah Porrello</td>
<td>Sarah Porrello</td>
<td>5/24/19</td>
</tr>
<tr>
<td></td>
<td>Gel was pulled out of mold, re-melted on a hot plate, and re-cast</td>
<td>Sarah Porrello</td>
<td>Sarah Porrello</td>
<td>5/27/19</td>
</tr>
<tr>
<td>2, 3, 4</td>
<td>N/A</td>
<td>Sarah Porrello</td>
<td>Sarah Porrello</td>
<td>5/24/19</td>
</tr>
<tr>
<td>5</td>
<td>N/A</td>
<td>Borna Sobati</td>
<td>Borna Sobati</td>
<td>5/27/19</td>
</tr>
<tr>
<td>6</td>
<td>Beaker covered with tin foil to prevent convective cooling</td>
<td>Borna Sobati</td>
<td>Borna Sobati</td>
<td>5/27/19</td>
</tr>
<tr>
<td>7</td>
<td>N/A</td>
<td>Tess Pate</td>
<td>Tess Pate</td>
<td>5/27/19</td>
</tr>
<tr>
<td>8</td>
<td>Only about half of the agarose gel was poured into the mold</td>
<td>Sarah Porrello</td>
<td>Sarah Porrello</td>
<td>5/27/19</td>
</tr>
<tr>
<td>9, 10, 11, 12, 13, 14, 15, 16, 17, 18</td>
<td>N/A</td>
<td>Tess Pate</td>
<td>Tess Pate</td>
<td>5/27/19</td>
</tr>
</tbody>
</table>

8.0 Conclusions and Recommendations

8.1 Recommendations

- Prior to pouring the conductive gel, it’s recommended to wait for about 5 minutes after taking the beaker off the hot plate before pouring into the mold. This way temperature of conductive gel would be low enough (~65°C) so that mold would not get deformed.
- It is more efficient and less time consuming to increase temperature of the hot plate to temperatures higher than 150°C temporarily while mixing the agar gel. If chosen to take this additional step, be careful not to let the gel “boil” and “foam” since it can overflow out of the beaker.
- For better soldering results, it’s recommended to set the temperature of soldering iron high (~400°C) and have the iron and the solder touch the designated point on the board for <2
seconds. This way, uniform soldering and minimal damage to the board/components may be expected.

8.2 Conclusions
The final prototype is a useful visual model of healthy, pre-AFib, and AFib conditions of the heart. LEDs that correspond with each electrode allow the user to view the conduction pattern of each mode, and a button toggles between them.

The conductive gel did not allow for a uniform conductivity and results were inconclusive. However, according to a study done on electrical properties of phantom gels, it was concluded that such gels cannot mimic the living human tissue in low frequencies [12]. Therefore, as a future step, we would recommend using a high frequency signal instead of direct current. It is important to test the voltage in the final prototype using mapping catheters that are available to the electrophysiologist, which was not available to us. To overcome this setback, one can potentially use an ECG device for a basic and relatively accurate recording of the signals.

9.0 Acknowledgements
We would like to thank our sponsor Dr. Christopher Porterfield, our Senior Project professor Dr. Michael Whitt and Mr. John Gerrity for supporting and guiding us through the course. We would also like to thank Dr. James Eason, Dr. Robert Szlavik, the California Polytechnic State University Biomedical Engineering and Chemistry Departments for providing us with information and equipment throughout our project.
10.0 Appendices

