Whole Heart Computational Modeling

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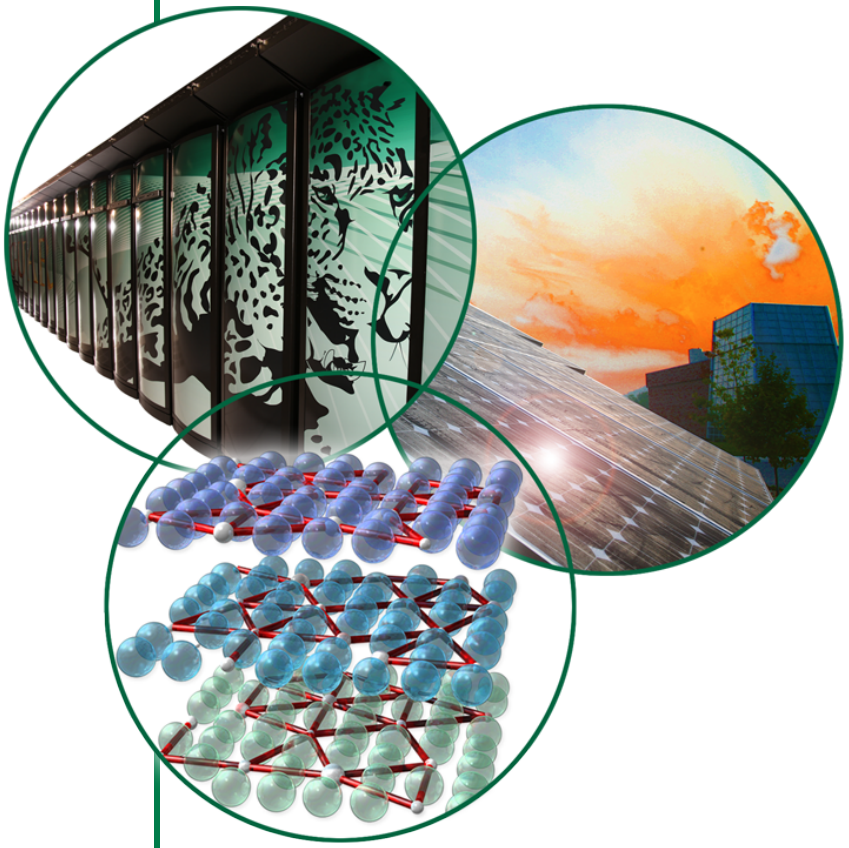

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Overview

- About *Continuity*
- Objectives
- Continuity models
- Model modifications
- Computing results
- Electrophysiology results
- Biomechanics results
- Conclusion
- Acknowledgments

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What is *Continuity*?

- Heart specific finite element modeling
- Developed by UCSD biomedical research team in effort solve common cardiac problems
- Models heart subsystems in three interconnected loops
  - Cellular (inner loop)
  - Electrophysiology (middle loop)
  - Biomechanics (outer loop)

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About *Continuity* models

- Cellular models
  - Foundations for Biomechanics (BM) and Electrophysiology (EP) models
  - Parameters embedded in BM and EP model editors
- Biomechanical Models
  - Solves and renders heart stress and strain data
- Electrophysiological Models
  - Renders paths of electrical current
  - Dependent on conductivity properties

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Objectives

- Understand *Continuity's* code
- Examine the inner loop (cellular) mechanisms
- Make modifications to all loops
- Observe, analyze, and report outcomes
- Simulate various heart anomalies (ischemia, arythmia)
- Port *Continuity* code to ORNL institutional clusters

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Electrophysiology model modifications

- Fitz-Hugh Nagumo model
  - Stimulus time
  - Transmembrane potential
  - Conductivity tensors
  - Membrane capacitance
- Beeler Reuter Ventricular Myocyte model
  - Stimulus time
  - Transmembrane potential
  - Conductivity tensors
  - Membrane capacitance
  - Sodium potential
  - Calcium concentration

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Biomechanical Model Modifications

- Closed loop left and right ventricular model (Circulatory)
  - Ventricular pressure
  - Mitral and tricuspid valve resistance
  - Arterial impedance
- Guccione (Cellular)
  - Intracellular calcium concentration
  - Sarcomere properties

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Computing Comparisons

Macintosh workstation (Serial: 1 Processor)

