Incorporation of the Living Heart Model (LHM) into the 4D XCAT Phantom for Cardiac Imaging Research

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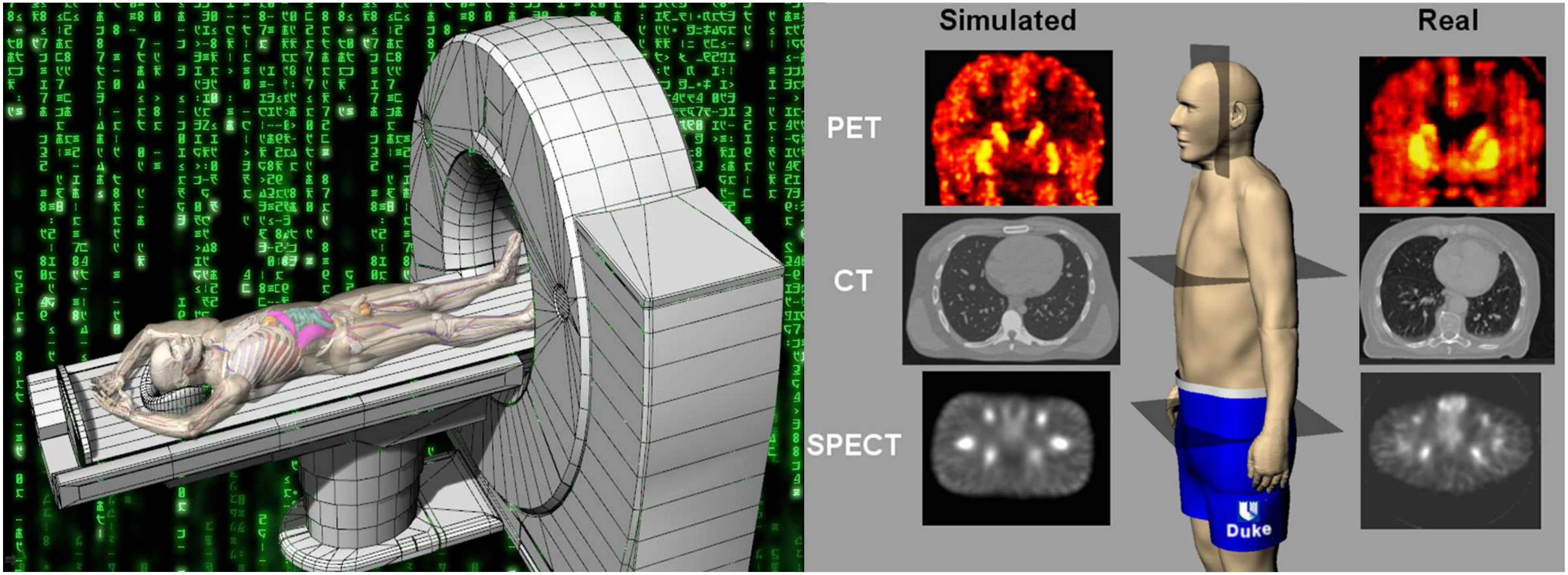
Medical Imaging Simulation