10.1 Appendix A: References
10.2 Appendix B: Project Plan (PERT Chart)

Figure 1. Initial PERT Chart for Winter Quarter

<table>
<thead>
<tr>
<th>Task ID</th>
<th>Task Mode</th>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
<th>Predecessors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Indications for Use</td>
<td>1 day</td>
<td>Mon 1/14/15</td>
<td>Mon 1/14/15</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Product Specification Matrix</td>
<td>1 day</td>
<td>Mon 1/14/19</td>
<td>Mon 1/14/19</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Sponsor Contact</td>
<td>1 day</td>
<td>Mon 1/14/15</td>
<td>Mon 1/14/15</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Materials Research</td>
<td>2 wks</td>
<td>Tue 1/15/19</td>
<td>Mon 1/28/15</td>
<td>1,2,3</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Electrode Research</td>
<td>1 wk</td>
<td>Tue 1/29/19</td>
<td>Mon 2/4/19</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Materials Acquisition</td>
<td>1 wk</td>
<td>Tue 2/5/19</td>
<td>Mon 2/11/19</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Creating Test Squares of Materials</td>
<td>1 wk</td>
<td>Tue 2/12/19</td>
<td>Mon 2/18/19</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Materials Testing (stiffness, conductivity, etc.)</td>
<td>2 wks</td>
<td>Tue 2/19/19</td>
<td>Mon 3/4/19</td>
<td>7</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Making LA 3D Print File</td>
<td>1 wk</td>
<td>Tue 1/15/19</td>
<td>Mon 1/21/19</td>
<td>1,2,3</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>3D Printing</td>
<td>1 wk</td>
<td>Tue 1/22/19</td>
<td>Mon 1/28/19</td>
<td>9</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Creating Prototype</td>
<td>1 wk</td>
<td>Tue 3/12/19</td>
<td>Mon 3/18/19</td>
<td>14,13</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Circuit Design</td>
<td>2 wks</td>
<td>Tue 2/5/19</td>
<td>Mon 2/18/15</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Programming</td>
<td>1 wk</td>
<td>Tue 2/19/19</td>
<td>Mon 2/25/15</td>
<td>12</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Molding and Casting</td>
<td>1 wk</td>
<td>Tue 3/5/19</td>
<td>Mon 3/11/15</td>
<td>8,10</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Design Review</td>
<td>1 wk</td>
<td>Tue 3/19/19</td>
<td>Mon 3/25/15</td>
<td>11</td>
</tr>
</tbody>
</table>

Figure 2. Task IDs for Winter Quarter PERT Chart
### Figure 3. Test and Manufacturing PERT Chart for Spring Quarter

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Dura.</th>
<th>Start</th>
<th>Finish</th>
<th>Resource Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast PE Test Sample</td>
<td>5 days</td>
<td>Sun 4/21/19</td>
<td>Thu 4/25/19</td>
<td>PE, Sodium Azide, Agar, 192-328: Mixing</td>
</tr>
<tr>
<td>Electrical Testing on PE Sample</td>
<td>3 days</td>
<td>Fri 4/26/19</td>
<td>Tue 4/30/19</td>
<td>EE SPL: Multimeter, Power Supply</td>
</tr>
<tr>
<td>Cut Header Slot in Gel Mold</td>
<td>5 days</td>
<td>Fri 4/26/19</td>
<td>Thu 5/2/19</td>
<td>Innovation Sandbox</td>
</tr>
<tr>
<td>Cast Humic Gel for Second Prototype</td>
<td>3 days</td>
<td>Fri 5/3/19</td>
<td>Tue 5/7/19</td>
<td>192-328: Hot Plate, Mixing</td>
</tr>
<tr>
<td>Cast PE Gel for Second Prototype</td>
<td>1 day</td>
<td>Wed 5/8/19</td>
<td>Wed 5/8/19</td>
<td>PE, Sodium Azide, Agar, 192-328: Mixing</td>
</tr>
<tr>
<td>Assemble Gel and Electronic Components for Second Prototype</td>
<td>1 day</td>
<td>Thu 5/9/19</td>
<td>Thu 5/9/19</td>
<td></td>
</tr>
<tr>
<td>Electrical Testing on Second Prototype</td>
<td>3 days</td>
<td>Fri 5/10/19</td>
<td>Tue 5/14/19</td>
<td>EE SPL: Multimeter, Power Supply</td>
</tr>
<tr>
<td>Test Square Wave Code</td>
<td>3 days</td>
<td>Fri 4/26/19</td>
<td>Tue 4/30/19</td>
<td>EE SPL: Multimeter, Power Supply, Oscilloscope</td>
</tr>
<tr>
<td>Test Sin Wave Code</td>
<td>3 days</td>
<td>Wed 5/1/19</td>
<td>Fri 5/3/19</td>
<td>EE SPL: Multimeter, Power Supply, Oscilloscope</td>
</tr>
<tr>
<td>PE Prototype Testing with Probe Catheter</td>
<td>7 days</td>
<td>Wed 5/15/19</td>
<td>Thu 5/23/19</td>
<td>Dr. Chris Porterfield’s Office: Probe Catheter</td>
</tr>
<tr>
<td>Cut Header Slots in Gel Mold</td>
<td>3 days</td>
<td>Fri 5/10/19</td>
<td>Tue 5/14/19</td>
<td></td>
</tr>
<tr>
<td>Cast Humic Gel for Multiple Header Prototype</td>
<td>3 days</td>
<td>Wed 5/15/19</td>
<td>Fri 5/17/19</td>
<td>192-328: Hot Plate, Mixing</td>
</tr>
<tr>
<td>Cast PE Gel for Multiple Header Prototype</td>
<td>1 day</td>
<td>Mon 5/20/19</td>
<td>Mon 5/20/19</td>
<td>PE, Sodium Azide, Agar, 192-328: Mixing</td>
</tr>
<tr>
<td>Assemble Gel and Electronic Components for Multiple Header Prototype</td>
<td>1 day</td>
<td>Tue 5/21/19</td>
<td>Tue 5/21/19</td>
<td></td>
</tr>
<tr>
<td>Electrical Testing on Multiple Header Prototype</td>
<td>3 days</td>
<td>Wed 5/22/19</td>
<td>Fri 5/24/19</td>
<td>EE SPL: Multimeter, Power Supply, Oscilloscope</td>
</tr>
<tr>
<td>Multiple Header Prototype Testing with Probe Catheter</td>
<td>3 days</td>
<td>Mon 5/27/19</td>
<td>Wed 5/29/19</td>
<td>Dr. Chris Porterfield’s Office: Probe Catheter</td>
</tr>
</tbody>
</table>