- Memory: 4GB RAM
- Processor speed: 2.0GHz
- EP calculations time: 4.79 minutes
- Biomechanics calculations time: 1.3 minutes
- RAM usage (basic): 1.15GB
- RAM usage (advanced): 2.6GB
- CPU usage (basic): 50%
- CPU usage (advanced): 60%

Macintosh workstation (Parallel: 2 Processors)

- Memory: 4GB RAM
- Processor speed: 2.0GHz
- EP calculations time: 3.02 minutes
- Biomechanics calculations time: 2.78 seconds
- RAM usage (basic): 100MB
- RAM usage (advanced): Est. 500MB
- CPU usage (basic): 86%
- CPU usage (advanced): 100%

ORNL Institutional Clusters

- Memory: 16GB RAM
- Processor speed: 3.0GHz
- EP calculations time: Serial: 30 s parallel: est t < 10 s
- Biomechanics calculations time: Est. 1.39 seconds
- RAM usage (basic): Est. 500MB
- RAM usage (advanced): Est. 1GB
- CPU usage (basic): Est. 60%
- CPU usage (advanced): Est. 80%

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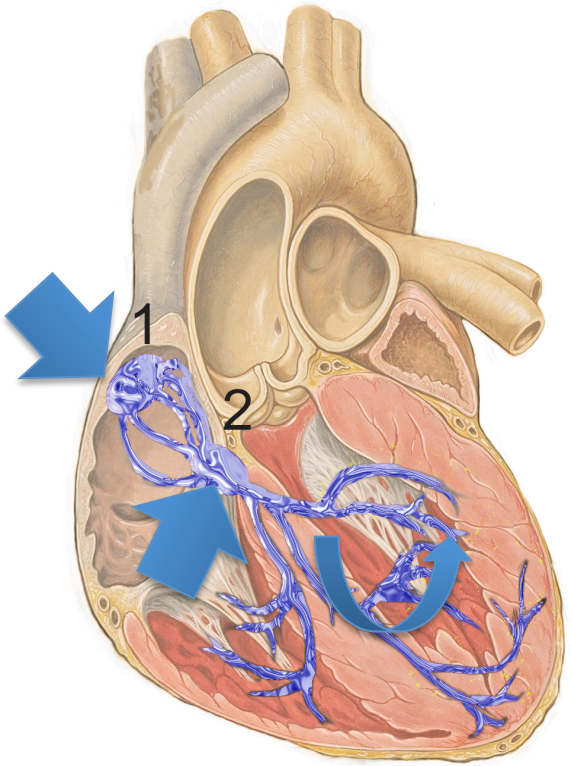
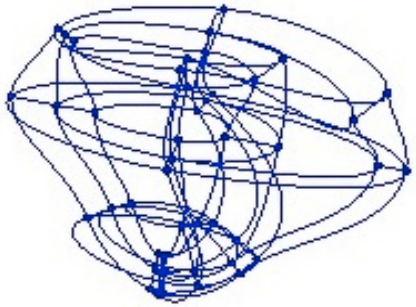
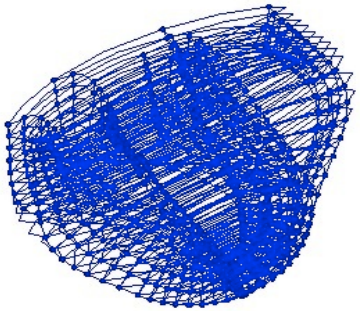
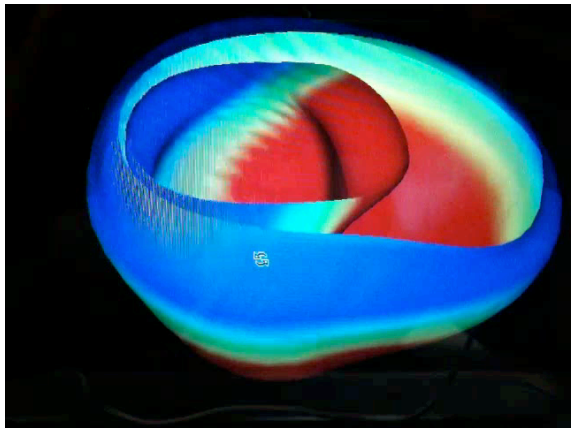
Continuity rendering analysis/results

