Subject-Specific Modeling of Cardiac Ischemia

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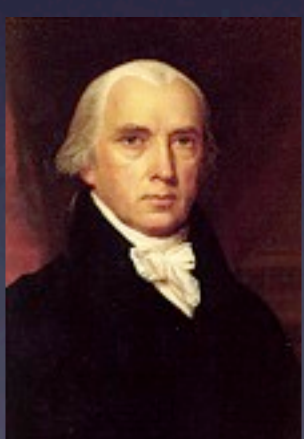
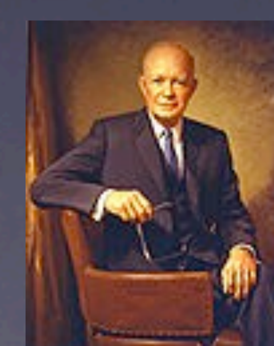



What is the leading cause of death among U.S. Presidents?





SCI INSTITUTE

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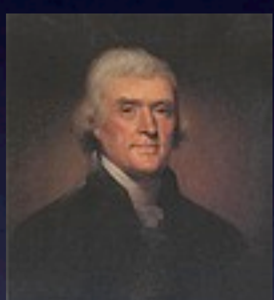
A. Stroke

B. Gun Shot

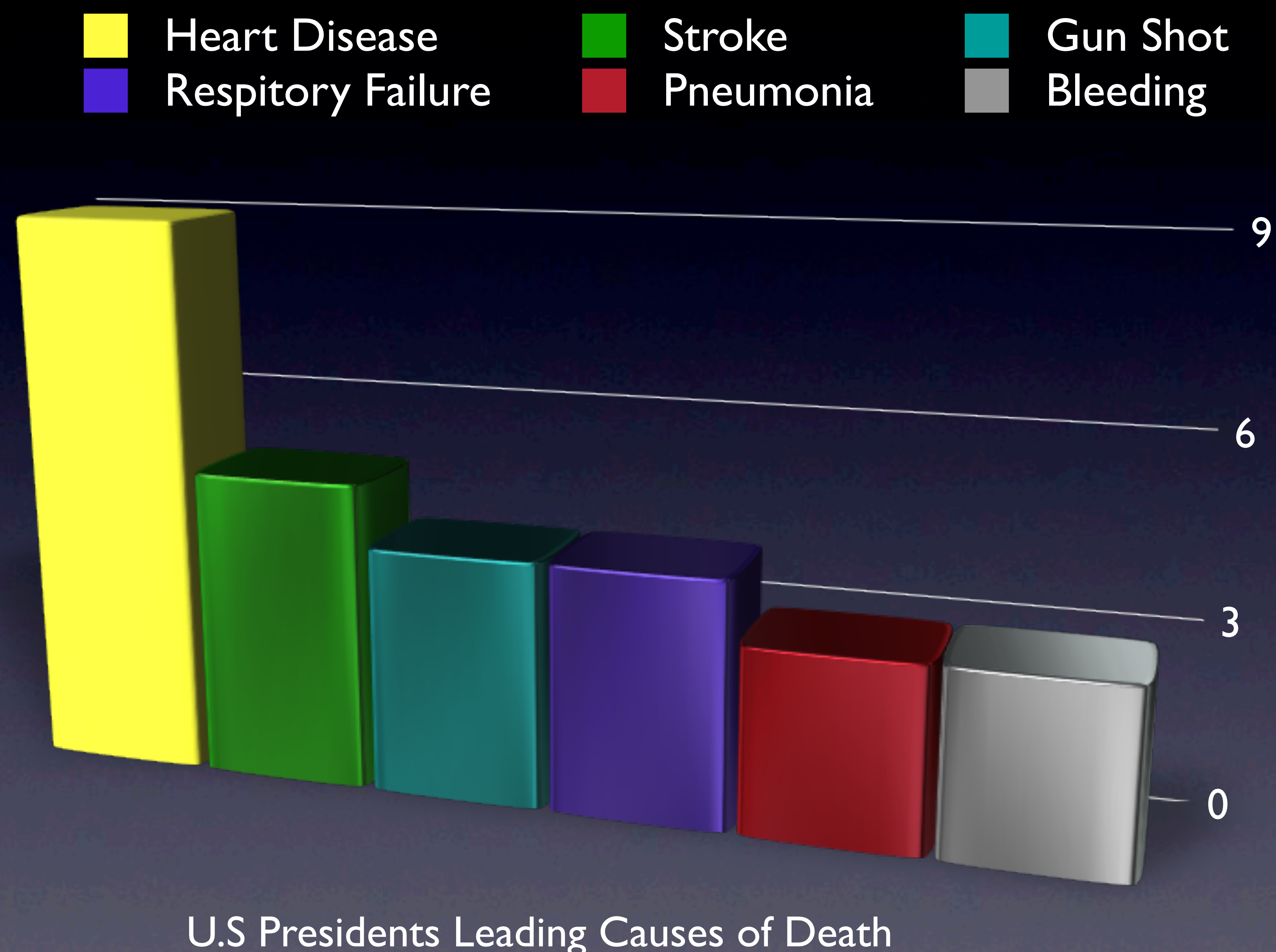
C. Heart Disease

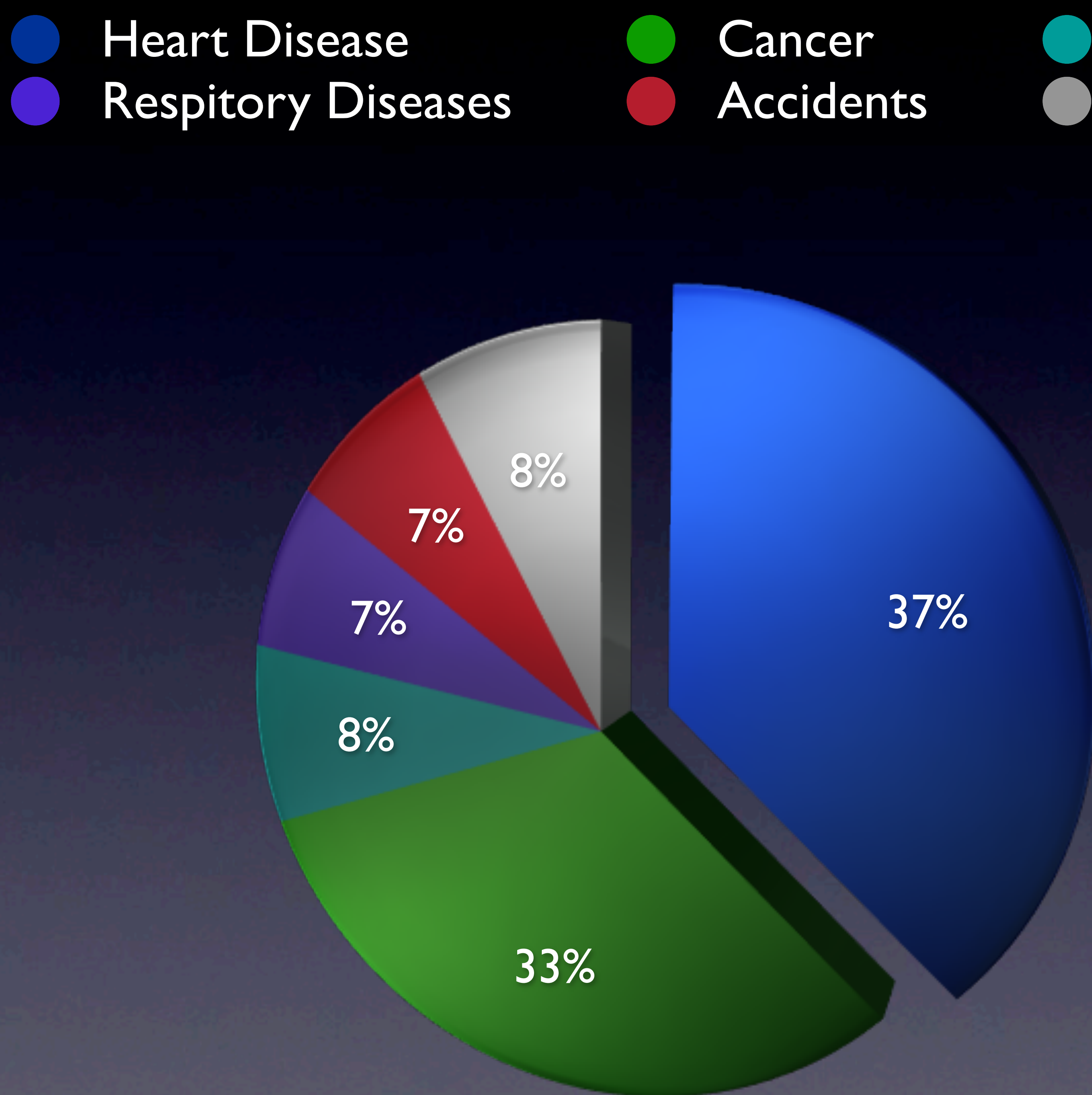




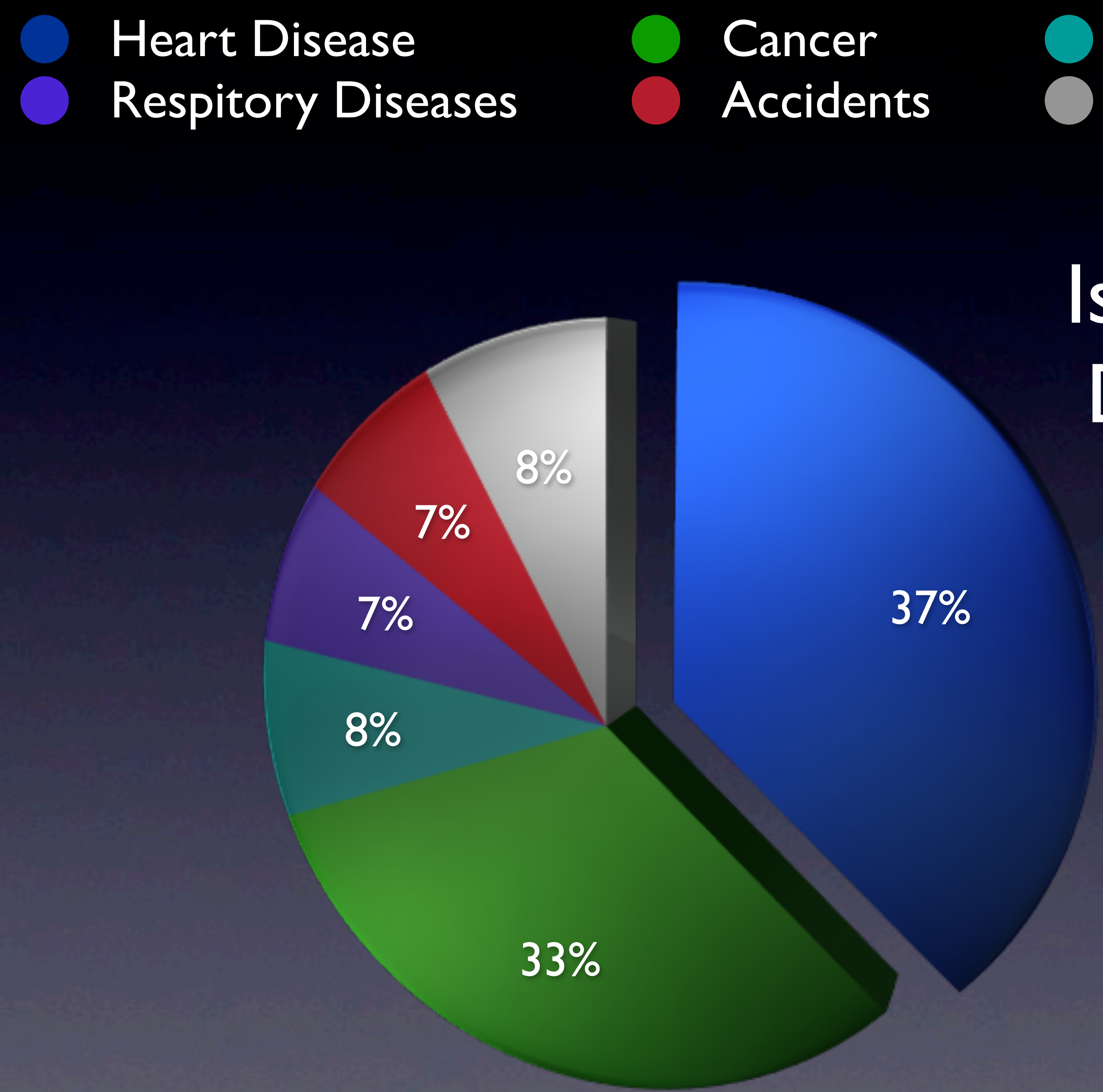






Heart Disease
Stroke
Gun Shot
Respitory Failure
Pneumonia
Bleeding
9
6
3
0
U.S Presidents Leading Causes of Death