### Figure 4. Task IDs for Test and Manufacturing PERT Chart
10.3 Appendix C: CAD Drawings

Figure 5. TinkerCAD Schematic of Button Breadboard

Figure 6. Eagle Schematic of Non-Inverting Amplifier and LED Output Circuit
Figure 7. Eagle Auto-routed PCB of Non-Inverting Amplifier and LED Output Circuit for Manufacture
10.4 Appendix D: FMEA, Hazard & Risk Assessment

**Failure Modes Effect Analysis:**

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Possible Failure Mode</th>
<th>Type</th>
<th>Cause of Failure</th>
<th>OCC</th>
<th>DET</th>
<th>SEV</th>
<th>RPN</th>
<th>Effect of Failure on System</th>
<th>Comments</th>
<th>Failure Improvement Alternative Actions (actions to fix the problem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>Bugs/ Glitches</td>
<td>W</td>
<td>Programming</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>648</td>
<td>Incorrect electrical stimuli</td>
<td>Running tests on every setting before putting into model</td>
<td></td>
</tr>
<tr>
<td>Soldering material</td>
<td>Insufficient Electrical conduction</td>
<td>M</td>
<td>Not enough solder</td>
<td>8</td>
<td>5</td>
<td>9</td>
<td>576</td>
<td>Cannot transmit electrical signal</td>
<td>Utilize proper soldering technique</td>
<td></td>
</tr>
<tr>
<td>3D mold</td>
<td>Crack</td>
<td>M</td>
<td>Insufficient fill when printing</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>567</td>
<td>Cannot create gel cast</td>
<td>Do test prints and stress test them</td>
<td></td>
</tr>
<tr>
<td>Wires</td>
<td>Fracture</td>
<td>M</td>
<td>Insufficient stress relief</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td>450</td>
<td>No signal transmission</td>
<td>Keep wires as straight as possible</td>
<td></td>
</tr>
<tr>
<td>Electrodes</td>
<td>Corrosion</td>
<td>M</td>
<td>Humidity</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>420</td>
<td>Inaccurate readings in probes</td>
<td>Electrodes are to be kept in a place/check before use and clean as needed</td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Warping</td>
<td>W</td>
<td>Improper casting</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>252</td>
<td>Not anatomically accurate</td>
<td>Pour gel slow so no bubbles arise</td>
<td></td>
</tr>
<tr>
<td>Medical gel</td>
<td>Melting</td>
<td>C</td>
<td>Heat from electrical components</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>210</td>
<td>Exposes electrodes so they are no longer set</td>
<td>Test the maximum temperature the electrodes can produce and see if it could melt the gel</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>Strips from wire</td>
<td>M</td>
<td>Friction of other parts</td>
<td>4</td>
<td>9</td>
<td>5</td>
<td>180</td>
<td>Can cause short in circuit</td>
<td>Ensuring all wires are securely housed</td>
<td></td>
</tr>
<tr>
<td>Microcontroller</td>
<td>Circuit failure</td>
<td>W</td>
<td>Abuse of quality</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>160</td>
<td>Lack of ability to control the pulse order through the electrodes</td>
<td>Monitor the voltage input/use high quality equipment</td>
<td></td>
</tr>
<tr>
<td>Controller box</td>
<td>Short circuit</td>
<td>M</td>
<td>Insufficient seal to saline solution</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>60</td>
<td>Circuit cannot connect program to device</td>
<td>Immediate shutdown, dry all components</td>
<td></td>
</tr>
<tr>
<td>Adhesive</td>
<td>Melts and no longer adheres</td>
<td>M</td>
<td>Heat from controller</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>24</td>
<td>Components shifting</td>
<td>Use Infrared thermometer to measure heat at point of adhesion</td>
<td></td>
</tr>
<tr>
<td>Conductive gel</td>
<td>Expired</td>
<td>M</td>
<td>Manufacture error</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>24</td>
<td>No longer conductive</td>
<td>Check all expiration dates before use</td>
<td></td>
</tr>
<tr>
<td>Screws</td>
<td>Stripping</td>
<td>M</td>
<td>Excessive tightening</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>Inability to make repairs</td>
<td>Screwing until sufficient</td>
<td></td>
</tr>
</tbody>
</table>