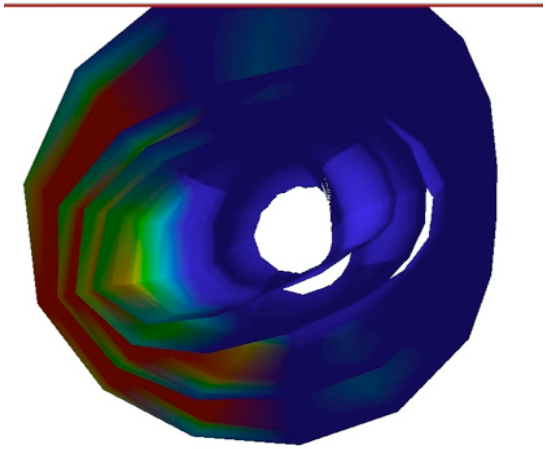
Meshing orientation examples (EP)











EP and mesh rendered data on
Continuity 6

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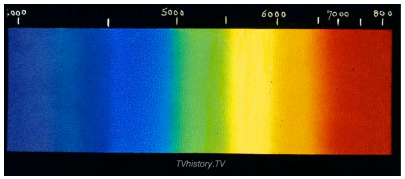
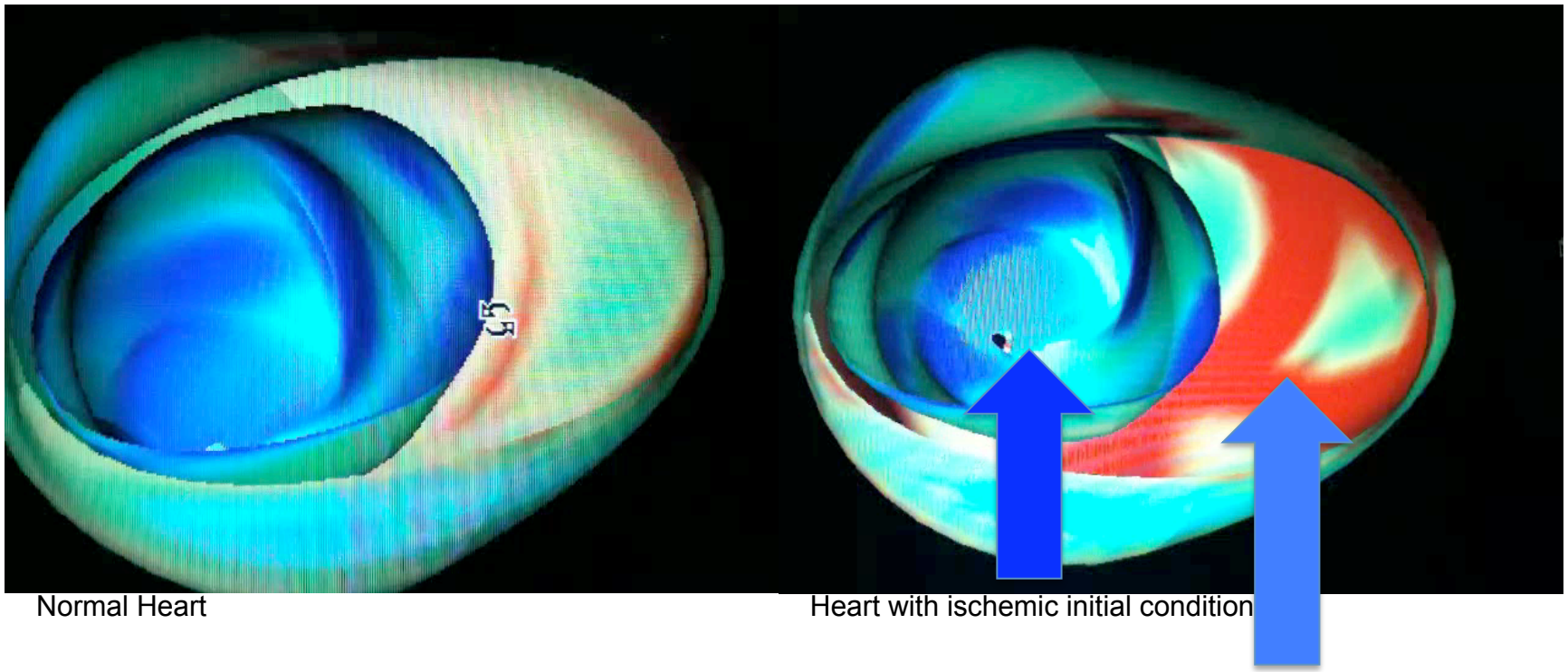
Biomechanics Results