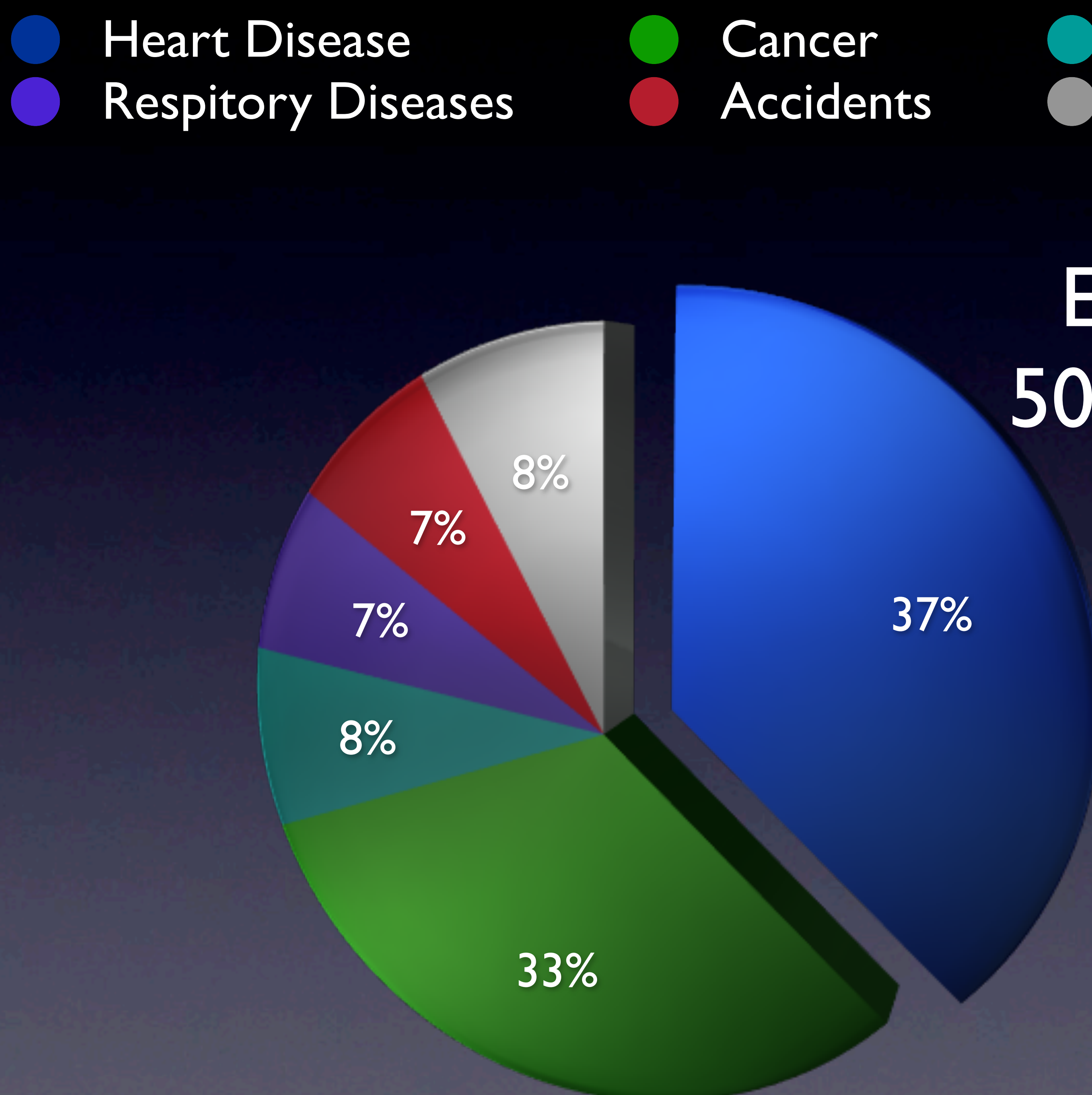


2006 Data from the Centers for Disease Control and Prevention



Ischemic Heart Disease ~19%

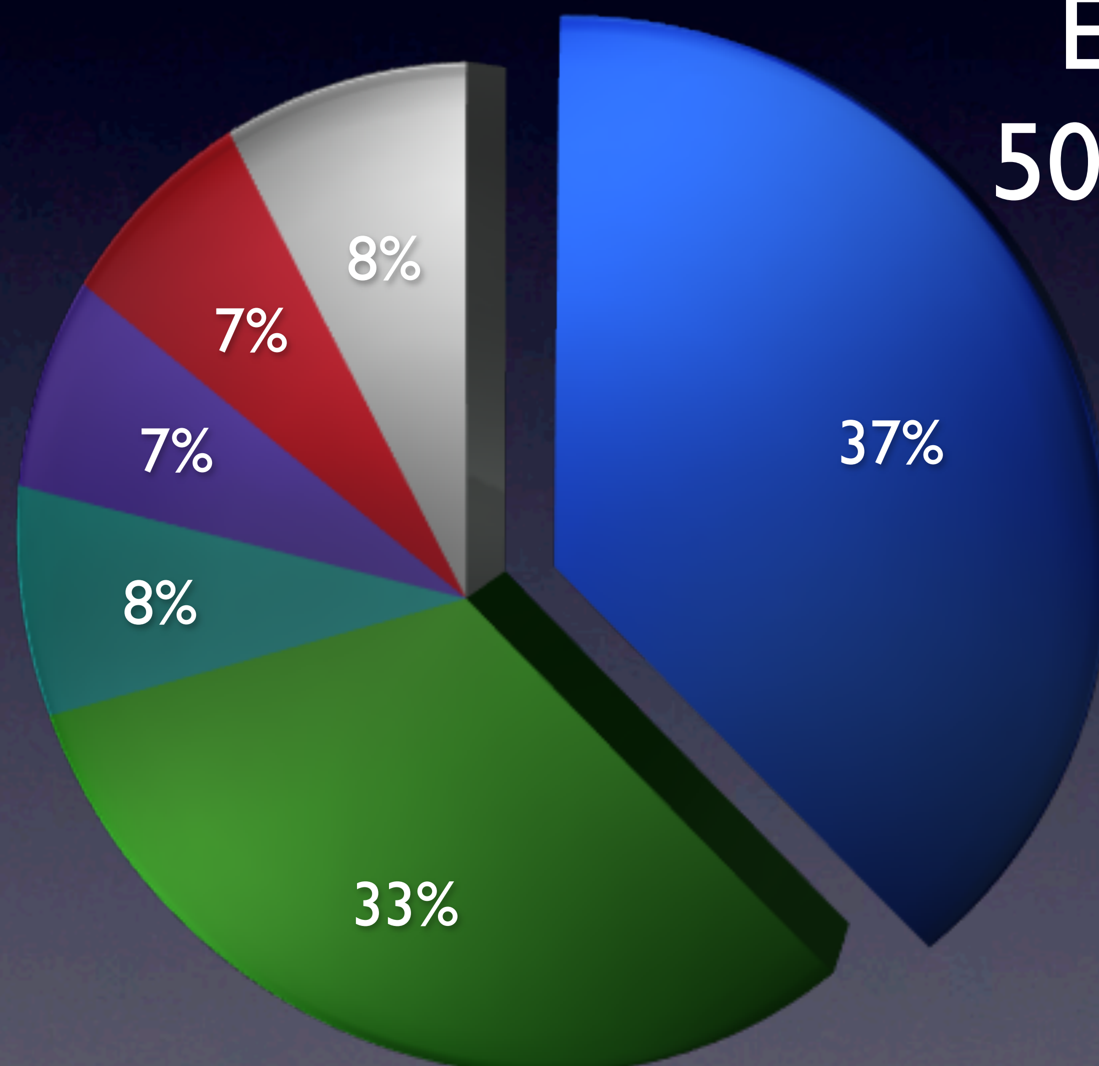
2006 Data from the Centers for Disease Control and Prevention



Early Detection
50%-70% Accurate

2006 Data from the Centers for Disease Control and Prevention

Heart Disease
Cancer
Stroke
Respitory Diseases
Accidents
Other



Early Detection
50%-70% Accurate

Why?

2006 Data from the Centers for Disease Control and Prevention

Cardiac Ischemia

Hearts are electrical organs

- Activation waves causes heart contraction
- Most Heart failures are electrical
- ECG's show the hearts electrical activity

Image provided by Dr. Tryanova, Johns Hopkins University

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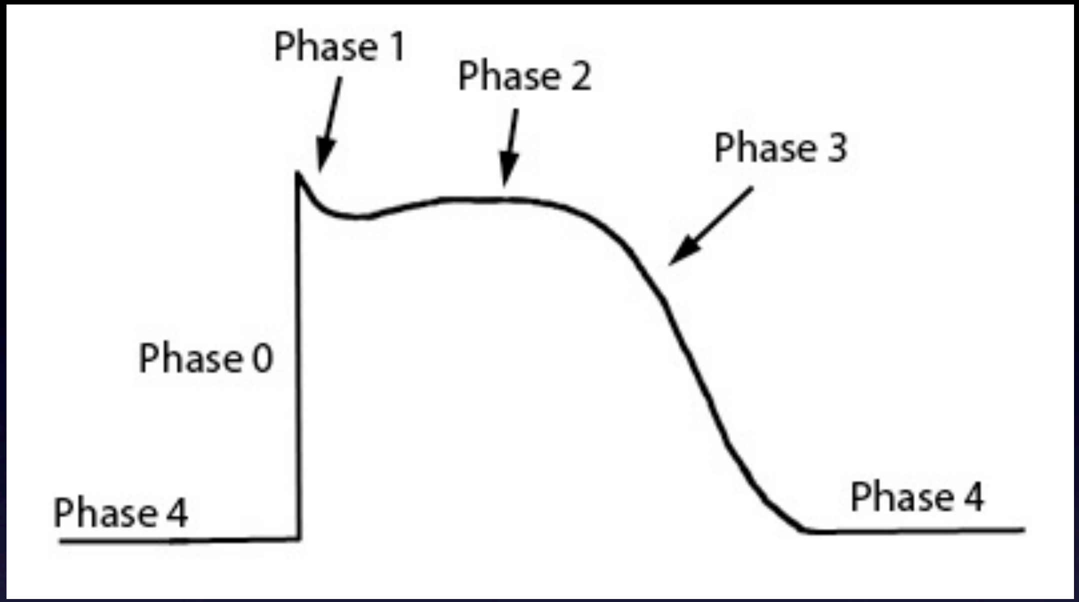
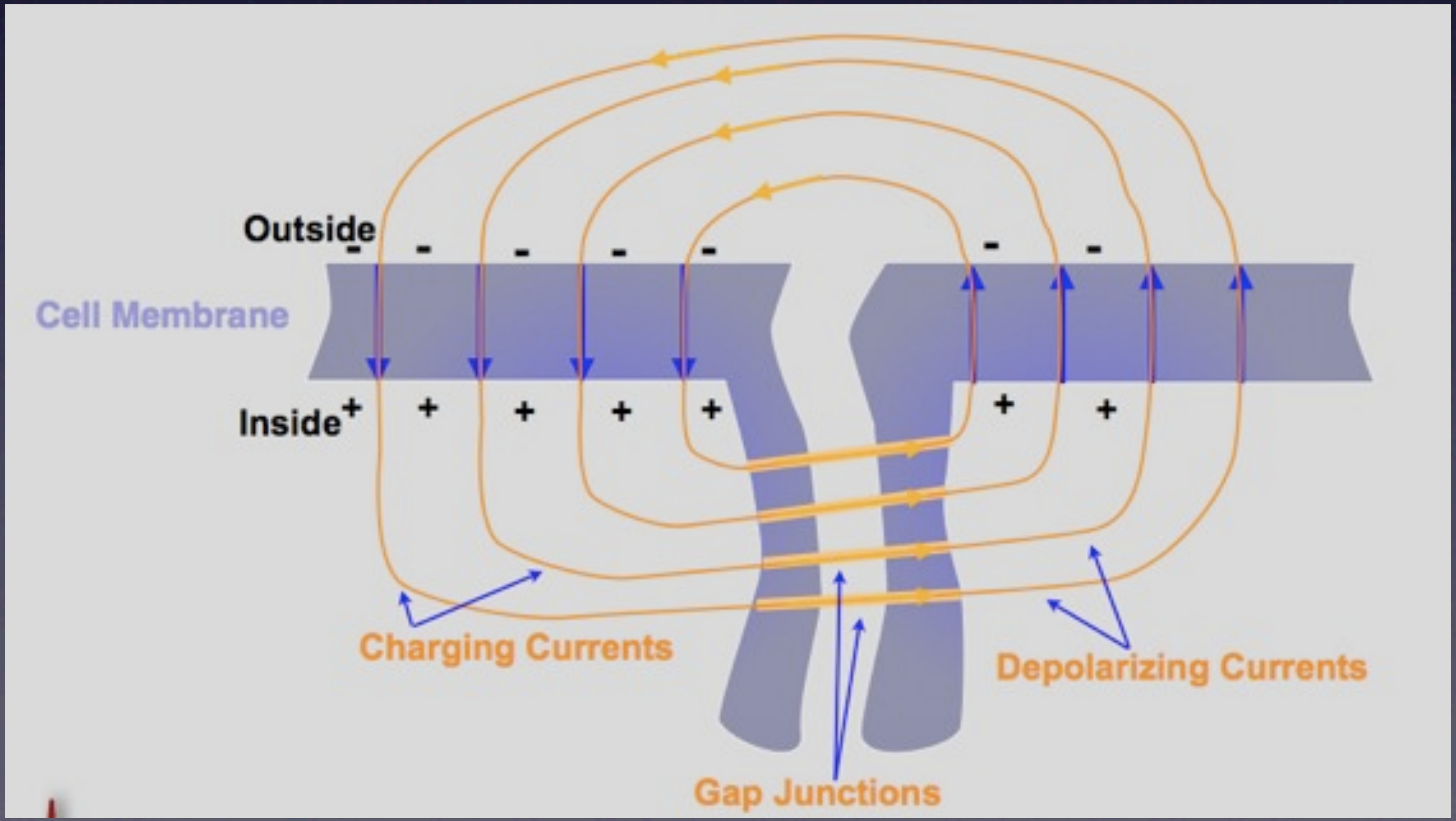
Action Potentials

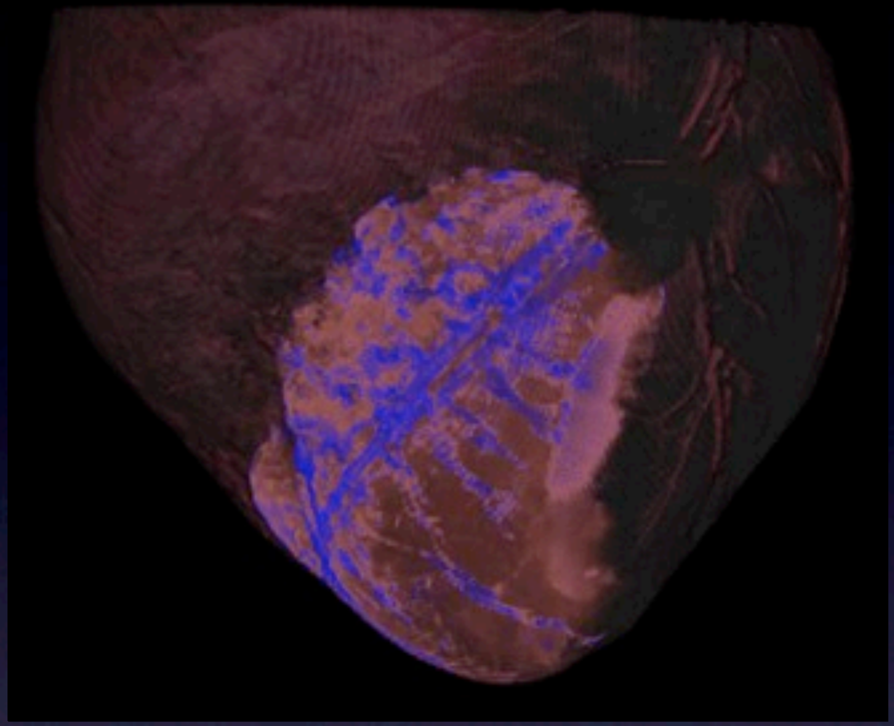




Cardiac Ischemia

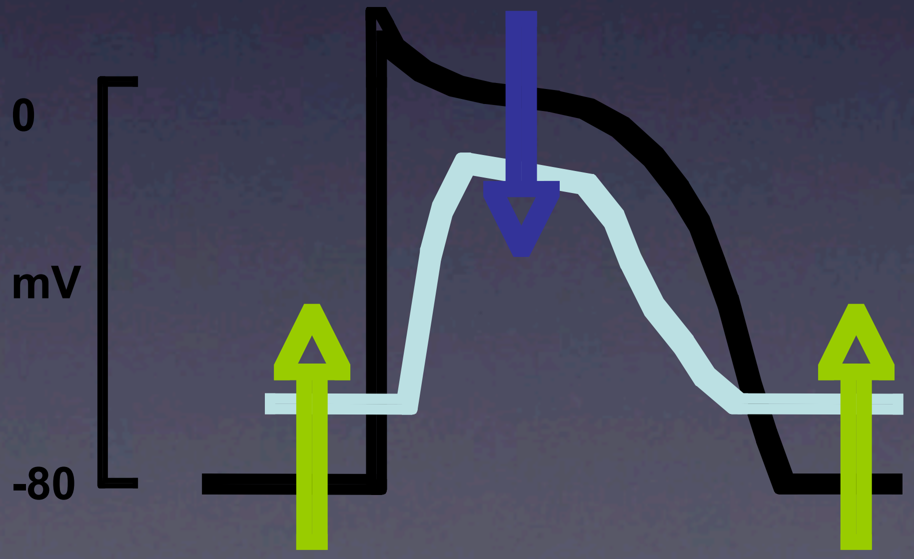
Inadequate blood flow

- Lack of nutrients (Oxygen)
- Changes electrical properties of tissue



Changes in Action Potential

- Decreased Amplitude
- Increased resting potential
- Decreased propagation velocity



Consequences

Blocked Artery

Decreased Nutrients

Cell Death

Reduced Cardiac Output

Pro-Arrhythmic Conditions

Ventricular Fibrillation

Death

Early Treatment

Drugs
Stents
Bypass

Blocked Artery → Healthy Heart

Decreased Nutrients

Cell Death

Reduced Cardiac Output

Pro-Arrhythmic Conditions

Ventricular Fibrillation

Death

Late Treatment

Drugs
Stents
Bypass

Blocked Artery

Arrhythmic Heart Defibrillators

Decreased Nutrients

Cell Death

Reduced Cardiac Output

Pro-Arrhythmic Conditions

Ventricular Fibrillation

~~Death~~

Detection

Detection Methods

- Blood Tests
- Angiogram

Take time
Invasive
Reliable

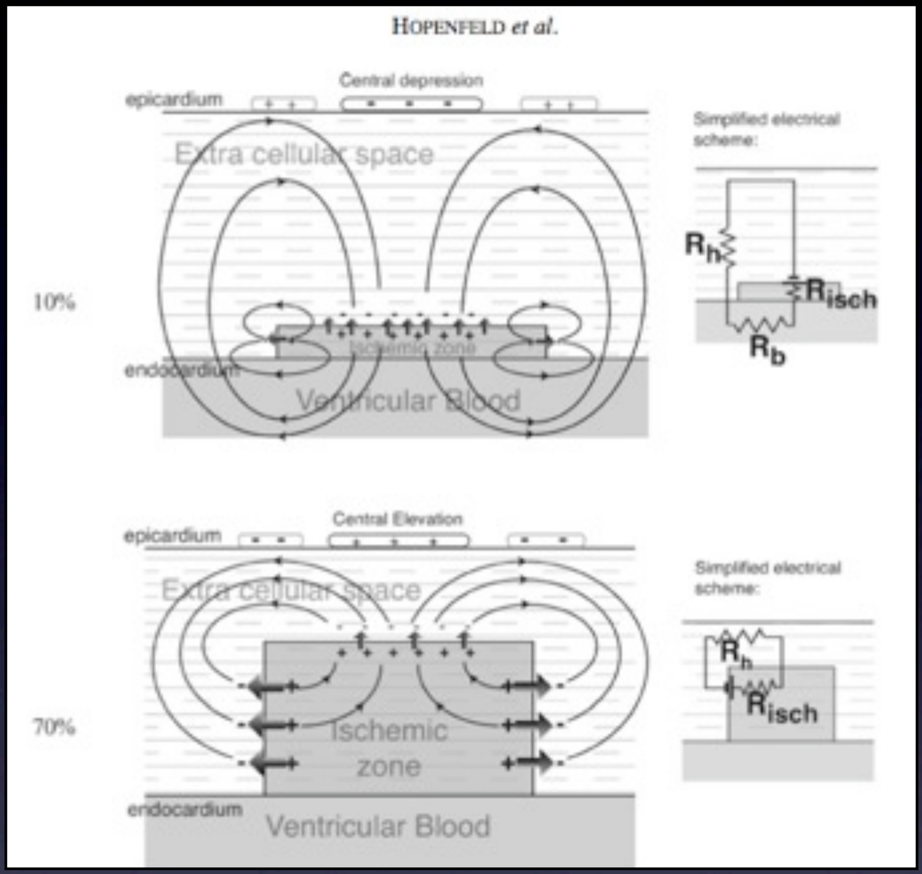
- Echocardiography
- ECG

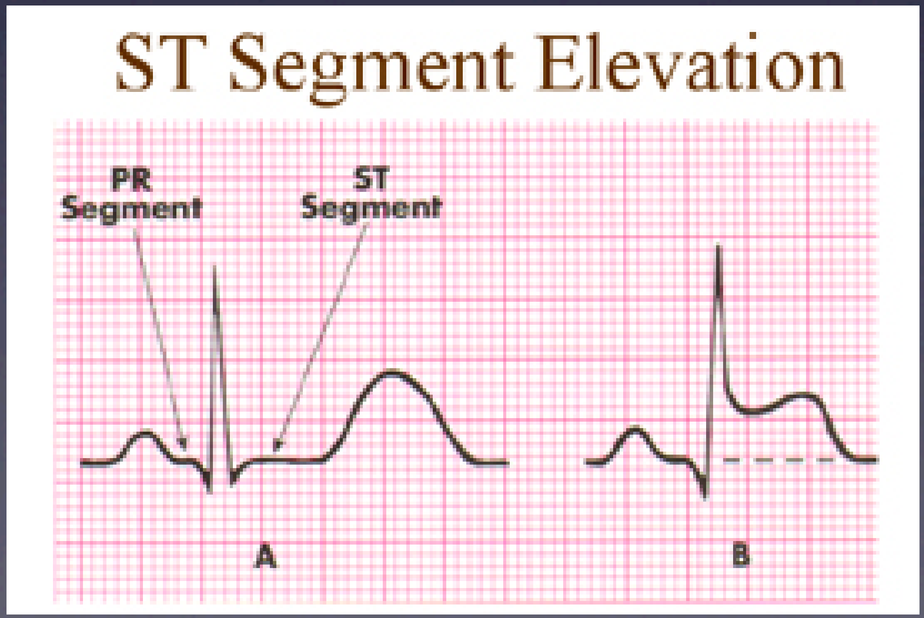
Fast
Non-Invasive
Portable
Inconclusive

ECG Methods

Why ECG Methods are Limited

- Complex current loops
- Lead Locations





Research Group Aims

What do the currents in the heart look like during early stages of ischemia?