Software risks will be mitigated by testing the software during development as well as the finished product. All solder joints will be inspected before assembly, and connections will be electrically tested to ensure that they are reliable. 3D mold issues will be mitigated by checking the print for rough edges and sanding it before casting.
Design Hazard Checklist:
Team: Left Atrial Model

1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points? Y
2. Can any part of the design undergo high accelerations/decelerations? N
3. Will the system have any large moving masses or large forces? N
4. Will the system produce a projectile? N
5. Would it be possible for the system to fall under gravity creating injury? N
6. Will a user be exposed to overhanging weights as part of the design? N
7. Will the system have any sharp edges? Y
8. Will any part of the electrical systems not be grounded? N
9. Will there be any large batteries or electrical voltage in the system above 40 V? N
10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids? Y
11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system? N
12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design? N
13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design? N
14. Can the system generate high levels of noise? N
15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc? N
16. Is it possible for the system to be used in an unsafe manner? N
17. Will there be any other potential hazards not listed above? N

<table>
<thead>
<tr>
<th>Description of Hazard</th>
<th>Planned Corrective Action</th>
<th>Planned Date</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>High melting point of the medical gel (200F-270F)</td>
<td>Use of gloves and tools that will help prevent direct contact with skin</td>
<td>02/12/2019</td>
<td>5/24/19</td>
</tr>
<tr>
<td>Possibly sharp edges of electrodes used in the model</td>
<td>Electrodes are to be handled with caution using clamping tools</td>
<td>02/12/2019</td>
<td>5/26/19</td>
</tr>
<tr>
<td>Use of batteries (potential for unexpected heating)</td>
<td>The device is not to be left unattended</td>
<td>02/12/2019</td>
<td>5/13/19</td>
</tr>
<tr>
<td>Burn risk while soldering</td>
<td>Use of gloves and prior training</td>
<td>5/26/19</td>
<td>5/26/19</td>
</tr>
</tbody>
</table>
Lead exposure risk from contact with solder joints on PCB | Washing hands after touching any soldered components | 5/26/19 | 5/26/19

10.5 Appendix E: Pugh Chart

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Concepts</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Physician access</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Portability</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Invasiveness</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Resemblance to human tissue</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Repeatability</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Life span</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td># of Pluses</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td># of Minuses</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Concept 1: Humimic gel covered in saline
Concept 2: Organic gel with salt dissolved
Concept 3: Humimic gel with enough wires to meet accuracy requirements without being conductive

The ballistics gel with salt model emerged as the frontrunner because of the versatility; we can use this idea with few electrodes or many, and the results should be consistent. While the other two concepts net neutral, concept 2 has a net positive of two + signs. When compared to animal testing, this concept is cost-effective, repeatable, and easy to use.
10.6 Appendix F: Vendor Information, Specifications, and Data Sheets

- **Humimic Medical: Gelatin #1**

- **Porcine Gel**
  SDS: [https://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Sigma/Product_information_Sheet/2/g2500pis.pdf](https://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Sigma/Product_information_Sheet/2/g2500pis.pdf)

- **Polyethylene powder**

- **Sodium Azide**

- **Agar**
  SDS: [https://www.fishersci.com/shop/msdsproxy?productName=AC400400050&productDescription=AGAR%252C+POWDER+5KG&catNo=AC400400050&vendorId=VN00032119&storeId=10652](https://www.fishersci.com/shop/msdsproxy?productName=AC400400050&productDescription=AGAR%252C+POWDER+5KG&catNo=AC400400050&vendorId=VN00032119&storeId=10652)