- Arterial impedance = low initial ventricular pressure, ischemic conditions
- More deformation in the right ventricle (blood transfer to lungs)
- More deformation in left ventricle (blood transfer to body)



Low stress High stress



Normal Heart

Heart with ischemic initial condition

Data rendered on USCD *Continuity 6*

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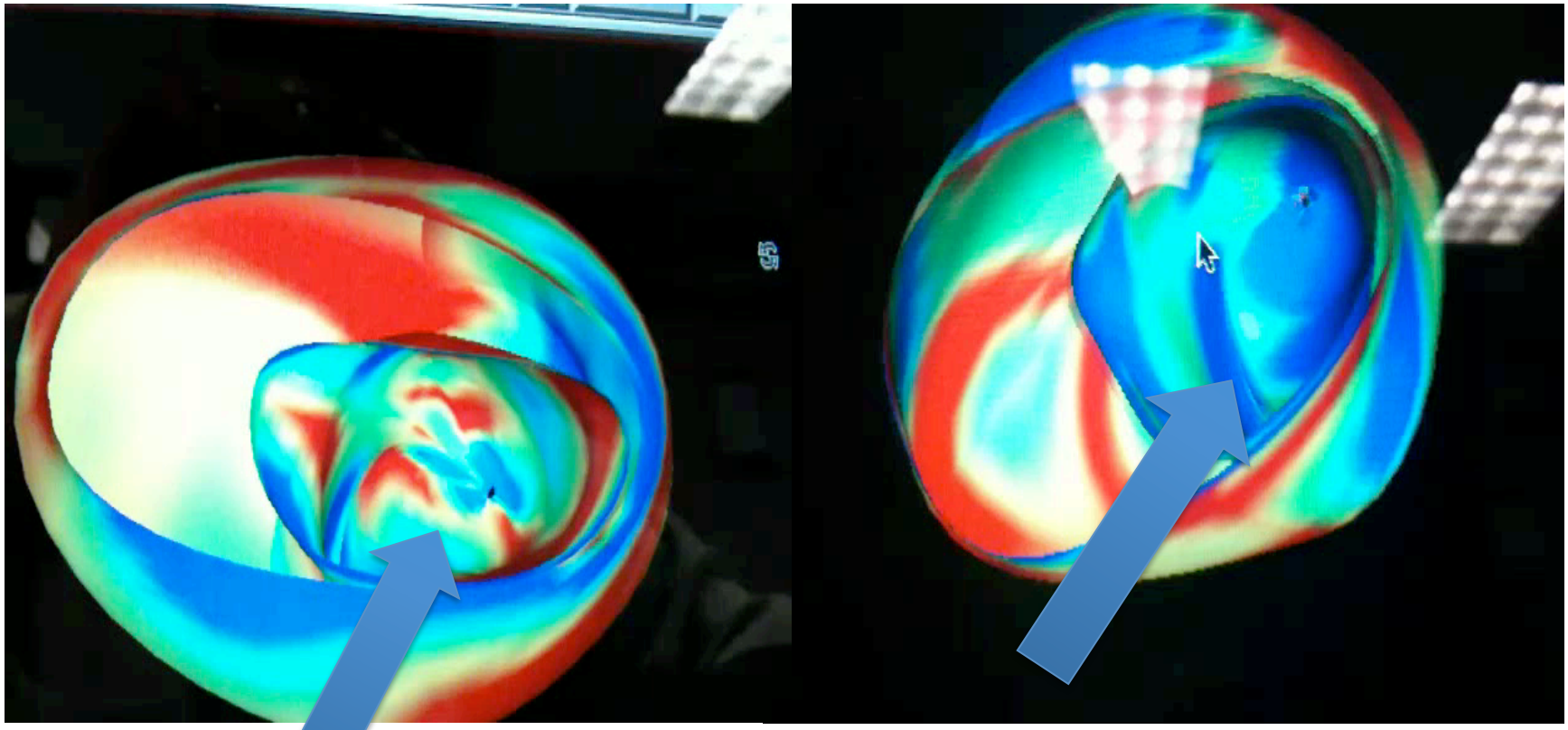
Biomechanics Results

- Sarcomere length (increased length 1.5 to 10.5μm)
- Significant change in left ventricular strain
- Minimal change in right ventricular strain