Can we simulate them?

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What do the currents in the heart look like during early stages of ischemia?

Can we simulate them?

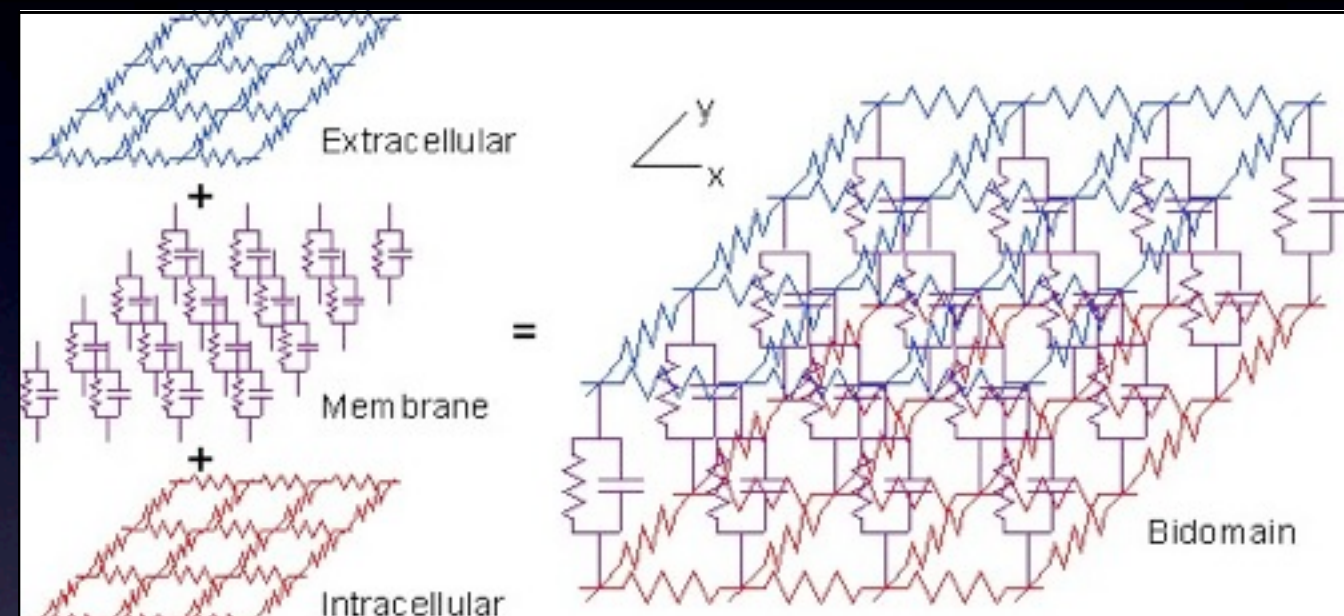
We are not the first to try.

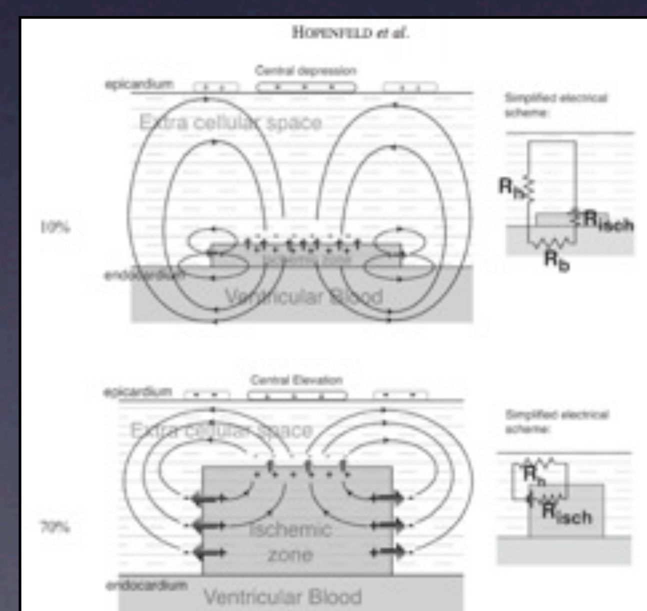
Modeling Ischemia

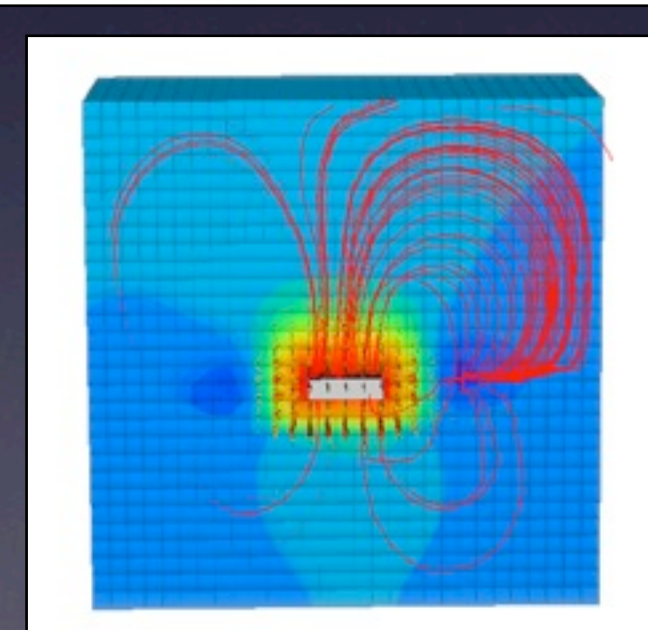
Bidomain Models

Validate current loops

Poor correlation to clinical data





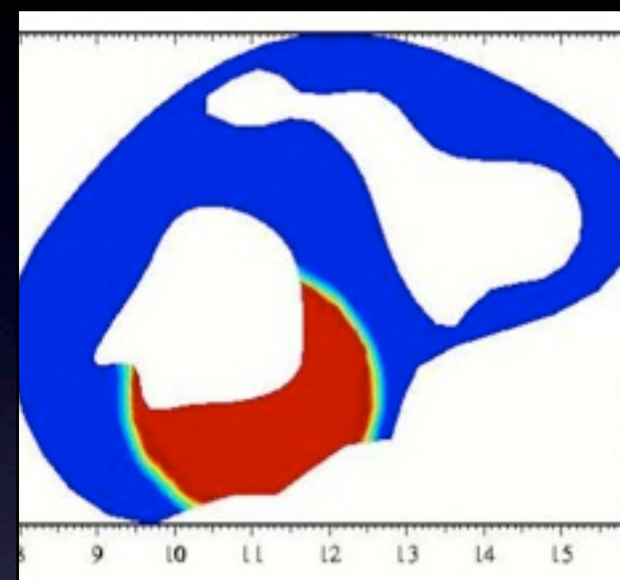


Previous Models

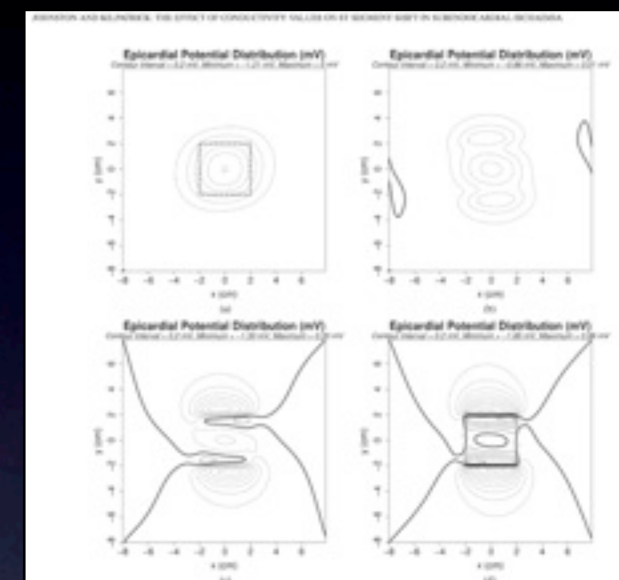
Poor correlation to clinical data due to

- Geometric accuracy
- Conductivity variability

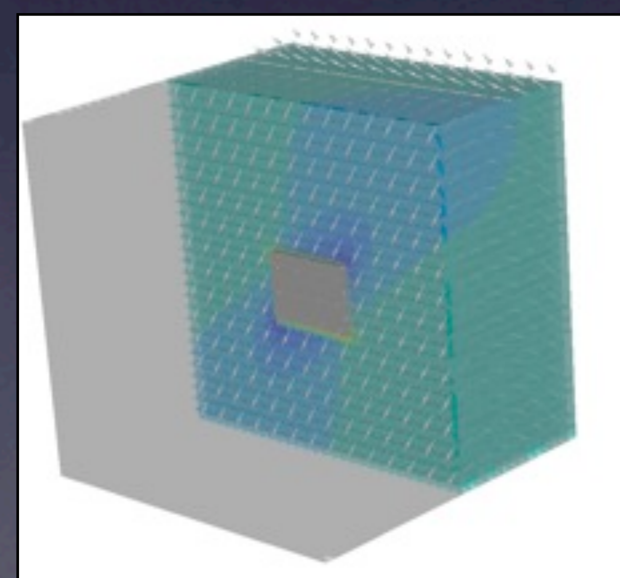
Kalkulo



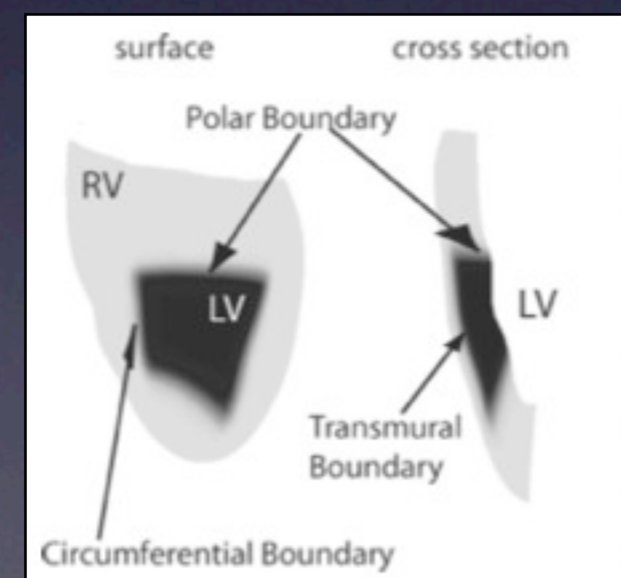
Kilpatrick



Generic



Hopenfeld



Specific Aims

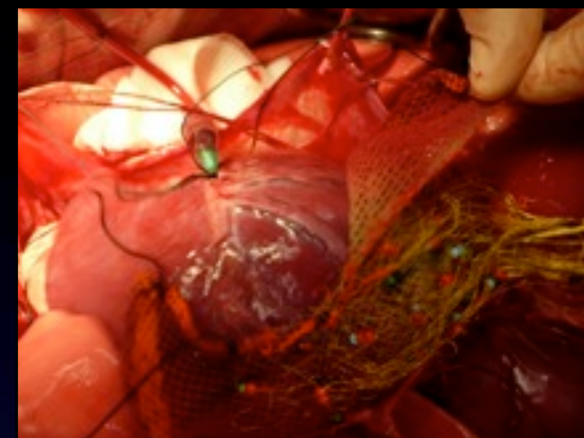
1. Subject Specific modeling of ischemia
2. Fiber Sensitivity study
3. Reduce Model Complexity/Anisotropic Meshing

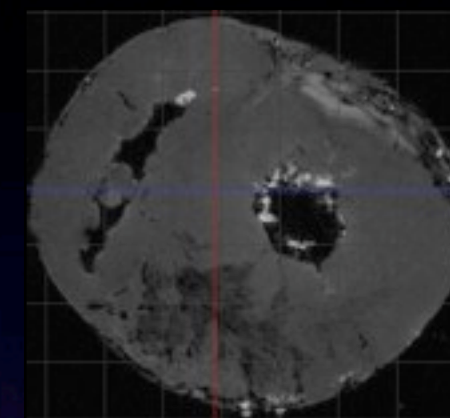
Specific Aim 1

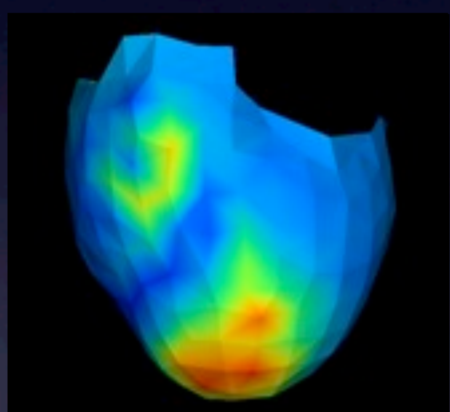
1. Propose, implement, and validate the effectiveness of a new geometric representation of the ischemic region and border zone.

- Derived from our experimental transmural electrode measurements
- A close correlation between simulated results and measured results