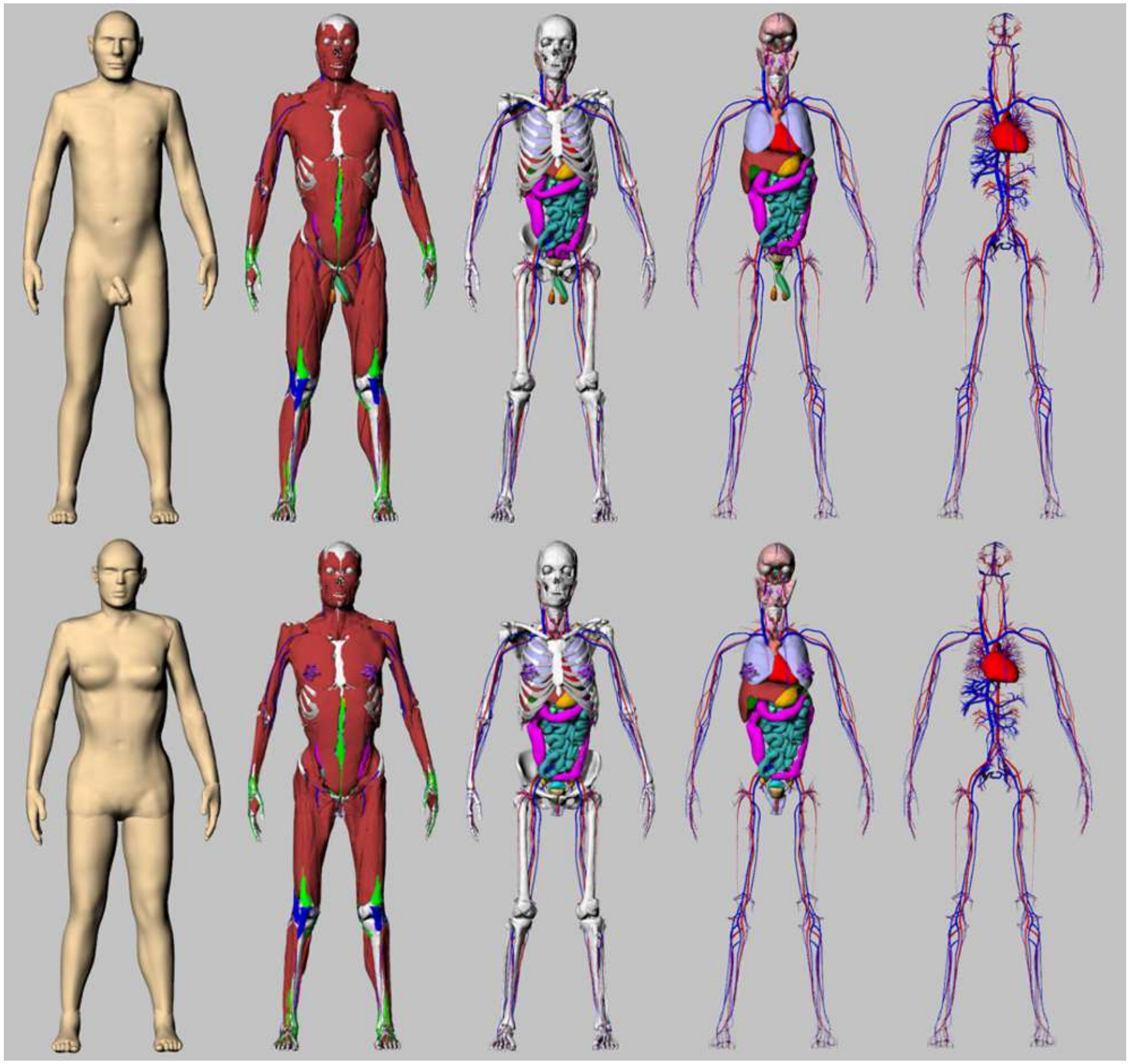
In medical imaging simulation, computational phantoms provide a virtual model of the patient's anatomy and physiology

Imaging data of a phantom can be generated as if it were a live patient using an accurate computerized model of the imaging process (including all the artifacts that affect current devices)

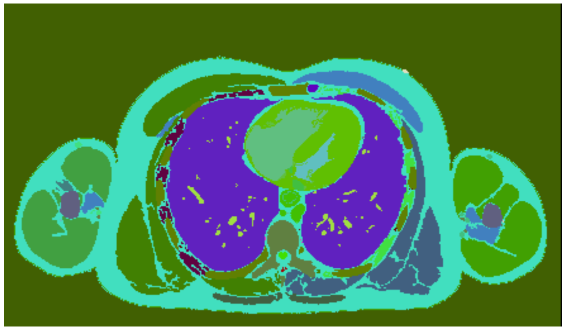
Medical Imaging Simulation

- Advantages:
  - Exact anatomy of the computer phantom is known providing a gold standard to evaluate, improve, and compare devices and techniques
    - Know precisely what the simulated images should reveal (organ volumes or boundaries, tumor locations, sizes, shapes, frequency of motion, etc). All of these things can be masked through artifacts of the imaging process
  - Computer phantoms have the potential to model different anatomies and medical situations providing a large population of subjects from which to perform research
  - No worries about overexposing the phantoms to radiation
    - Can alter the scanning parameters to anything and witness their effect on the resulting images
- Simulation provides a virtual domain to perform studies that would be impossible with human subjects
- In order for results to be valid, however, realistic phantoms are essential