Normal heart

Heart with 10X sarcomere length

Data rendered on USCD *Continuity 6*

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Biomechanics Results

- Intracellular calcium concentration:
  - High calcium concentration: minimal stress/strain effects
  - Low calcium concentration: minimal stress/strain effects
- Mitral and tricuspid valve resistance
  - High resistance to flow: no stress/strain effects
    - Time dependency problem

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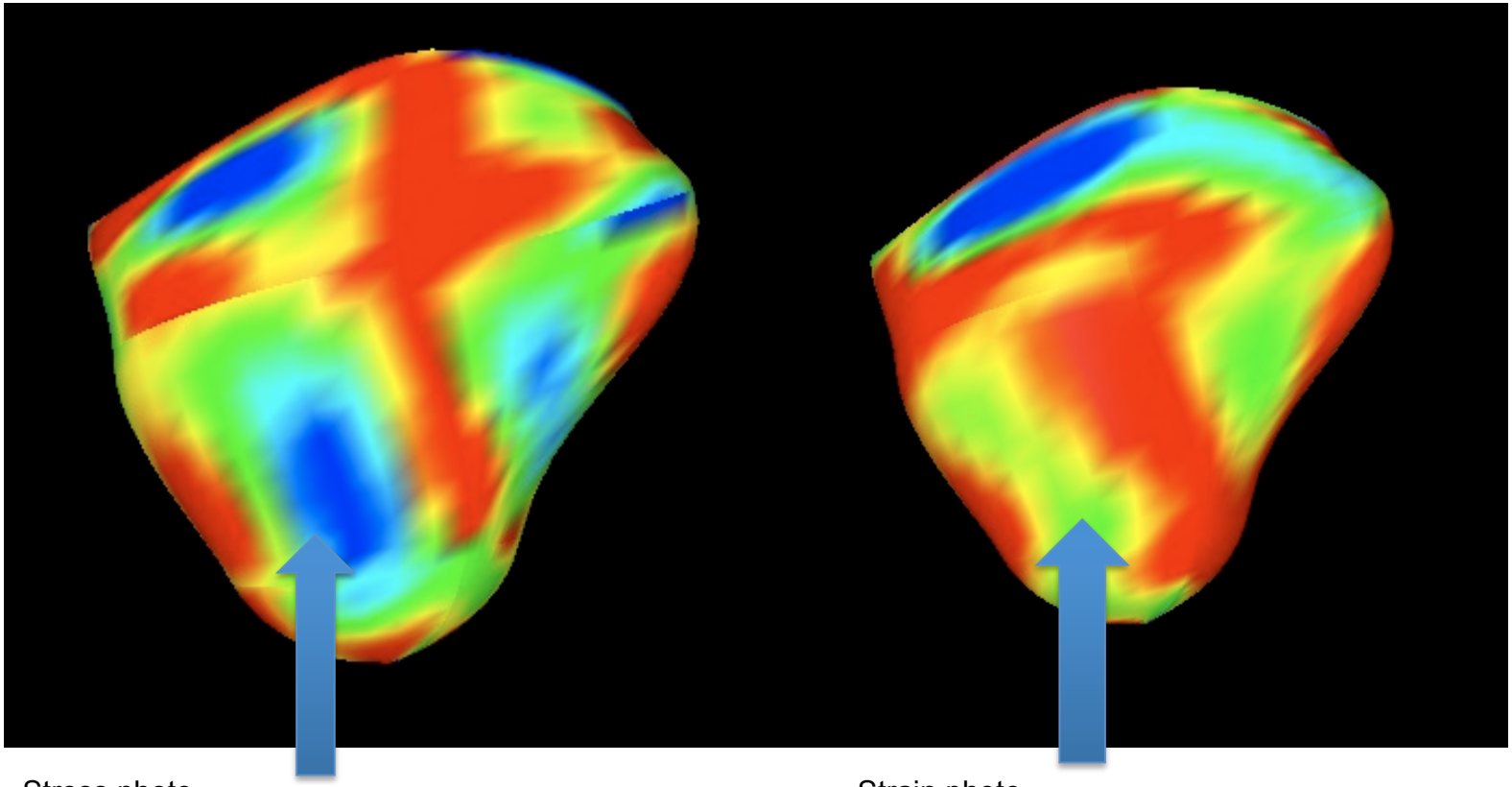
Biomechanics Results Stress/Strain Relations