Subject-Specific Model

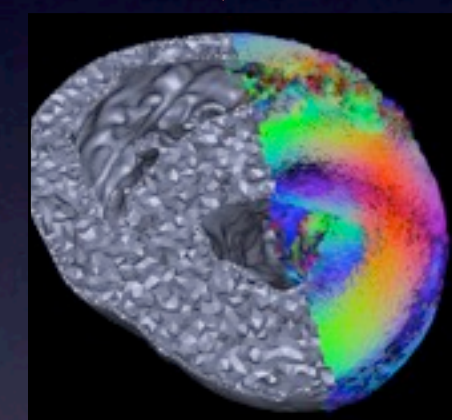


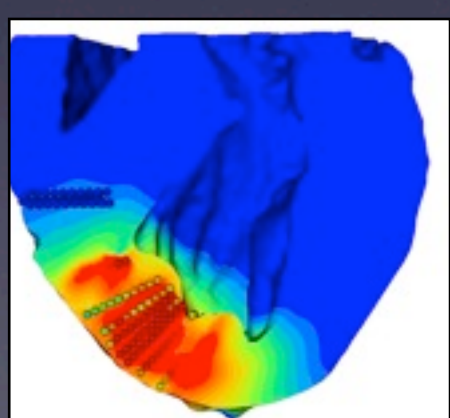


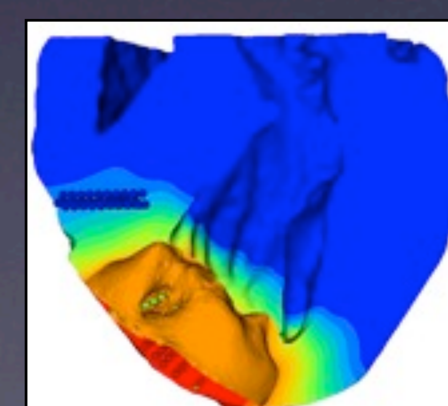


Experimental
Data

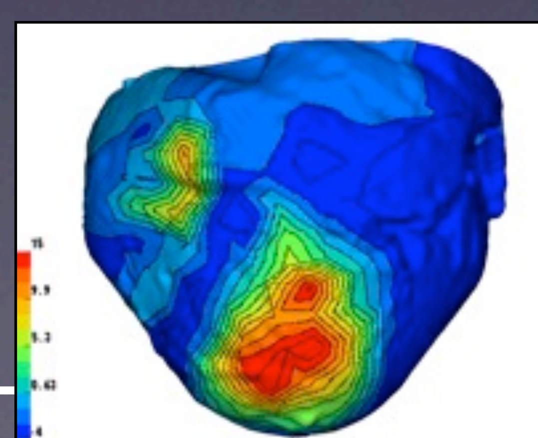
Subject Specific
Model

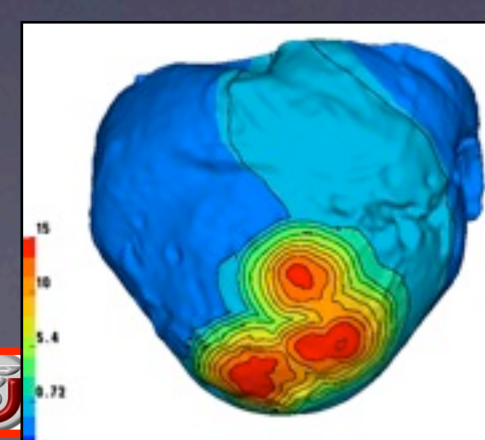






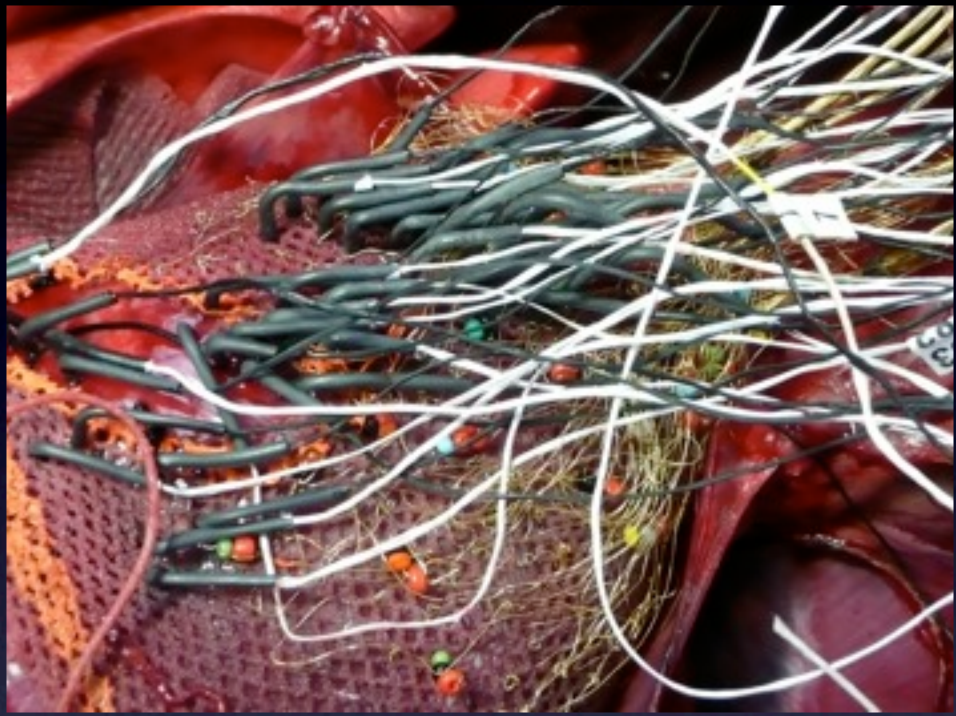
Compare Measured Data to Simulated Data

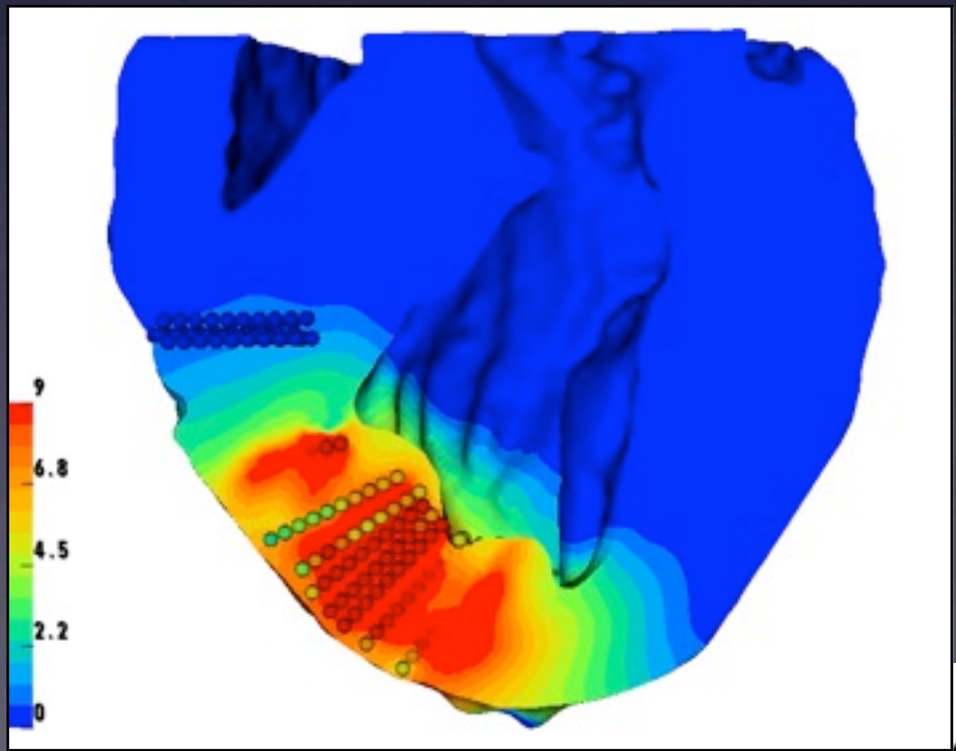




Experimental Data

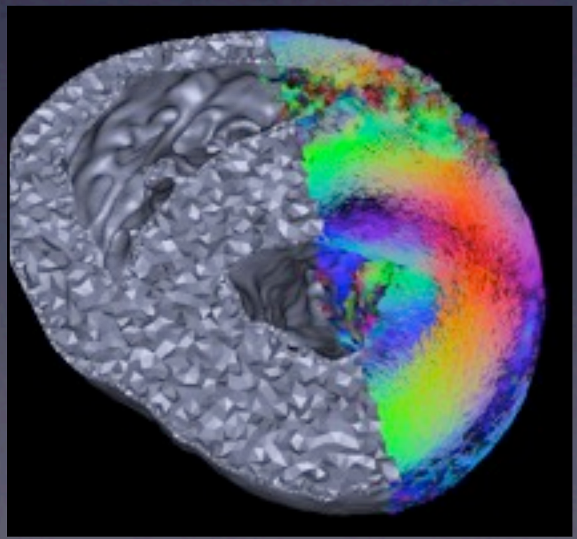
- Ischemia induced in canine LAD
- 247 electrode sock and 450 plunge needle electrodes used to record data
- Registered to landmarks on the heart for alignment with the MRI
- Linear and volumetric Laplacian interpolation for the sock and needle data

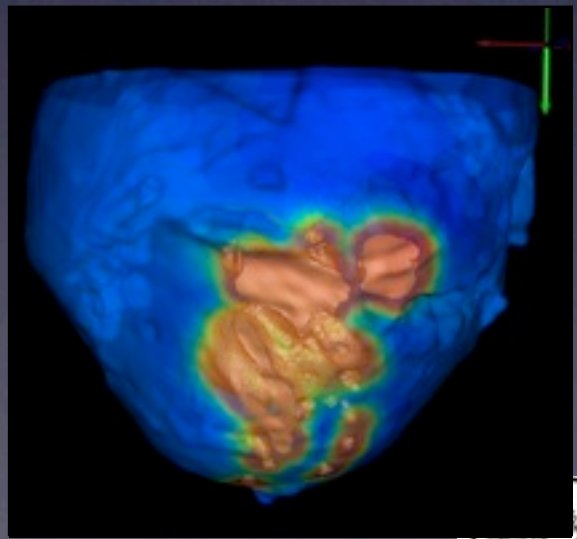




Model Creation

- MRI and DTI Scans
- Segmentation - Seg3D software.sci.utah.edu
- Marching cubes isosurfacing and Tetgen meshing - SCIRun
- Mapped fiber orientations to mesh - SCIRun
- Ischemic zone from needle





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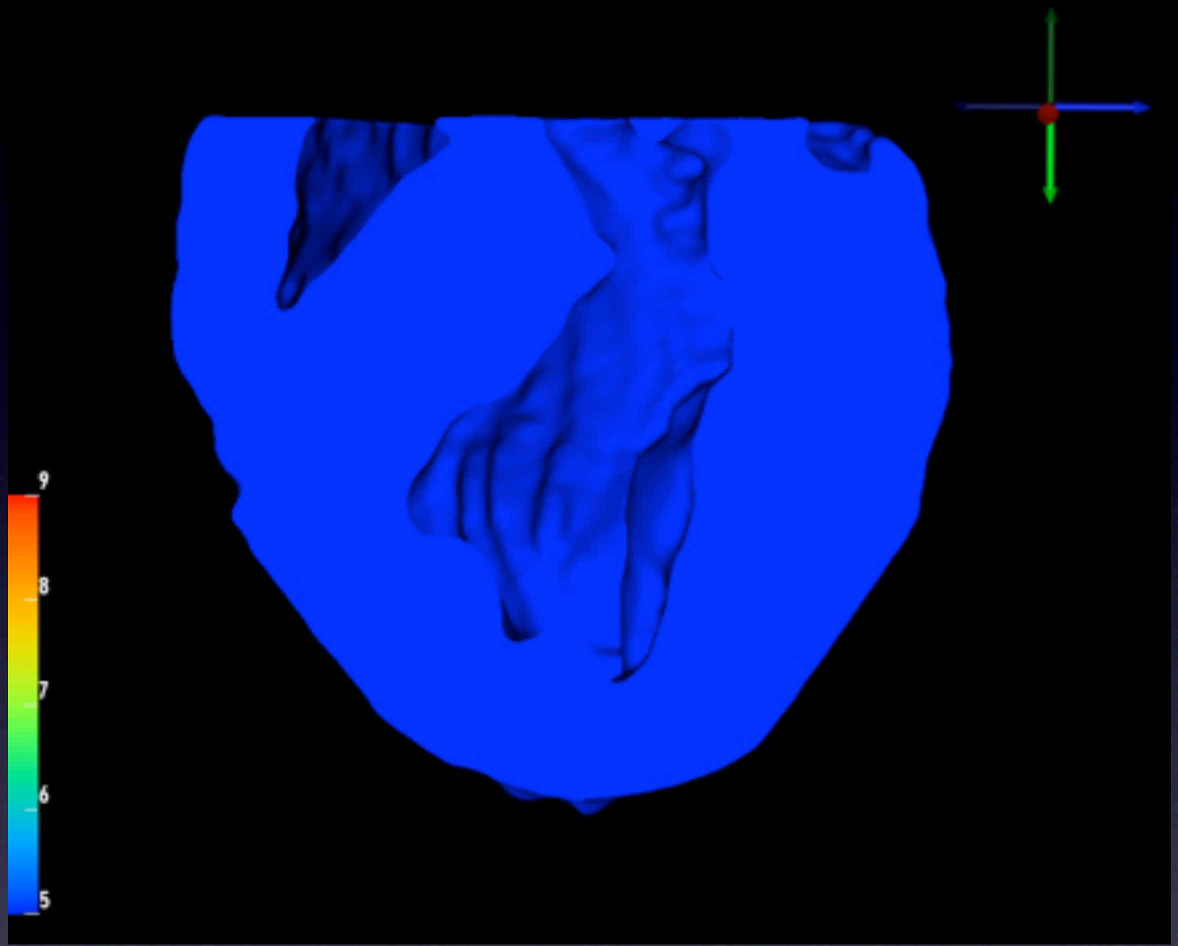
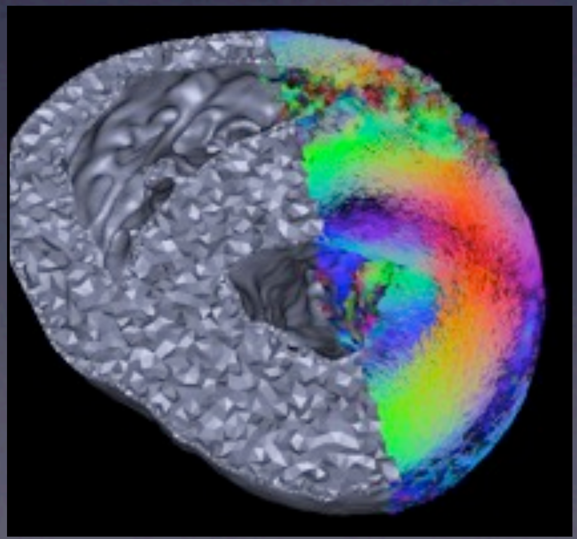
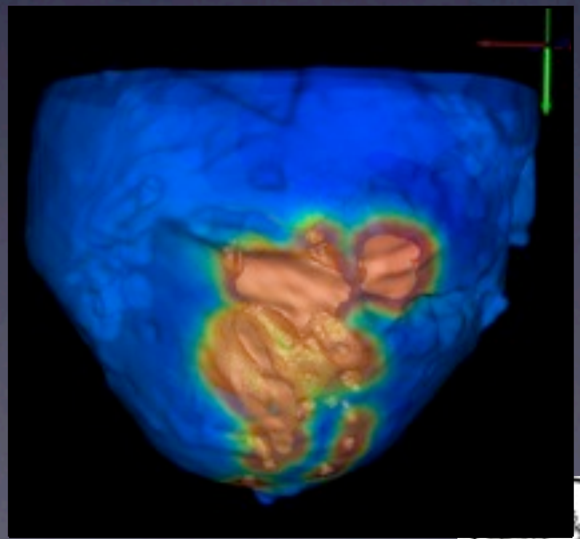




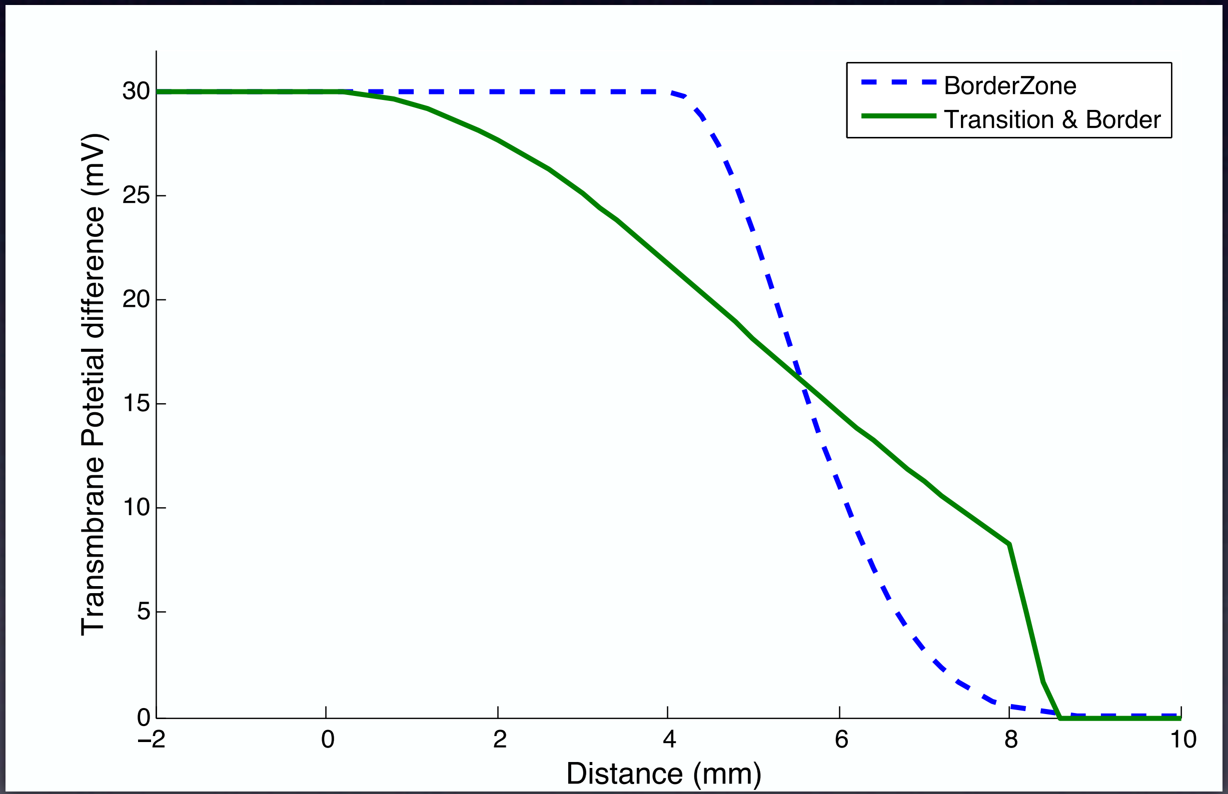


Border Zone Simulation

- Bidomain equation we assume a transmembrane potential profile

$$\nabla \cdot (M_i + M_e)\nabla \phi_e = -\nabla \cdot M_i \nabla \phi_m$$

- Conductivity from Stinstra et al



- Gaussian blurring of the edge for traditional distribution

- Explicitly modeled transition region for new distribution

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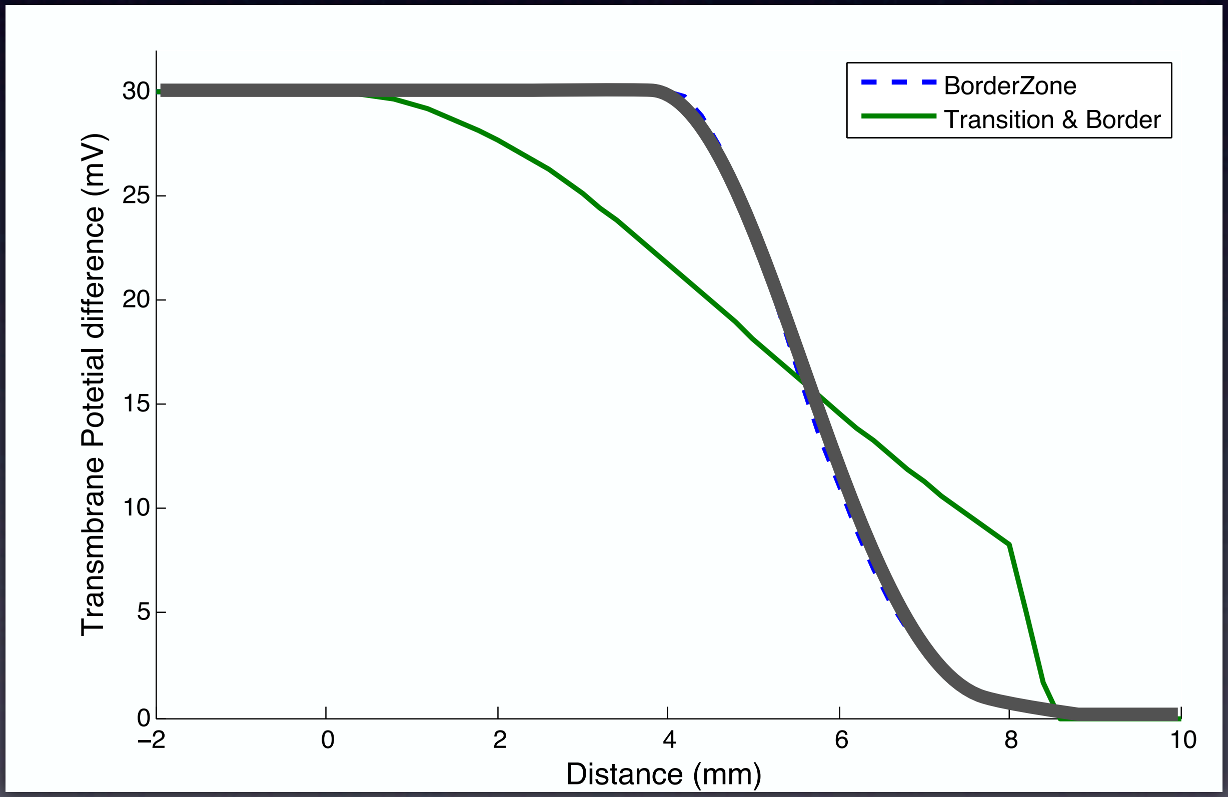