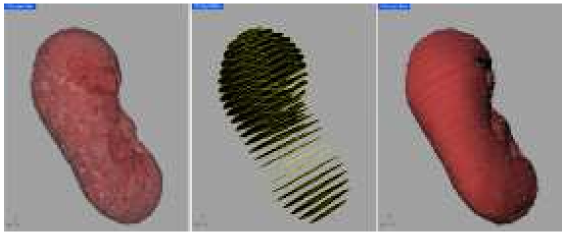
4D eXtended CArdiac-Torso (XCAT) Phantom



Visible Human Data



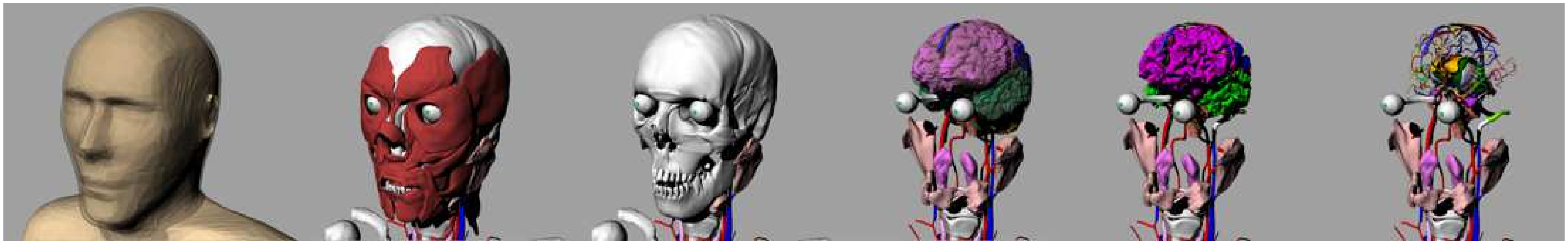
Segmented



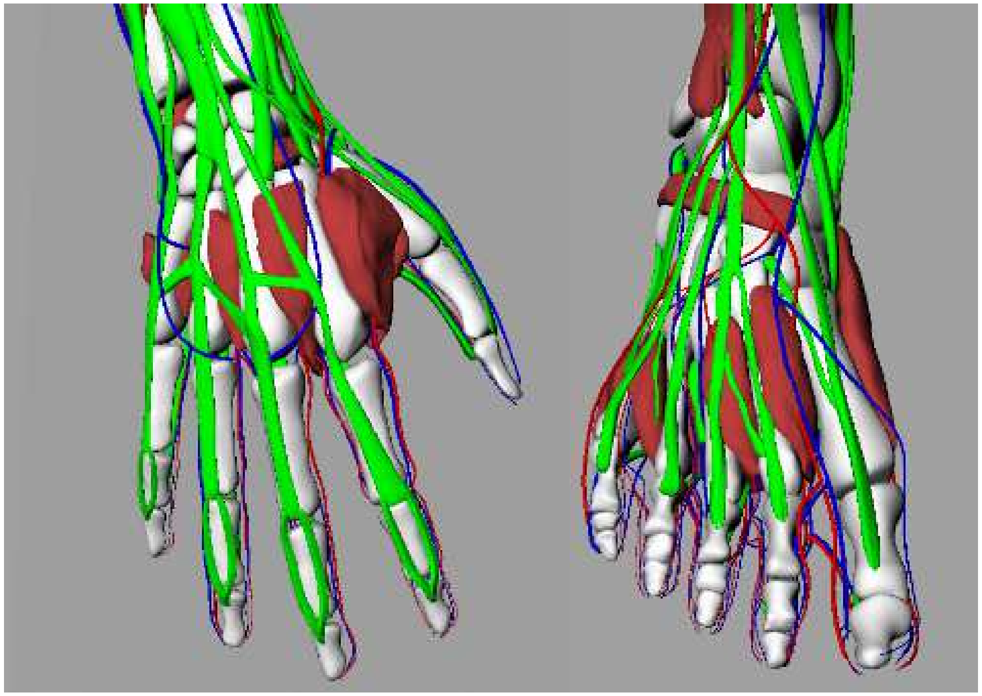
Converted to NURBS Surfaces

Segars el al, 4D XCAT phantom for multimodality imaging research, Med Phys, 37(9), (2010).