- **PCB**

10.7 Appendix G: Budget

<table>
<thead>
<tr>
<th>Item Description</th>
<th>Product Number</th>
<th>Purpose</th>
<th>Associated Task</th>
<th>Unit</th>
<th>Quantity</th>
<th>Cost/Unit</th>
<th>Total Cost</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballistics gel</td>
<td>852844007406</td>
<td>Lab modeling</td>
<td>11- Materials Testing</td>
<td>1 lb</td>
<td>1</td>
<td>$21.98</td>
<td>$21.98</td>
<td>Humimic gelatin #1</td>
</tr>
<tr>
<td>3D printed cast</td>
<td>N/A</td>
<td>Casting</td>
<td>14- Casting &amp; Molding</td>
<td>EA</td>
<td>1</td>
<td>$0</td>
<td>$0</td>
<td>Innovation sandbox free printing</td>
</tr>
<tr>
<td>PCB</td>
<td>43227-2</td>
<td>To attach the electrodes</td>
<td>8- Circuit Design</td>
<td>10 pcs</td>
<td>2</td>
<td>$7.50</td>
<td>$15.00</td>
<td>Amazon</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>EL-10T-003</td>
<td>control electrodes</td>
<td>11- Creating prototype</td>
<td>1 set</td>
<td>2</td>
<td>$100</td>
<td>$200</td>
<td>4Day</td>
</tr>
<tr>
<td>Electrode array 60EcoMRA</td>
<td></td>
<td>stimulate electrical activity</td>
<td>11- Creating prototype</td>
<td>1 set</td>
<td>2</td>
<td>$100</td>
<td>$200</td>
<td>4Day</td>
</tr>
<tr>
<td>Power supply</td>
<td>PEVIA ATX-VS450W Venus</td>
<td>Drive the electrodes</td>
<td>11- Creating prototype</td>
<td>EA</td>
<td>1</td>
<td>$42.10</td>
<td>$42.10</td>
<td>Sigma-Aldrich</td>
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<tr>
<td>Porcine Gelatin</td>
<td>02018-1000</td>
<td>Casting</td>
<td>14- Casting &amp; Molding</td>
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<td>$22.99</td>
<td>Amazon</td>
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Total $127.97
10.8 Appendix H: DHF

Engineering Specifications/Product Specification

<table>
<thead>
<tr>
<th>Customer Requirement</th>
<th>Engineering Metric</th>
<th>Specification</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>As precise as the probe</td>
<td>&lt; 9 mm² precision</td>
<td>Model electrode size</td>
<td>Must test probe accuracy</td>
</tr>
<tr>
<td>Surface electrical characteristics of the left atrium</td>
<td>5-7 mV</td>
<td>Model electrode voltage</td>
<td>Function with mapping catheter</td>
</tr>
</tbody>
</table>

### Ease of Use

<table>
<thead>
<tr>
<th>Button Response</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction velocity and pattern of healthy and arrhythmic tissue</td>
<td>70 cm/s ± 50 cm/s</td>
<td>Programmability of electrodes</td>
<td>Model healthy and arrhythmic conduction patterns</td>
</tr>
</tbody>
</table>

Conductivity mimics cardiac tissue

<table>
<thead>
<tr>
<th>Conductivity of murine myocardium</th>
<th>Ion content of the gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16 S/m (murine left ventricular)</td>
<td></td>
</tr>
</tbody>
</table>

DHR/LHR

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Process</th>
<th>Responsible Party</th>
<th>Signature</th>
<th>Date (MM/DD/YYYY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Melt 103g of Humimic ballistics gel in a glass beaker on a hot plate at 150°C until it has completely liquified</td>
<td>Sarah Porrello</td>
<td>Sarah Porrello</td>
<td>5/23/2019</td>
</tr>
</tbody>
</table>

2 | Fix two 40 pin M-F headers in the slots of the 3D printed mold with the M pins pointing up & the F pins flush with the bottom of the mold; place the assembly in a glass dish | Sarah Porrello    | Sarah Porrello  | 5/23/2019         |