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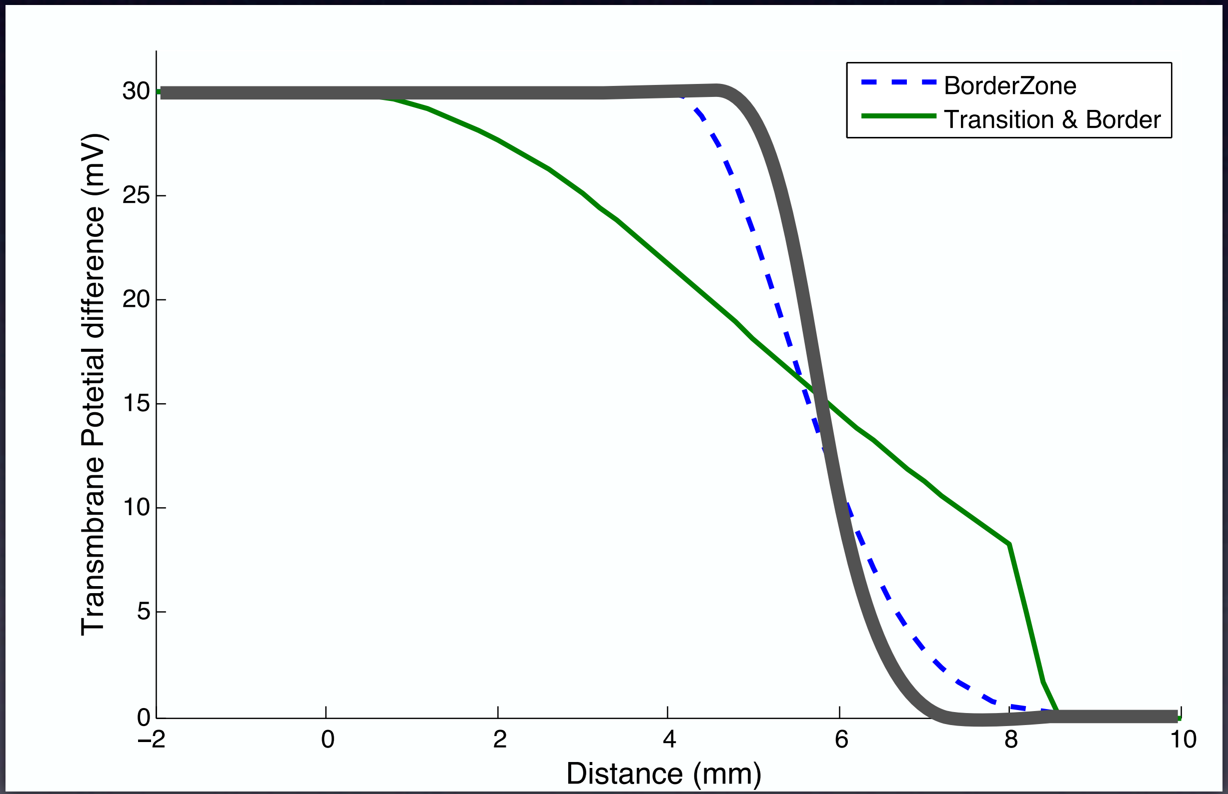

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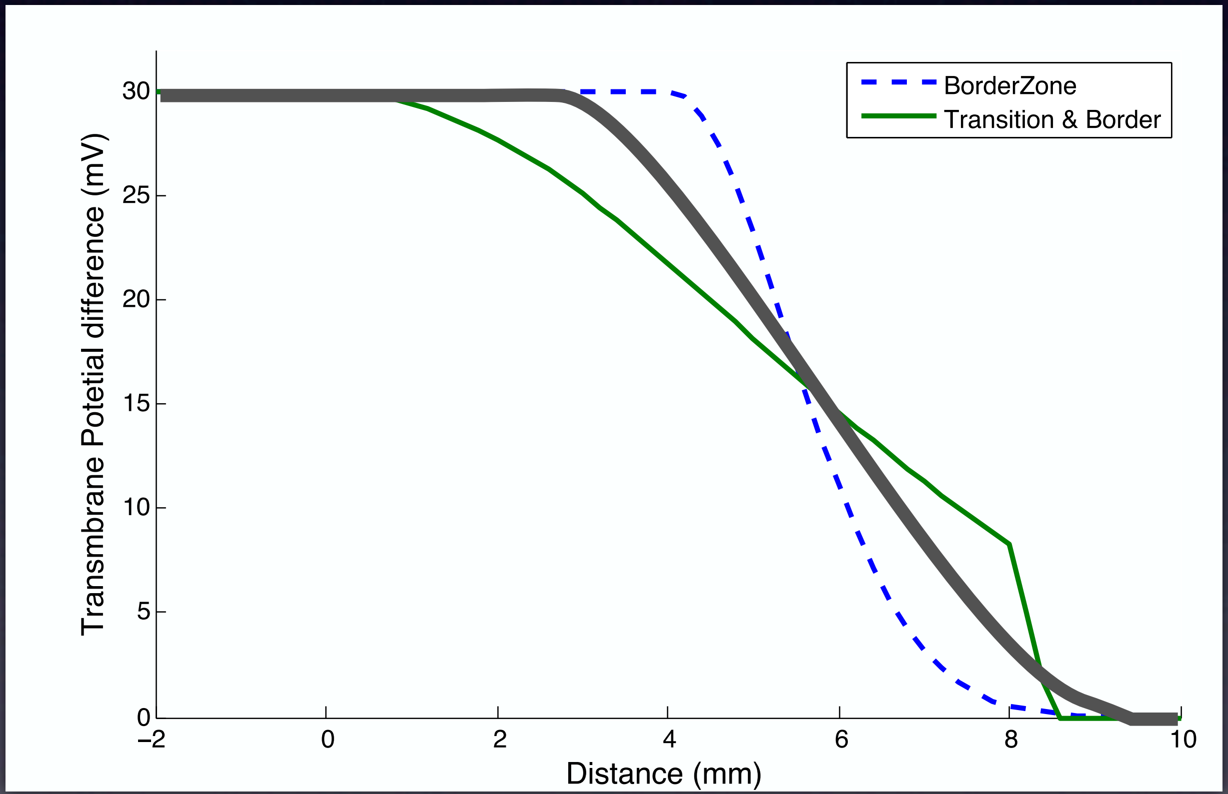

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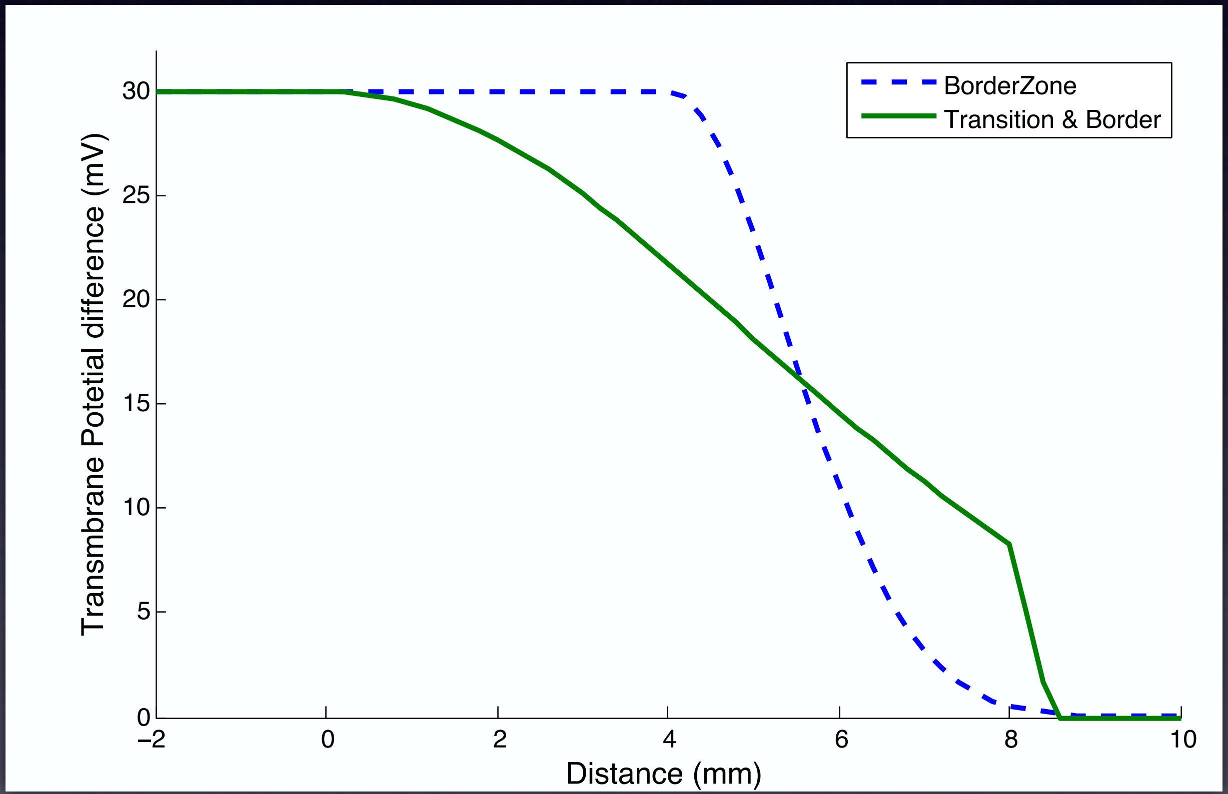
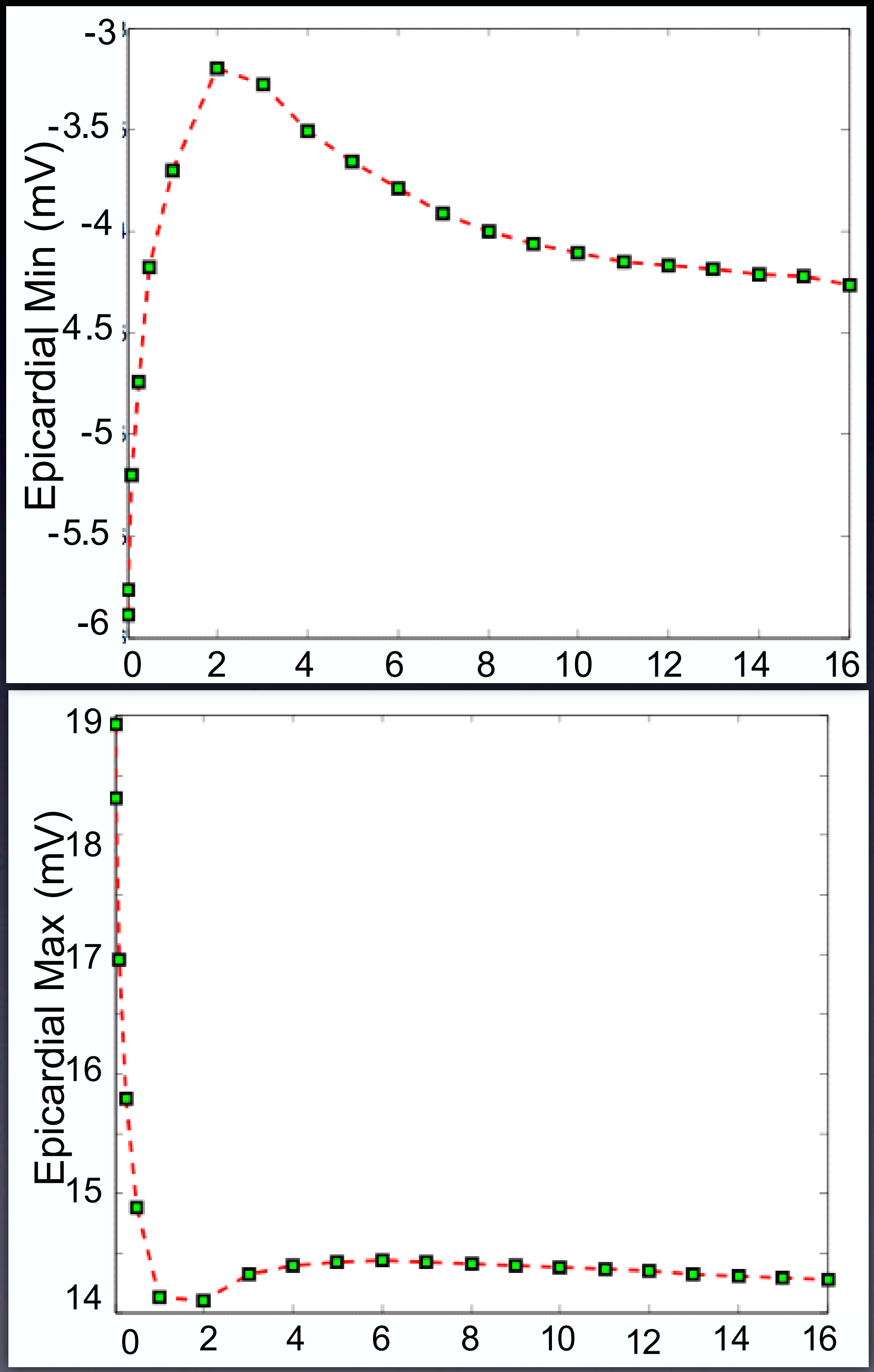


Border Zone Sensitivity

- Adjusted the variance of the Gaussian distribution
- Highly sensitive for border zones less then a variance of 2 ~ 3mm
- Sharper transitions produced more localized depressions