- Stress has moderate relationship with strain
- Indicator of fiber elasticity and strength



Stress photo

Strain photo

Data rendered on USCD *Continuity 6*

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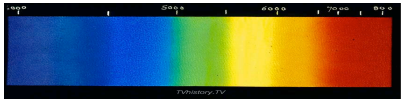
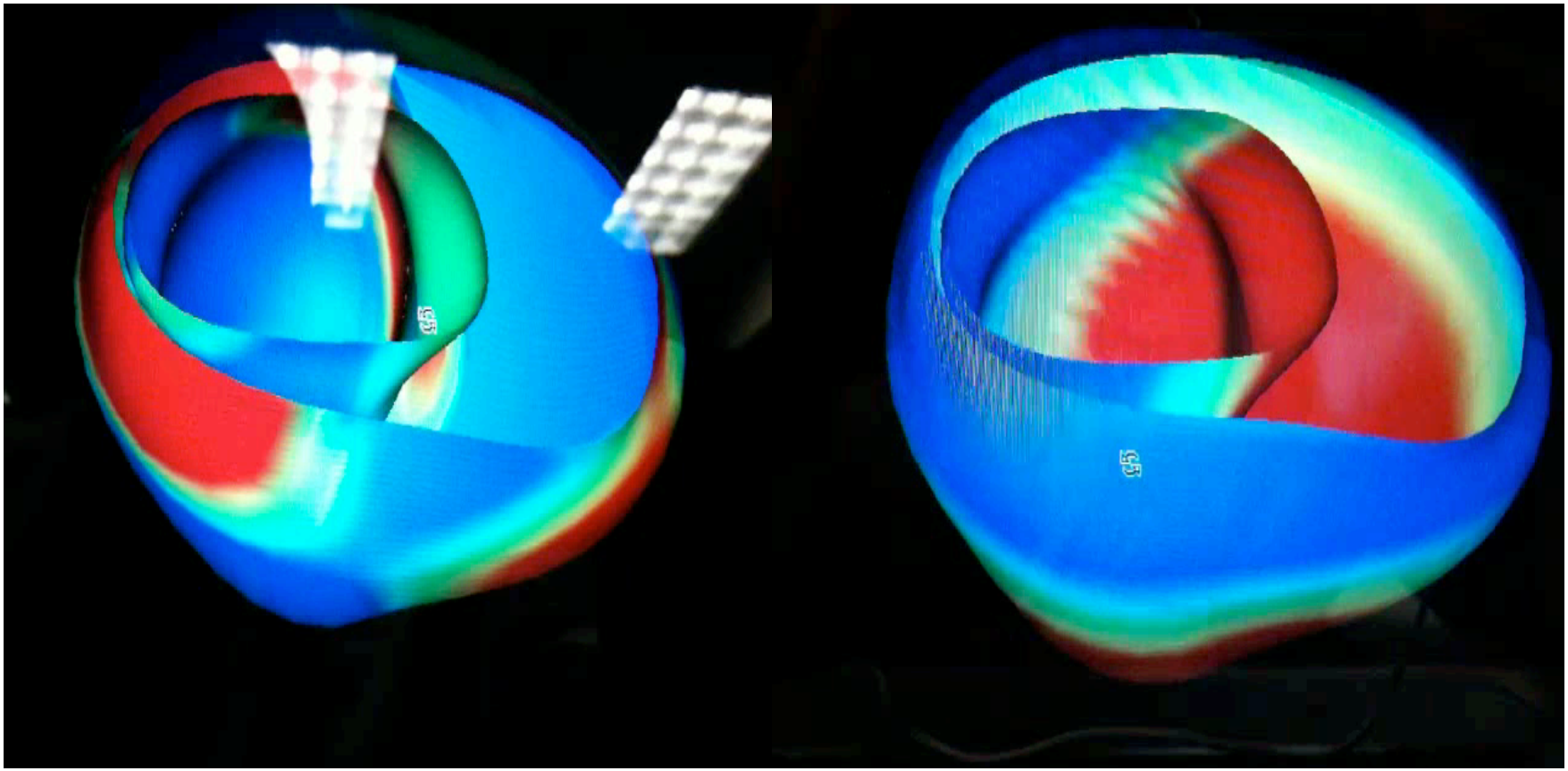
Electrophysiology Results