3 | Pour the Humimic ballistics gel into the 3D | Sarah Porrello    | Sarah Porrello  | 5/23/2019         |
<table>
<thead>
<tr>
<th></th>
<th>printed mold, avoiding the header pins and evenly distributing the gel</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Allow ballistics gel to cool completely and remove any gel that may be stuck to the pins</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>5</td>
<td>Measure out 2 g of agar powder, 0.5 g of NaCl, 100 mL of deionized water and combine in one beaker</td>
<td>Borna Sobati</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>6</td>
<td>Heat the mixture on a hot plate to 95°C</td>
<td>Borna Sobati</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>7</td>
<td>Cover the beaker with a layer of aluminum foil and mix with a magnetic stir bar at 800 rpm until the flakes of agar are dissolved and the mixture is homogeneous (about 10 minutes)</td>
<td>Borna Sobati</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>8</td>
<td>Pour the agarose gel into the mold, covering the Humimic gel and embedding the header pins</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>9</td>
<td>Refrigerate the gels for 15 minutes to allow the agarose gel to set</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>10</td>
<td>Outsource PCB manufacturing using Eagle board file ‘sr proj 2 quad op amps cap.brd’</td>
<td>Tess Pate</td>
<td>5/25/2019</td>
</tr>
<tr>
<td></td>
<td>Task Description</td>
<td>Author</td>
<td>Date</td>
</tr>
<tr>
<td>---</td>
<td>----------------------------------------------------------------------------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>11</td>
<td>Solder all components to the PCB per the PCB schematic</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>12</td>
<td>Connect 16 jumper wires to the headers and solder the other ends to the PCB output pads per PCB board schematic (8 wires per header, 4 gaps are placed between each wire, with the first wire plugged into the outermost slot)</td>
<td>Borna Sobati</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>13</td>
<td>Connect 2 jumper wires (1 per header) to the outermost slot on the other side of the header as a ground (There should be 3 gaps between this ground and the nearest wire)</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>14</td>
<td>Plug the other ends of the 2 ground wires into the ground plate on the small breadboard</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>15</td>
<td>Wire the button and 3 indicator LEDs on a breadboard per the button schematic</td>
<td>Sarah Porello</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>16</td>
<td>Program the DUE R3 outputs: use Arduino file ‘propagate_button16.ino’</td>
<td>Tess Pate</td>
<td>5/27/2019</td>
</tr>
<tr>
<td>17</td>
<td>Wire corresponding PCB inputs to DUE R3 Board digital I/O ports</td>
<td>Borna Sobati</td>
<td>5/27/2019</td>
</tr>
</tbody>
</table>
per PCB board schematic

| 18 | Ensure op amps rails are powered by 18V supplies and DUE R3 board is powered via USB connection | Borna Sobati | Borna Sobati | 5/27/2019 |

### 10.9 Appendix I: Raw Data

**Testing Electrode Voltage:**

1.8 Porcine, 15mL water, No NaCl

<table>
<thead>
<tr>
<th>distance from source [in]</th>
<th>voltage [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.9</td>
</tr>
<tr>
<td>0.2</td>
<td>3.6</td>
</tr>
<tr>
<td>0.3</td>
<td>11.7</td>
</tr>
<tr>
<td>0.4</td>
<td>8.6</td>
</tr>
<tr>
<td>0.5</td>
<td>14.3</td>
</tr>
<tr>
<td>0.6</td>
<td>22.2</td>
</tr>
<tr>
<td>0.7</td>
<td>19.5</td>
</tr>
<tr>
<td>0.8</td>
<td>17.8</td>
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<tr>
<td>0.9</td>
<td>17.1</td>
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<tr>
<td>1.0</td>
<td>20.4</td>
</tr>
<tr>
<td>1.1</td>
<td>11.1</td>
</tr>
<tr>
<td>1.2</td>
<td>6.1</td>
</tr>
<tr>
<td>1.3</td>
<td>4.2</td>
</tr>
<tr>
<td>1.4</td>
<td>30.1</td>
</tr>
<tr>
<td>1.5</td>
<td>5.1</td>
</tr>
<tr>
<td>1.6</td>
<td>12.3</td>
</tr>
<tr>
<td>1.7</td>
<td>GND</td>
</tr>
</tbody>
</table>
**1.8 Porcine, 15mL water, 0.2g NaCl**

<table>
<thead>
<tr>
<th>distance from source</th>
<th>voltage [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>0.3</td>
<td>4.5</td>
</tr>
<tr>
<td>0.4</td>
<td>3.6</td>
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<tr>
<td>0.5</td>
<td>9.5</td>
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<tr>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>0.7</td>
<td>1.3</td>
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<tr>
<td>0.8</td>
<td>6.5</td>
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<td>0.9</td>
<td>5.2</td>
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<tr>
<td>1.7</td>
<td>GND</td>
</tr>
</tbody>
</table>