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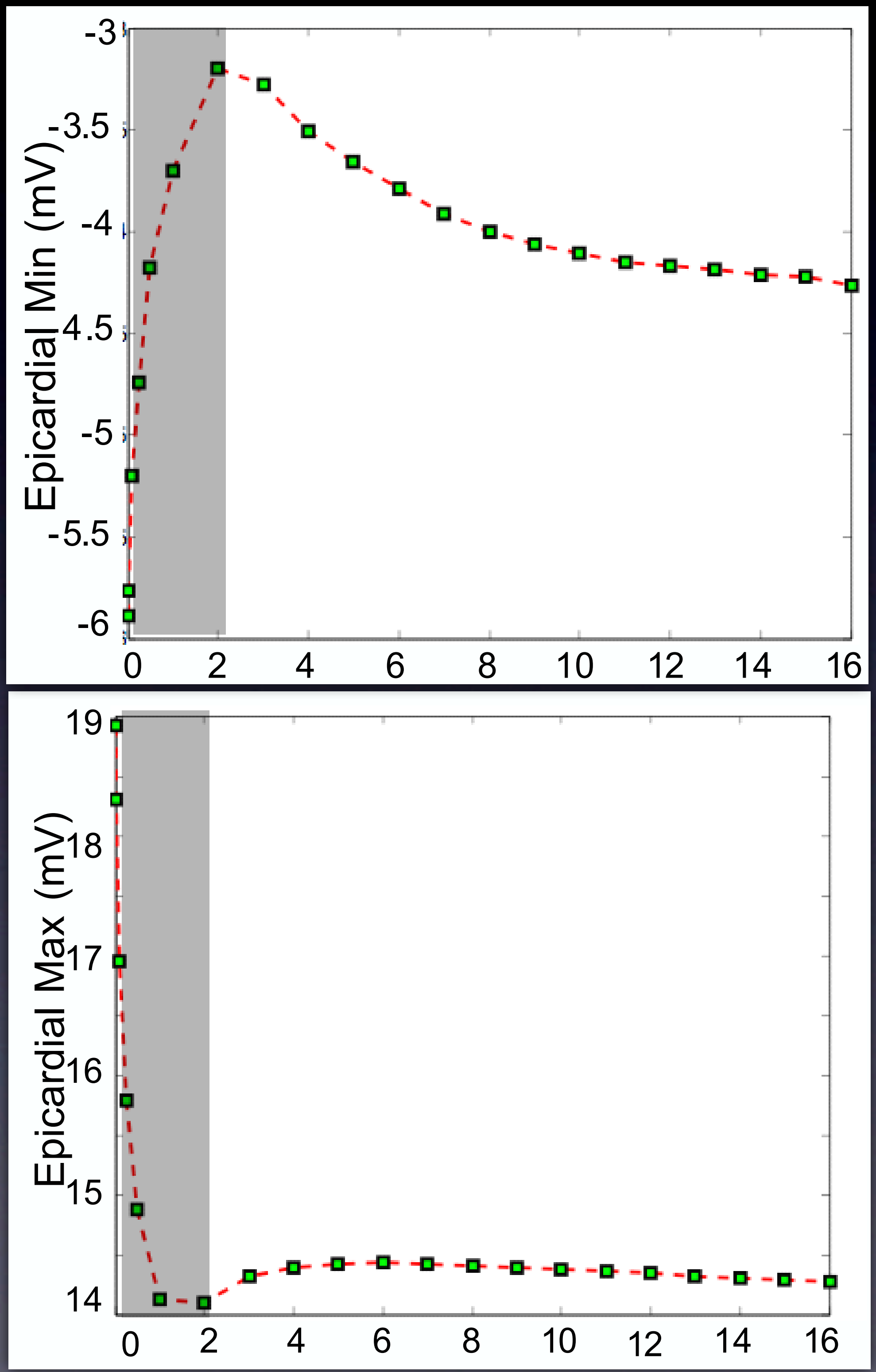
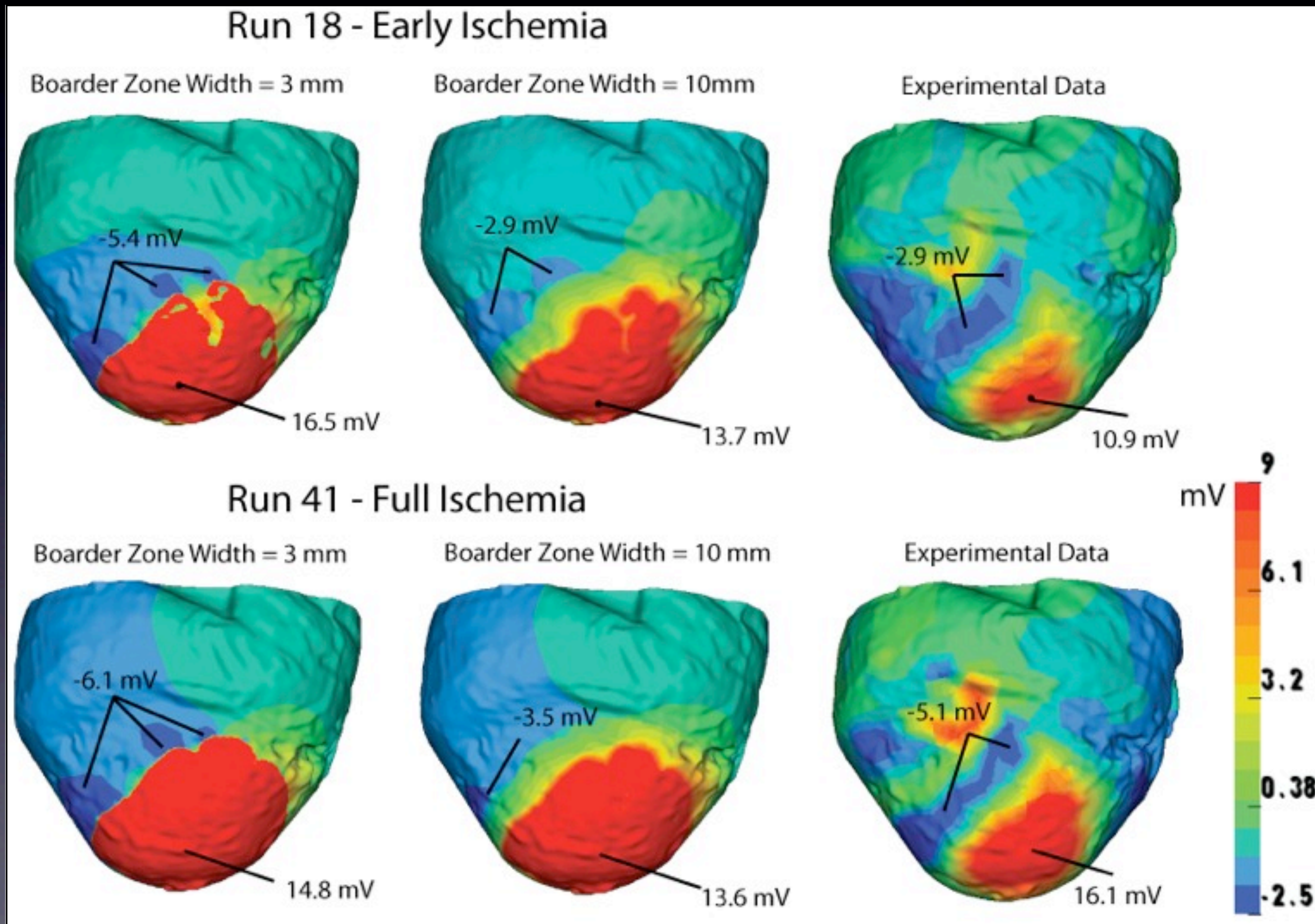


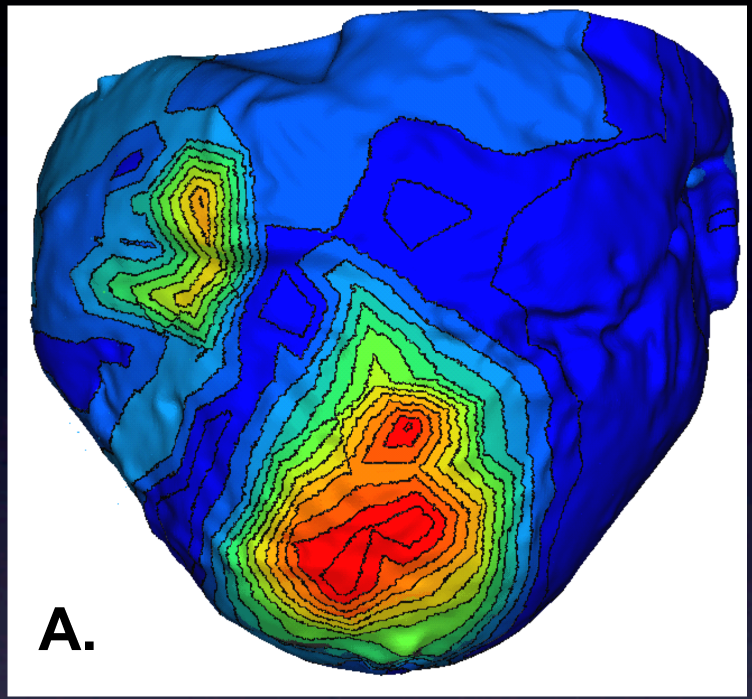
Border Zone Sensitivity



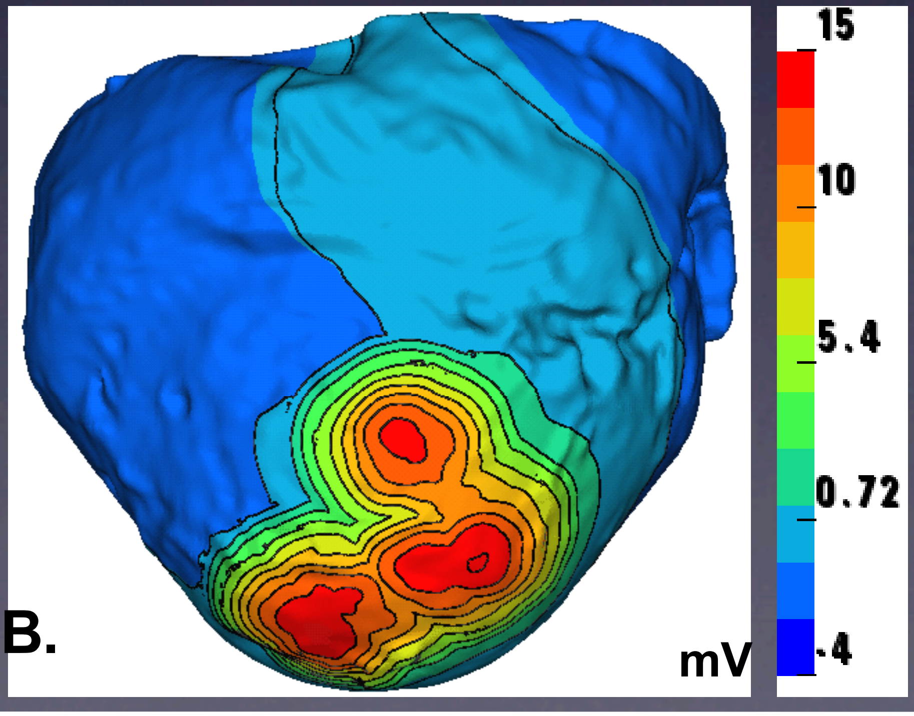
Gradient Magnitude

- Unable to match the field gradients using the traditional model of a border zone
- Absence of a distinct ischemic border in the needle data
- The transition region created field gradient and magnitudes similar to those in the recorded data

Recorded



Simulated



Conclusions

- Border zone profile plays a significant role in the epicardial potentials distribution
- The border zone requires complex modeling
- Improved geometric representations of the border zone, adding a transition region, improves the simulation results

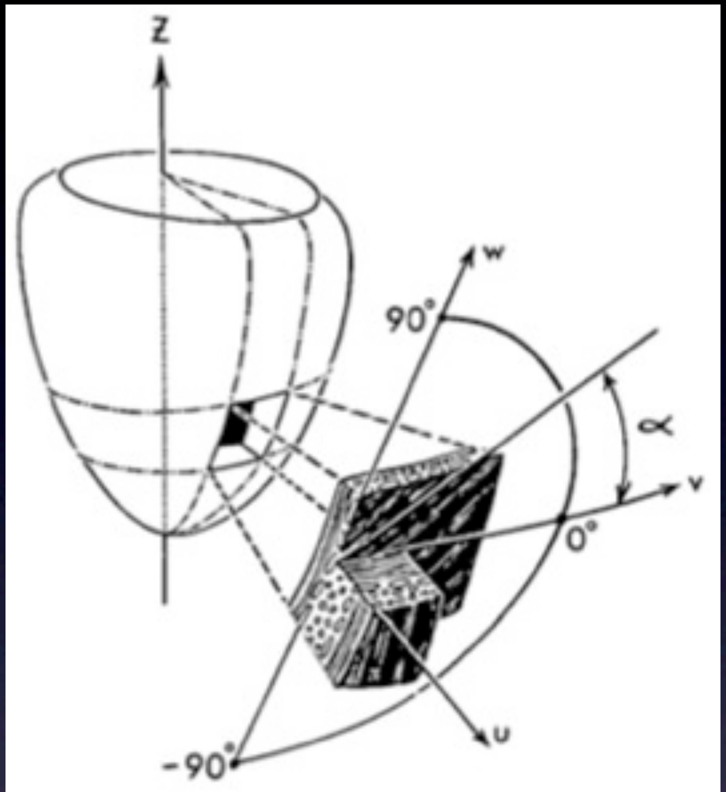
Future Work

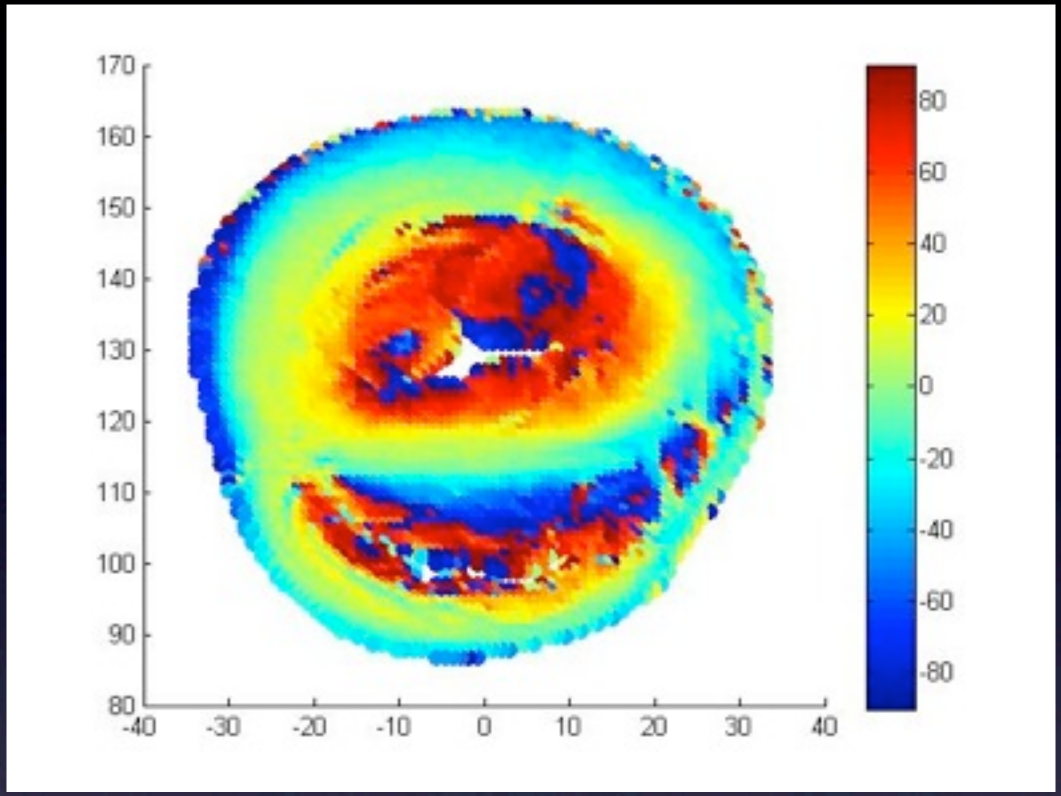
- Use transmural needles to quantify border zone profile
- Extend model to multiple species, including the role of fiber structure
- Improve registration techniques

Specific Aim 2

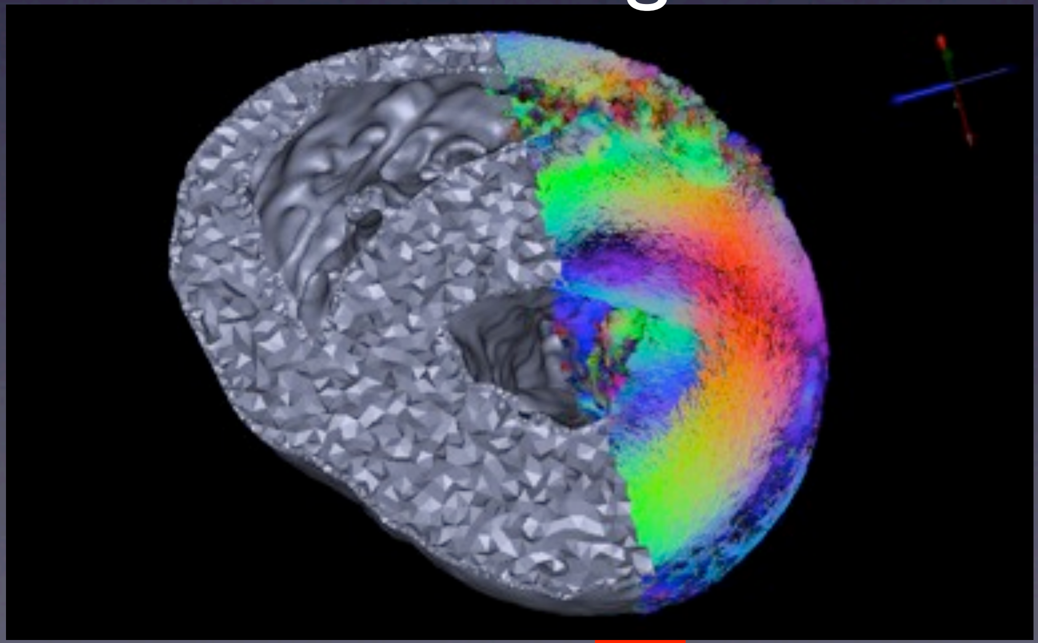
2. Identify the sensitivity of computational models of ischemia to variations in myocardial fiber orientation as they occur between systole and diastole, as well as from subject to subject.