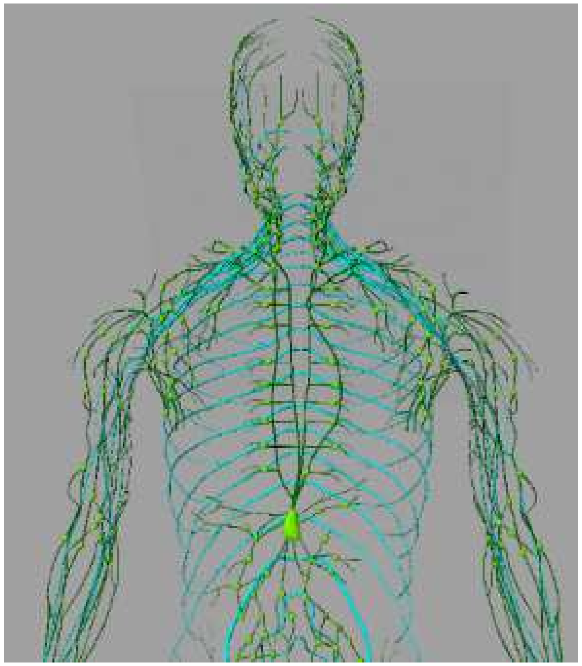
4D eXtended CArdiac-Torso (XCAT) Phantom