*Graph showing voltage [mV] vs. distance from source.*
1.8 Porcine, 15mL water, 0.015g NaCl (with header)

<table>
<thead>
<tr>
<th>distance from source</th>
<th>voltage [mV]</th>
</tr>
</thead>
<tbody>
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<td>0.1</td>
<td>57</td>
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<tr>
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<tr>
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<td>99</td>
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<tr>
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<td>25.1</td>
</tr>
<tr>
<td>1.7</td>
<td>GND</td>
</tr>
</tbody>
</table>
1.8 Porcine, 15mL water, 0.015g NaCl
(without header)

<table>
<thead>
<tr>
<th>distance from source</th>
<th>voltage trial 2 [mV]</th>
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</thead>
<tbody>
<tr>
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<td>102</td>
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<tr>
<td>0.2</td>
<td>103</td>
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<tr>
<td>0.3</td>
<td>99</td>
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<td>45</td>
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<tr>
<td>distance from source</td>
<td>voltage [mV]</td>
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<td>-------------</td>
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<td>-14</td>
</tr>
<tr>
<td>1.7</td>
<td>GRND</td>
</tr>
</tbody>
</table>

![Graph of Distance [in] and Voltage [mV]](image-url)
Agarose Gel (2 wt% agar, 0.2 wt% NaCl)

<table>
<thead>
<tr>
<th>Distance From Source (in)</th>
<th>Potential (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>42</td>
</tr>
<tr>
<td>0.2</td>
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<td>55</td>
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<tr>
<td>0.5</td>
<td>42</td>
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<tr>
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<td>41</td>
</tr>
<tr>
<td>0.7</td>
<td>45</td>
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<tr>
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<td>38</td>
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<tr>
<td>0.9</td>
<td>40</td>
</tr>
<tr>
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<td>50</td>
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<tr>
<td>1.1</td>
<td>41</td>
</tr>
<tr>
<td>1.2</td>
<td>42</td>
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<tr>
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<td>36</td>
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<tr>
<td>1.4</td>
<td>42</td>
</tr>
<tr>
<td>1.5</td>
<td>60</td>
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<tr>
<td>1.6</td>
<td>60</td>
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<tr>
<td>1.7</td>
<td>52</td>
</tr>
<tr>
<td>1.8</td>
<td>50</td>
</tr>
<tr>
<td>1.9</td>
<td>GRND</td>
</tr>
</tbody>
</table>

![Agarose Gel Graph](image)
The code used for simulation:

`propagate_button16.ino`

```c
const int button = 5; //button pin
int frequency = 100; //Set frequency in Hertz
int buttonPushCounter = 0; //counter for button presses
int buttonState = 0; //Read button status
int lastButtonState = 0;
int afib = 1; //type of rhythm
int red = 2; //indicator LED: ON if afib and during button push
int yellow = 3;
int green = 4;
```
double delayTime = 90; //Pulse length
double butdelayTime = 1000; //button delay

void setup()
{
pinMode(button, INPUT);
pinMode(6, OUTPUT);
pinMode(7, OUTPUT);
pinMode(8, OUTPUT);
pinMode(9, OUTPUT);
pinMode(10, OUTPUT);
pinMode(11, OUTPUT);
pinMode(12, OUTPUT);
pinMode(13, OUTPUT);
pinMode(22, OUTPUT);
pinMode(23, OUTPUT);
pinMode(24, OUTPUT);
pinMode(25, OUTPUT);
pinMode(26, OUTPUT);
pinMode(27, OUTPUT);
pinMode(28, OUTPUT);
pinMode(29, OUTPUT);
pinMode(red, OUTPUT);
pinMode(yellow, OUTPUT);
pinMode(green, OUTPUT);
}

void loop()
{
buttonState = digitalRead(button);

//if button is pressed, switch afib state
if ((buttonState != lastButtonState) && (buttonState == 1))
{
afib++;
if(afib>2) afib =0;
}