DTI Mapped Fibers





Helical Angle

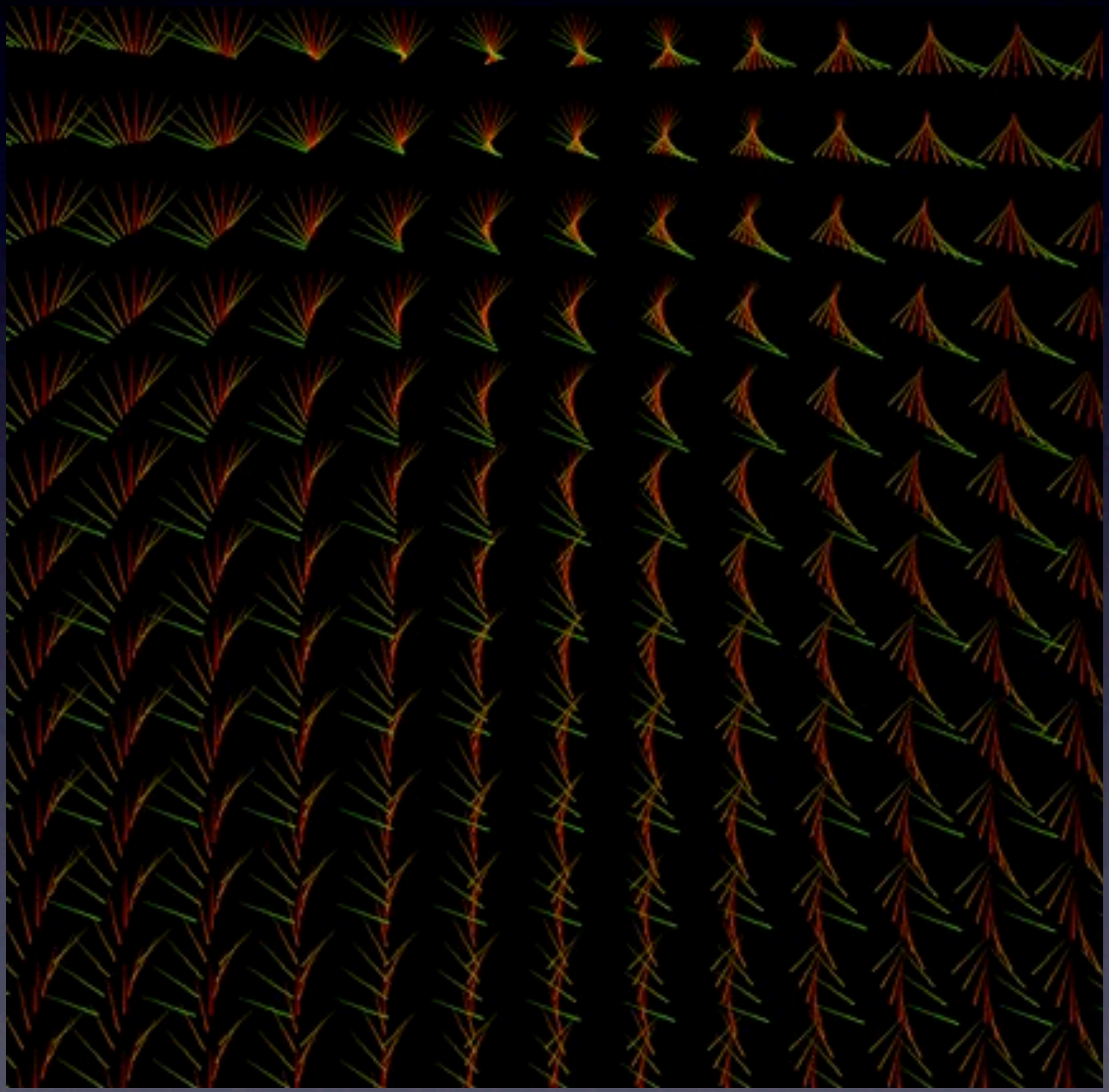


Fiber Sensitivity

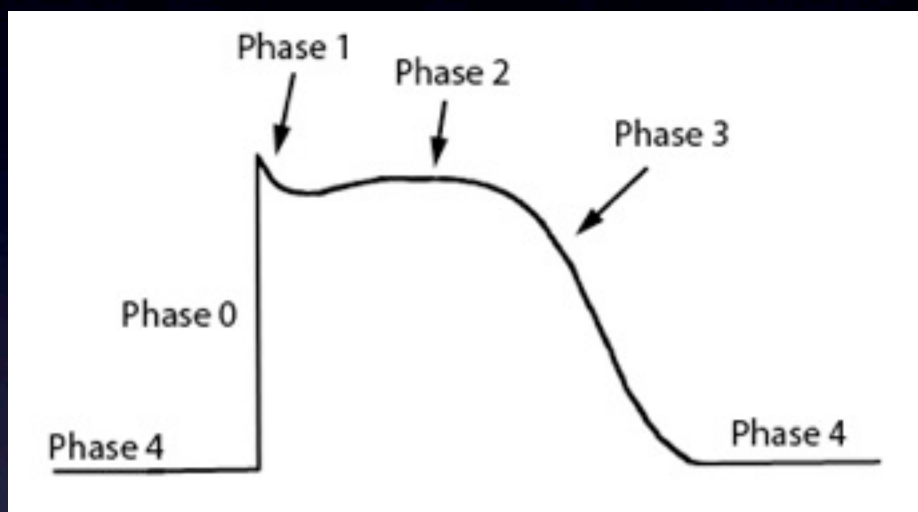
Helical angles from literature

Vary the helical angle

- Ischemia model from Aim 1
- Propagation model of ischemia

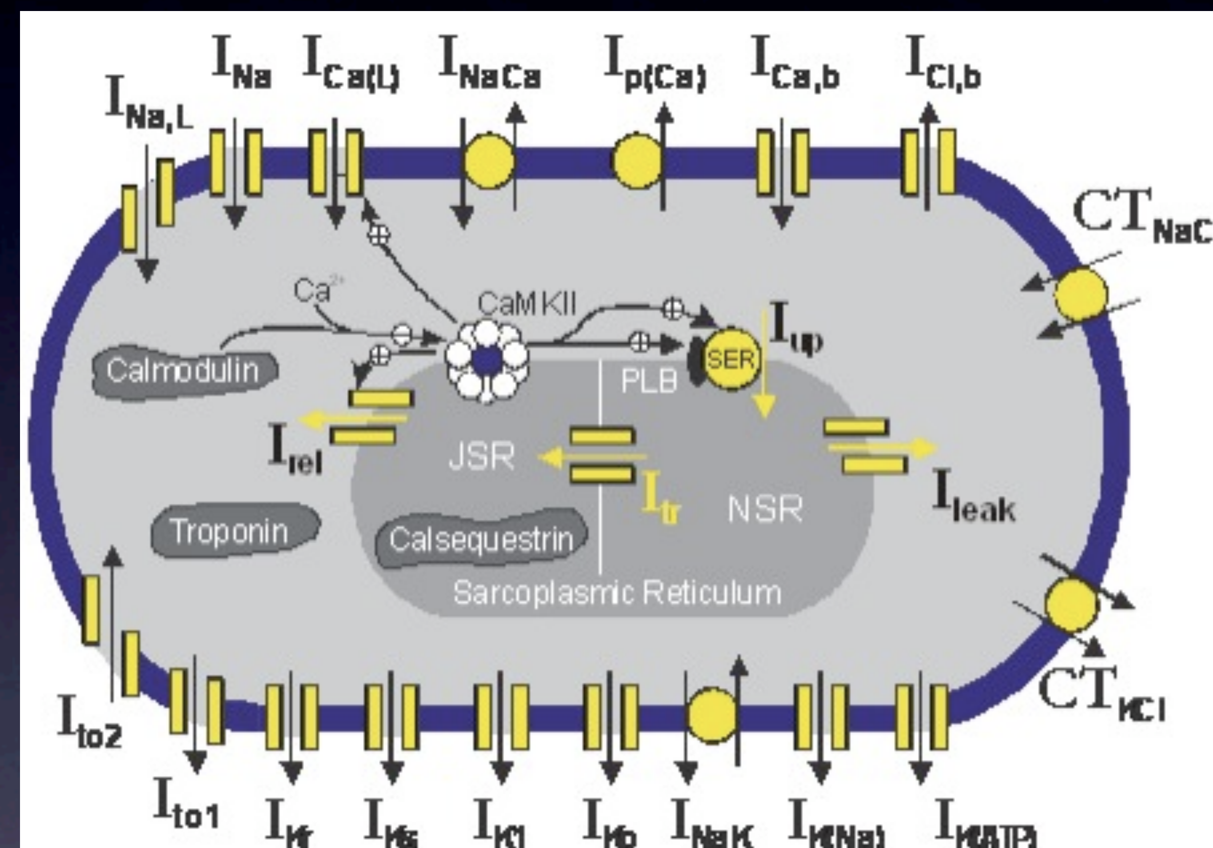


Membrane Currents



$$\nabla \cdot M_e \nabla \Phi_e = -I_m$$

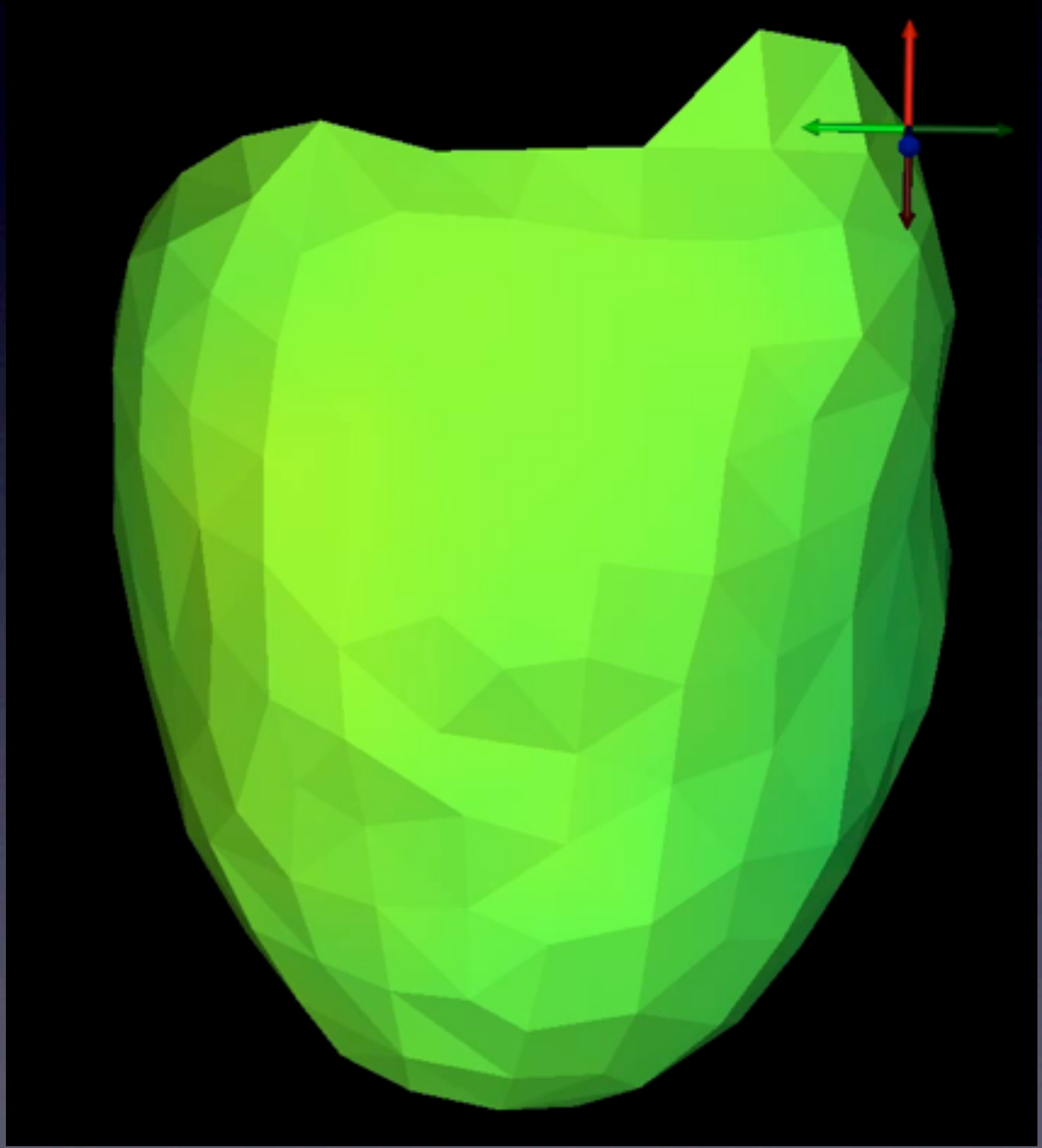
$$\nabla \cdot M_i \nabla \Phi_i = I_m$$

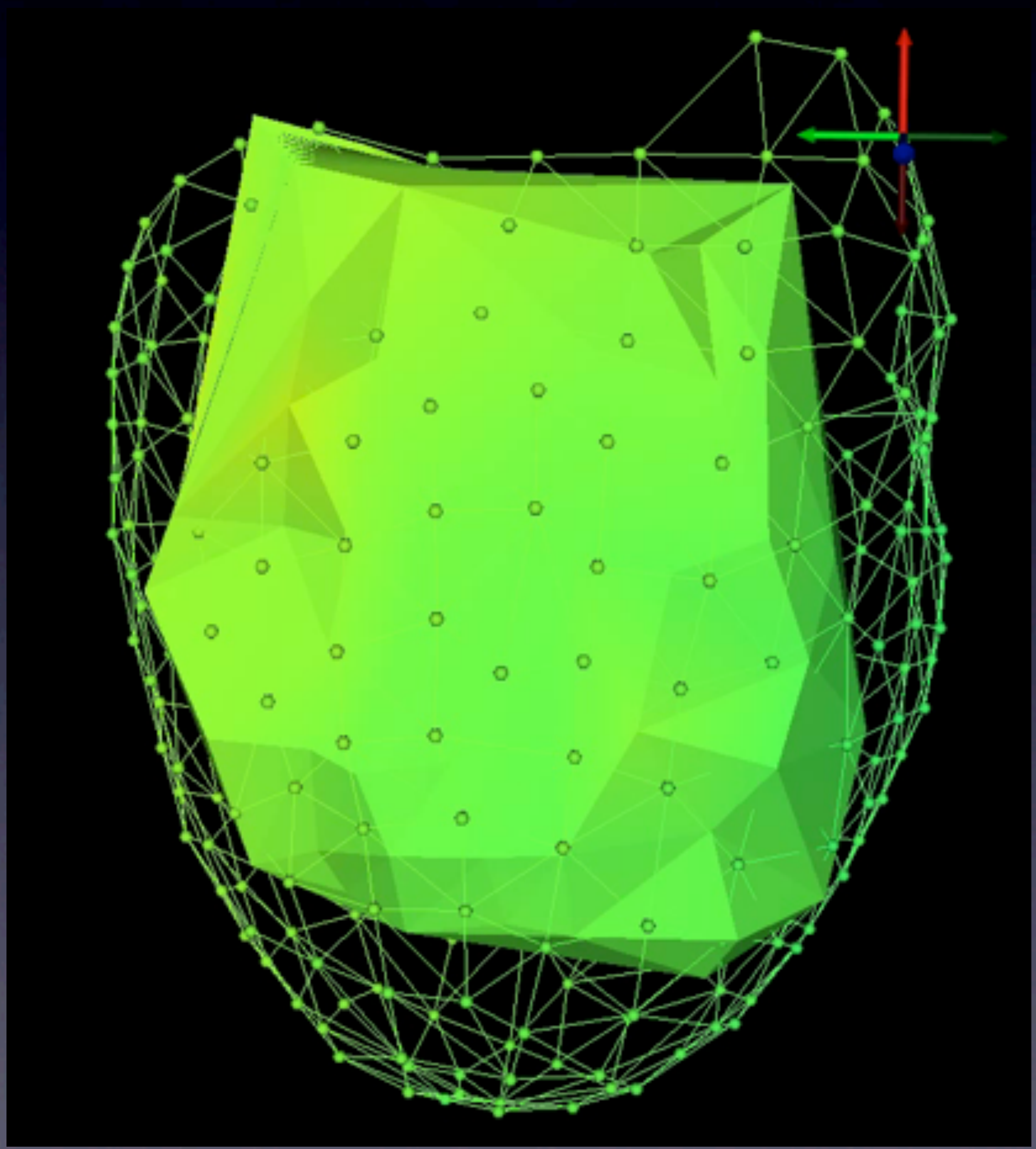


Hund-Rudy dynamic model

Model of Activation

Model of Activation





Validation

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i^{sim} - V_i^{m})^2}$$

$$CC = \frac{\sum_{i=1}^{n}(V_i^{sim} - \bar{V}_i^{sim})(V_i^{m} - \bar{V}_i^{m})}{\sqrt{\sum_{i=1}^{n}(V_i^{sim} - \bar{V}_i^{sim})^2}\sqrt{\sum_{i=1}^{n}(V_i^{m} - \bar{V}_i^{m})^2}}$$

$$MaxGradRE = MAX\left(\frac{\nabla V_i^{sim} - \nabla V_i^{m}}{\nabla V_i^{m}}\right)$$

Conclusions

Can we use heart atlases?