stimulus time affects rendering of stimulus paths

Low Current  High Current



Time Step from 1ms to 3ms

Time Step 0ms to 220ms

Data rendered on USCD *Continuity 6*

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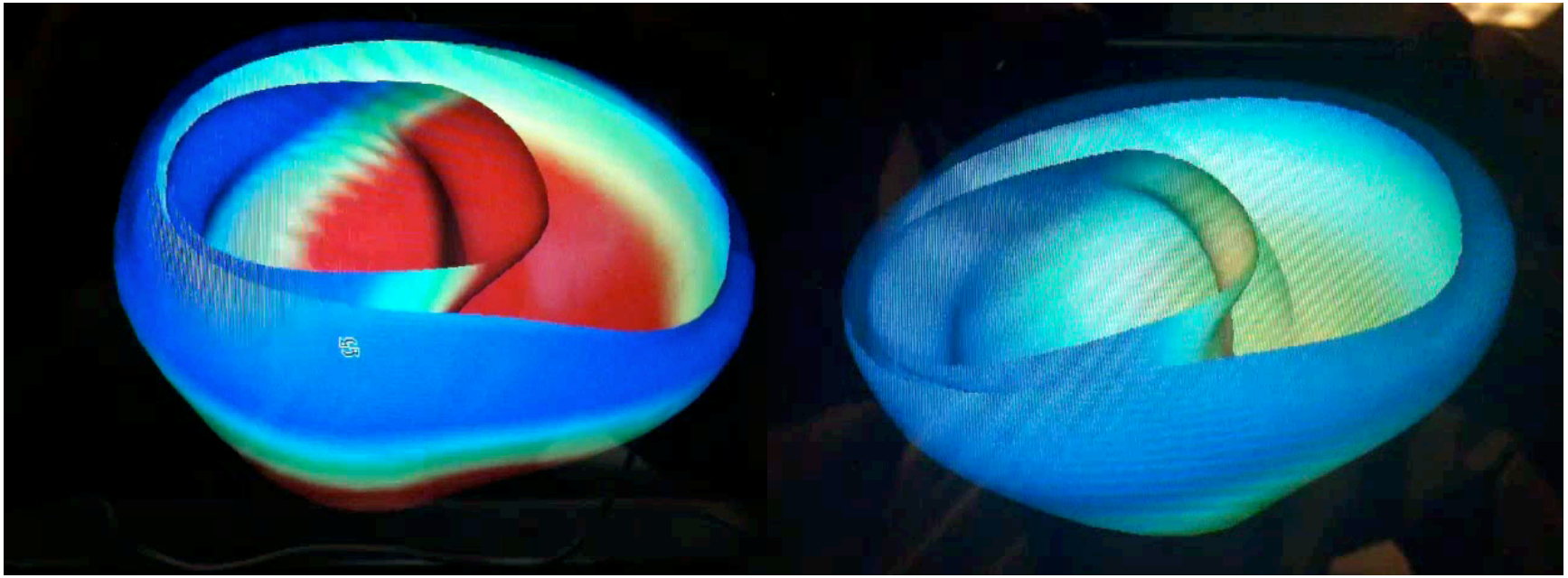
Electrophysiology Results

Large changes in conductivity tensors affect flow of stimulus current



Data rendered on USCD *Continuity 6*

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Electrophysiology Results

- Transmembrane potential: + or – significantly changes path of stimulus current
- Membrane capacitance
  - ⬆capacitance = stimulus path narrows, current intensity varies
- Beeler Reuter model
  - Instability in specific heart meshes
  - 50% solution rendered before memory error
  - Problem Solution = Finer mesh
  - Requires = OIC

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Conclusions

1. Circulation model analysis through *Continuity* biomechanics models is a new approach in analysis of common cardiac problems and their effects.
2. Nodal and elemental orientation, boundary conditions, and constraints of the finite element heart model are very important.
3. Cellular analysis through *Continuity* is useful in the analysis of some of the worlds most common cardiac problems
4. OIC advanced computing abilities will enhance abilities in long term and detailed heart model calculations

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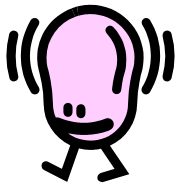
Future Research Objectives



1. Compile and simulate Luo-Rudy cellular Models as well as any other CellML models
2. Build and simulate all models on the OIC
3. Use OIC or larger HPC to simulate the cause of asymmetric redirection of blood flow in humans

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