//propagate if 0, pre-afib if 1, afib if 2
//begin propagate code
if (afib == 0)
{
digitalWrite(green, HIGH); //indicates healthy
digitalWrite(yellow, LOW); //
digitalWrite(red, LOW); //
digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW); //3.3V is high, 0 is low
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);
delay(500);
digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
}
digitalWrite(12, LOW);
digitalWrite(13, HIGH);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, HIGH);
digitalWrite(13, HIGH);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, HIGH);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, HIGH);
digitalWrite(12, HIGH);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, HIGH);
digitalWrite(29, HIGH);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, HIGH);
digitalWrite(11, HIGH);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, HIGH);
digitalWrite(28, HIGH);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, HIGH);
digitalWrite(10, HIGH);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, HIGH);
digitalWrite(27, HIGH);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, HIGH);
digitalWrite(9, HIGH);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, HIGH);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, HIGH);
digitalWrite(8, HIGH);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, HIGH);
digitalWrite(7, HIGH);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, HIGH);
digitalWrite(24, HIGH);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, HIGH);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, HIGH);
digitalWrite(23, HIGH);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
delay(delayTime);

} //begin afib condition
if (afib == 1)
{
  digitalWrite(green, LOW); //
  digitalWrite(yellow, HIGH): //indicates pre-afib
  digitalWrite(red, LOW); //</

digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW); //</3.3V is high, 0 is low
  digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
delay(delayTime);

digitalWrite(6, LOW);
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digitalWrite(29, LOW);
delay(delayTime);
digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, HIGH);
digitalWrite(13, HIGH);
digitalWrite(22, LOW);
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digitalWrite(24, LOW);
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digitalWrite(26, LOW);
digitalWrite(27, LOW);
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digitalWrite(29, HIGH);
delay(delayTime);
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delay(delayTime);
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delay(delayTime);
digitalWrite(6, LOW);
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delay(delayTime);
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digitalWrite(25, LOW);
digitalWrite(26, HIGH);
digitalWrite(27, HIGH);
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digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
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digitalWrite(8, HIGH);
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digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, HIGH);
digitalWrite(27, LOW);
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digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, HIGH);
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digitalWrite(27, HIGH);
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digitalWrite(29, HIGH);
delay(delayTime);

digitalWrite(6, HIGH);
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digitalWrite(24, HIGH);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, HIGH);
digitalWrite(28, LOW);
digitalWrite(29, HIGH);
delay(delayTime);

digitalWrite(6, HIGH);
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digitalWrite(22, HIGH);
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digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, HIGH);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
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digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, HIGH);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, HIGH);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

//begin afib condition
if (afib == 2) {
  digitalWrite(green, LOW); //
  digitalWrite(yellow, LOW); //
  digitalWrite(red, HIGH); //indicates afib

digitalWrite(6, HIGH);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW); //3.3V is high, 0 is low

digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
digitalWrite(7, HIGH);
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delay(delayTime);

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delay(delayTime);

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digitalWrite(27, LOW);
digitalWrite(28, HIGH);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, LOW);
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delay(delayTime);

digitalWrite(6, LOW);
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digitalWrite(8, LOW);
digitalWrite(9, HIGH);
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digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, HIGH);
digitalWrite(27, HIGH);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);
digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(8, HIGH);
digitalWrite(9, HIGH);
digitalWrite(10, LOW);
digitalWrite(11, HIGH);
digitalWrite(12, HIGH);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);
digitalWrite(6, LOW);
digitalWrite(7, HIGH);
digitalWrite(8, HIGH);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, LOW);
digitalWrite(24, HIGH);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, LOW);
digitalWrite(29, LOW);
delay(delayTime);
digitalWrite(6, HIGH);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, HIGH);
digitalWrite(13, LOW);
digitalWrite(22, LOW);
digitalWrite(23, HIGH);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, HIGH);
digitalWrite(28, LOW);
digitalWrite(29, HIGH);
delay(delayTime);
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digitalWrite(8, HIGH);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, HIGH);
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digitalWrite(24, LOW);
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digitalWrite(24, LOW);
digitalWrite(25, HIGH);
digitalWrite(26, LOW);
digitalWrite(27, LOW);
digitalWrite(28, HIGH);
digitalWrite(29, LOW);
delay(delayTime);

digitalWrite(6, HIGH);
digitalWrite(7, LOW);
digitalWrite(8, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(11, LOW);
digitalWrite(12, LOW);
digitalWrite(13, LOW);
digitalWrite(22, HIGH);
digitalWrite(23, LOW);
digitalWrite(24, LOW);
digitalWrite(25, LOW);
digitalWrite(26, LOW);
digitalWrite(27, HIGH);
digitalWrite(28, LOW);
digitalWrite(29, HIGH);
delay(delayTime);

}]
}

IQ/OQ

see Section 7.0

Bill of Materials

see Appendix G

FMEA

see Appendix D