Do we need full tensor fields or just a subset?

What is the error assosiated with these inaccuracies?

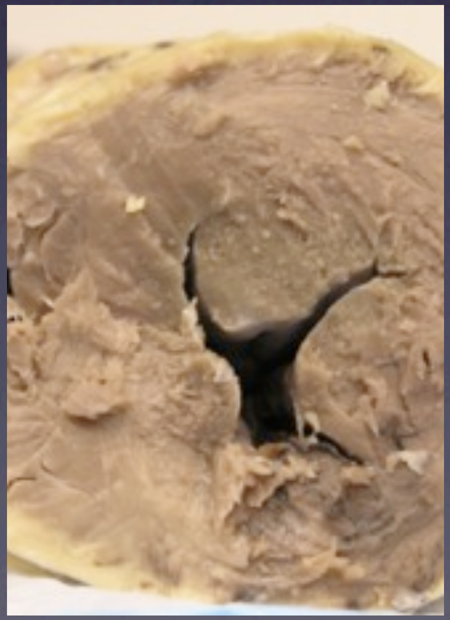
Specific Aim 3

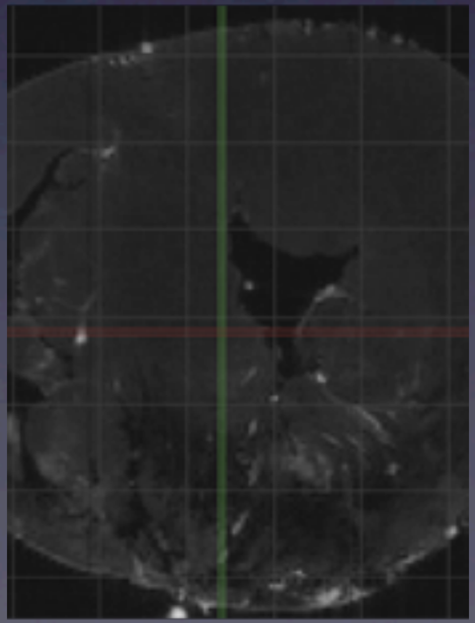
3. Based on the results from the first two specific aims, investigate approaches to model simplification that maintain suitable accuracy while reducing computational cost.

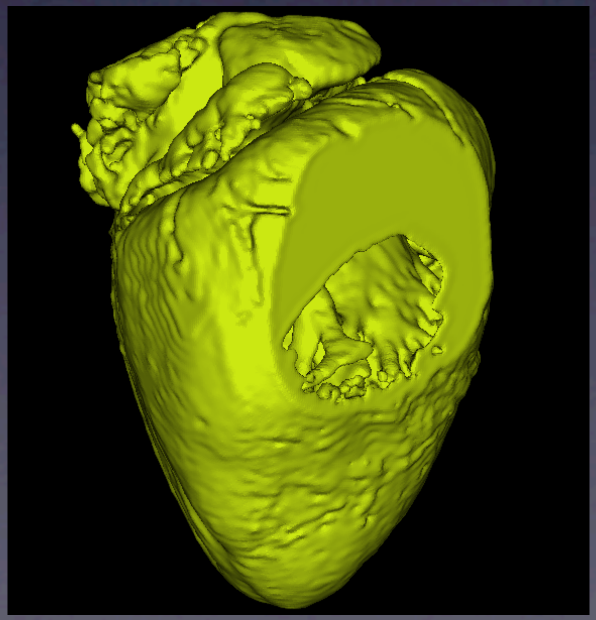
Two methods of simplification

Geometric simplification

- Which structures are important







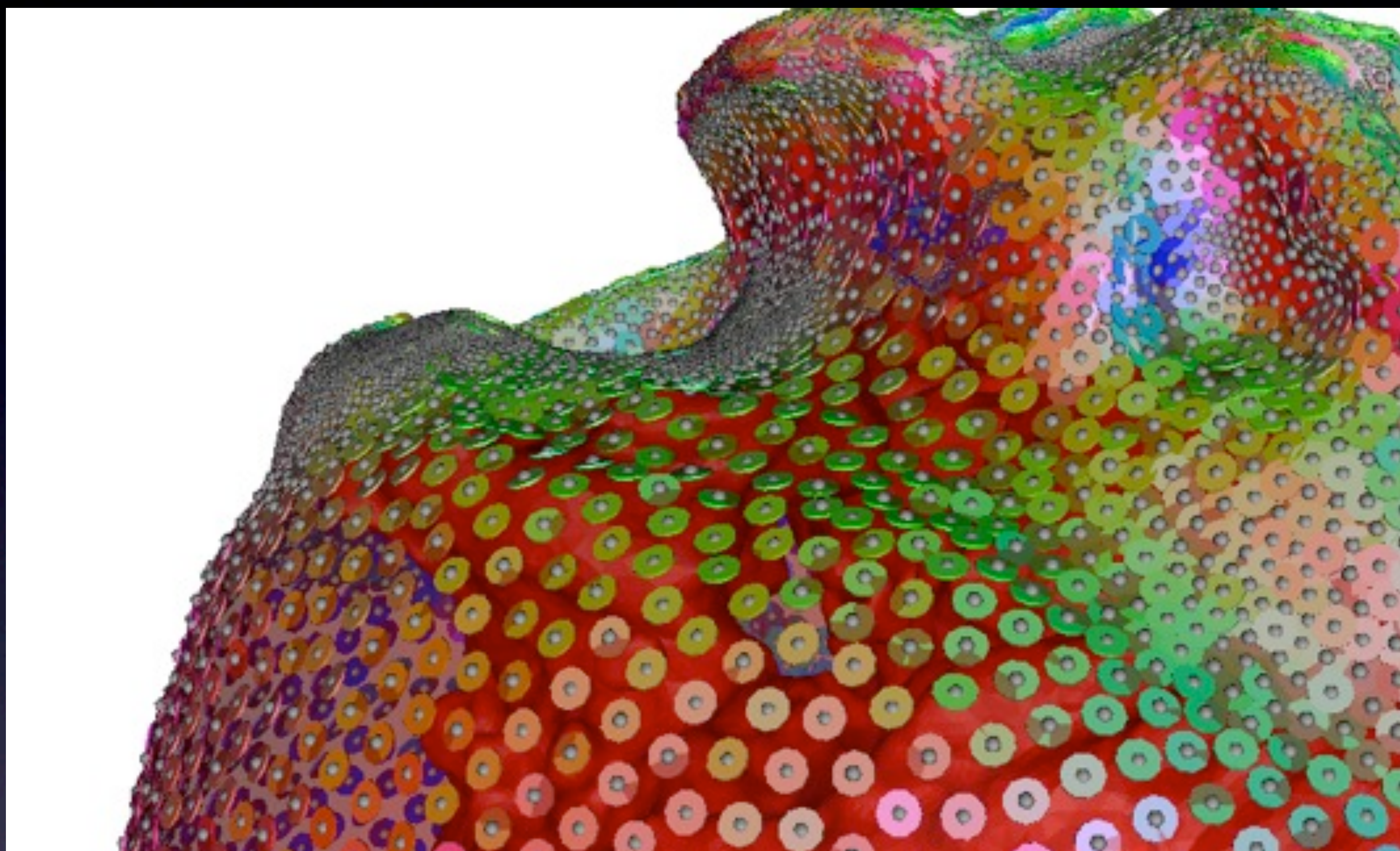
Two methods of simplification

Geometric simplification

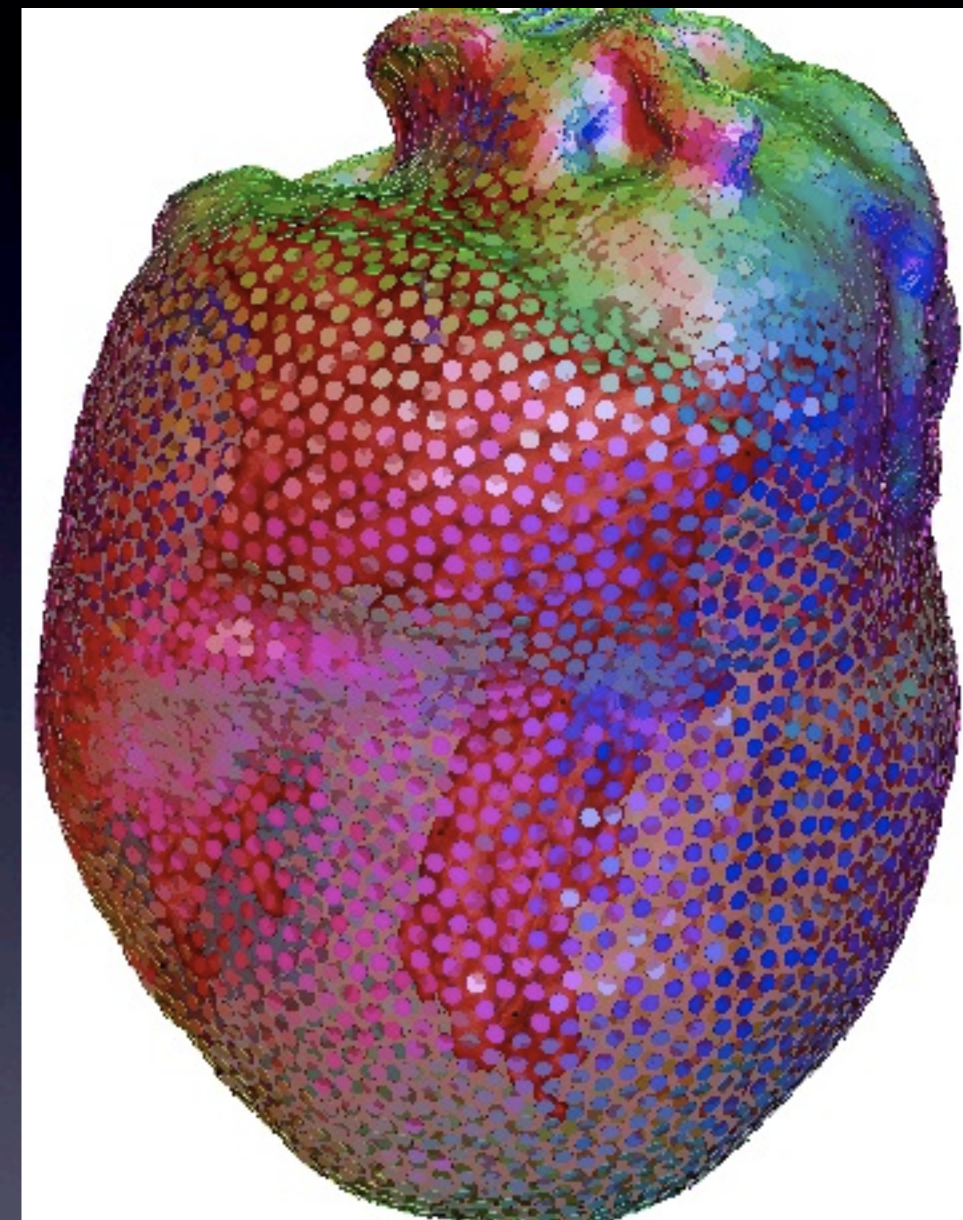
- Which structures are important

Mesh size reduction

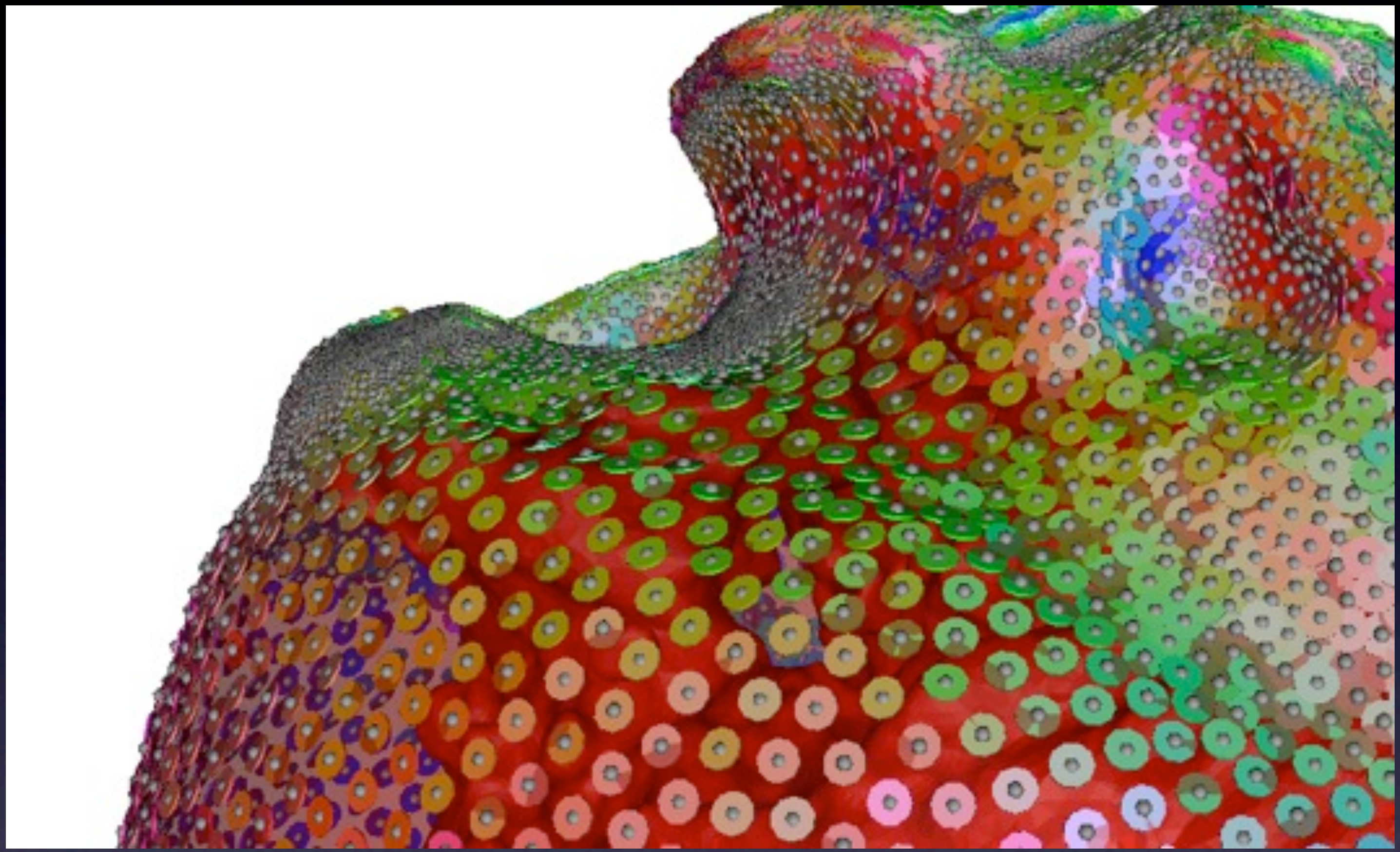
Particle System



Sizing field based on
Medial Axis



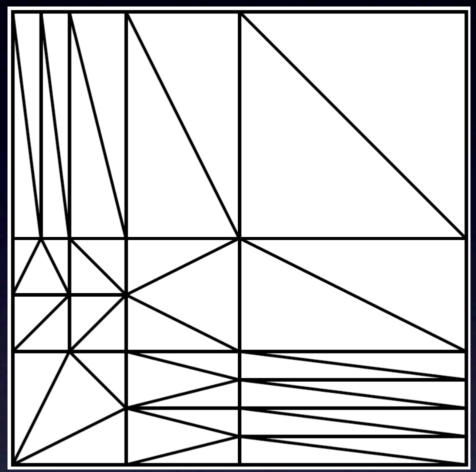
Particle System



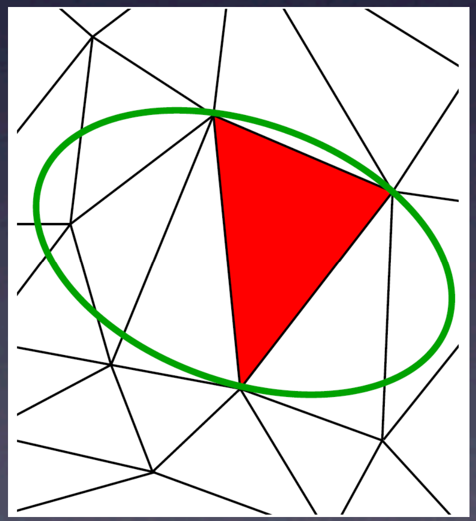
Sizing field based on fiber anisotropy

Anisotropic Meshes Complications

Quadtree-based methods- No diagonal stretching



Delaunay triangulations lose optimality properties. No "empty circumellipse"



François Labelle and Jonathan Richard Shewchuk
University of California at Berkeley

Possible Solutions

- Anisotropic Voronoi Diagrams - Distance field calculations
- Morph then Delaunay and then invert
- Non-Delaunay meshing
- Mixed element type meshing

Summary

Ultimate goal: Bring patient specific models (engineering solutions) into a clinical setting.

- Computational resources are available
- Physiology is making great progress
- The need exists
- Technology exists

Pres. William McKinley

Shot a few yards from an x-ray machine (American Exposition in Buffalo, NY)

Doctors could not locate the bullet

Did not occur to them to utilizes available engineering resources

Thanks!