Detailed Brain Model based on MRI

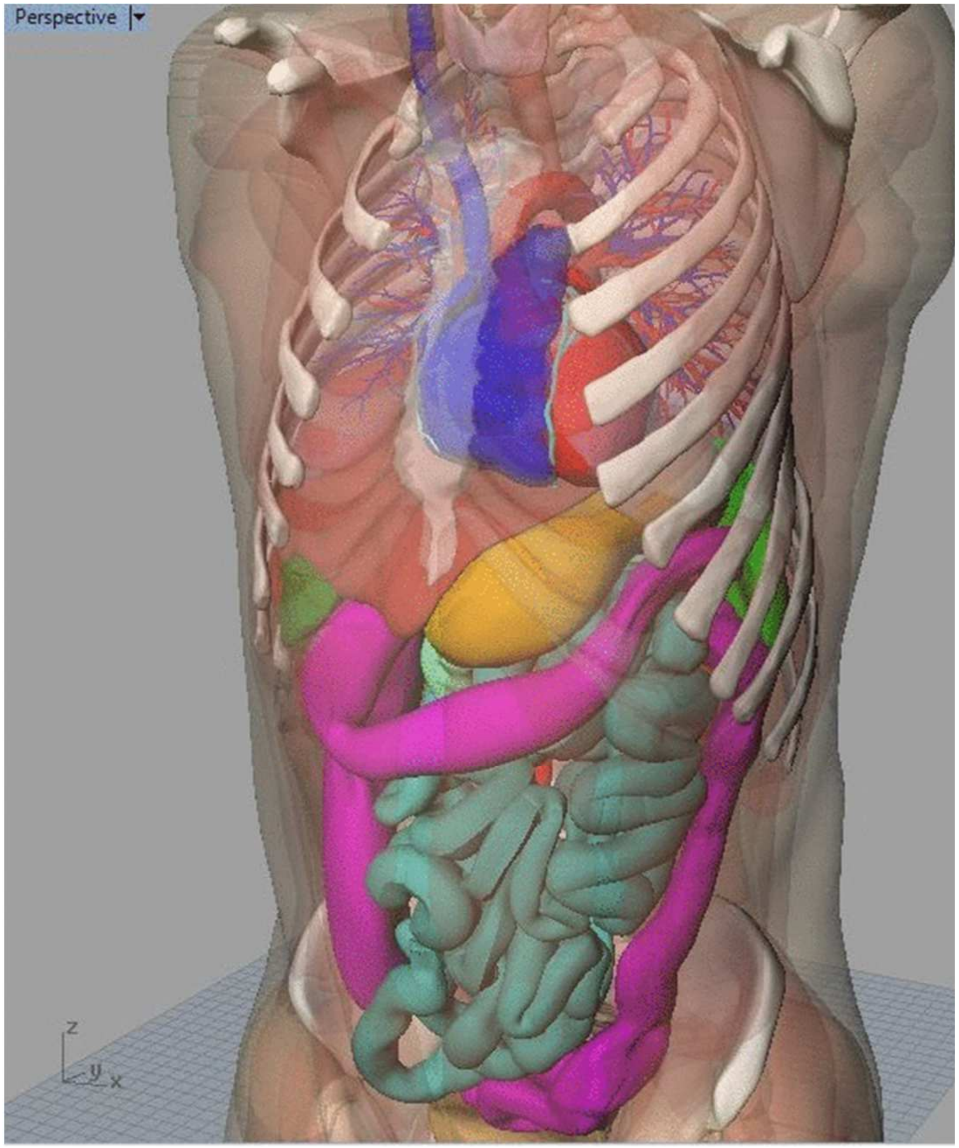


Detail in the hands and feet

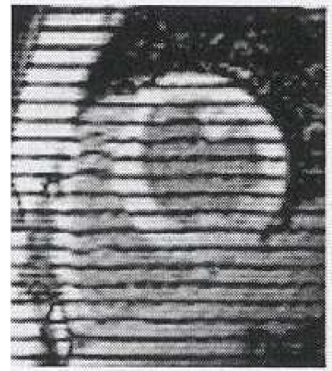


Adding nervous and lymphatic systems

XCAT Cardiac and Respiratory Motions



Cardiac-gated Tagged MRI



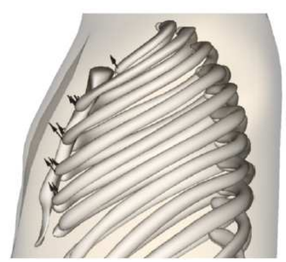
End-diastole

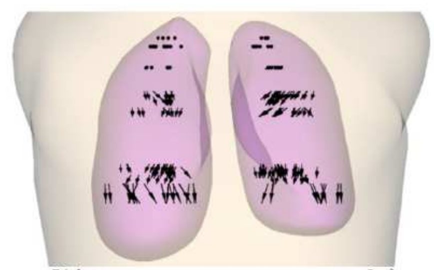
End-systole

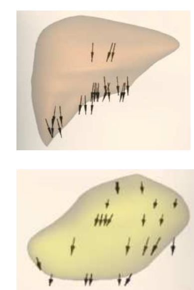
Respiratory-gated CT

End-expiration

End-inspiration





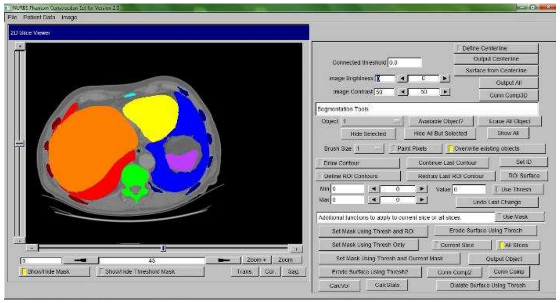


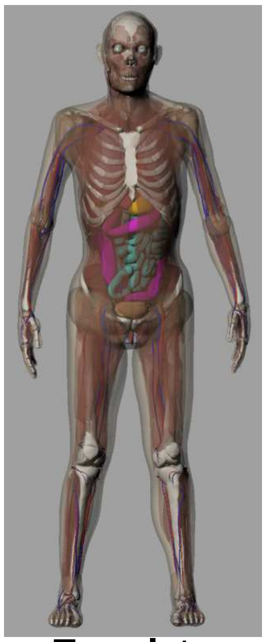
4D eXtended CArdiac-Torso (XCAT) Phantom

- To extend the XCAT beyond the adults, we are developing a population of models based on patient CT data from Duke Database
  - Targeted different ages and sizes (modeling patient variability is essential for research)
- Each model includes cardiac and respiratory motions for 4D simulations
- Library of 4D phantoms

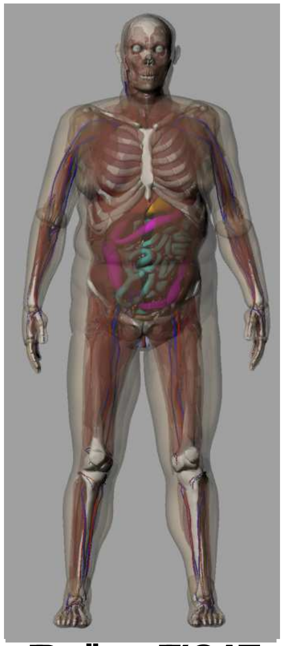
4D eXtended CArdiac-Torso (XCAT) Phantom

- Segment patient CT data (bones and major organs) to create an initial model
  - Fit arms/legs to patient model using XCAT models scaled to patient size
- Select template XCAT phantom that best matches the patient target
  - As the library grows, get better templates
- Utilize mapping algorithm to morph template XCAT to the target model
  - Defines unsegmented structures (vessels, muscles, tendons, ligaments)
  - No need to segment all structures, more efficient



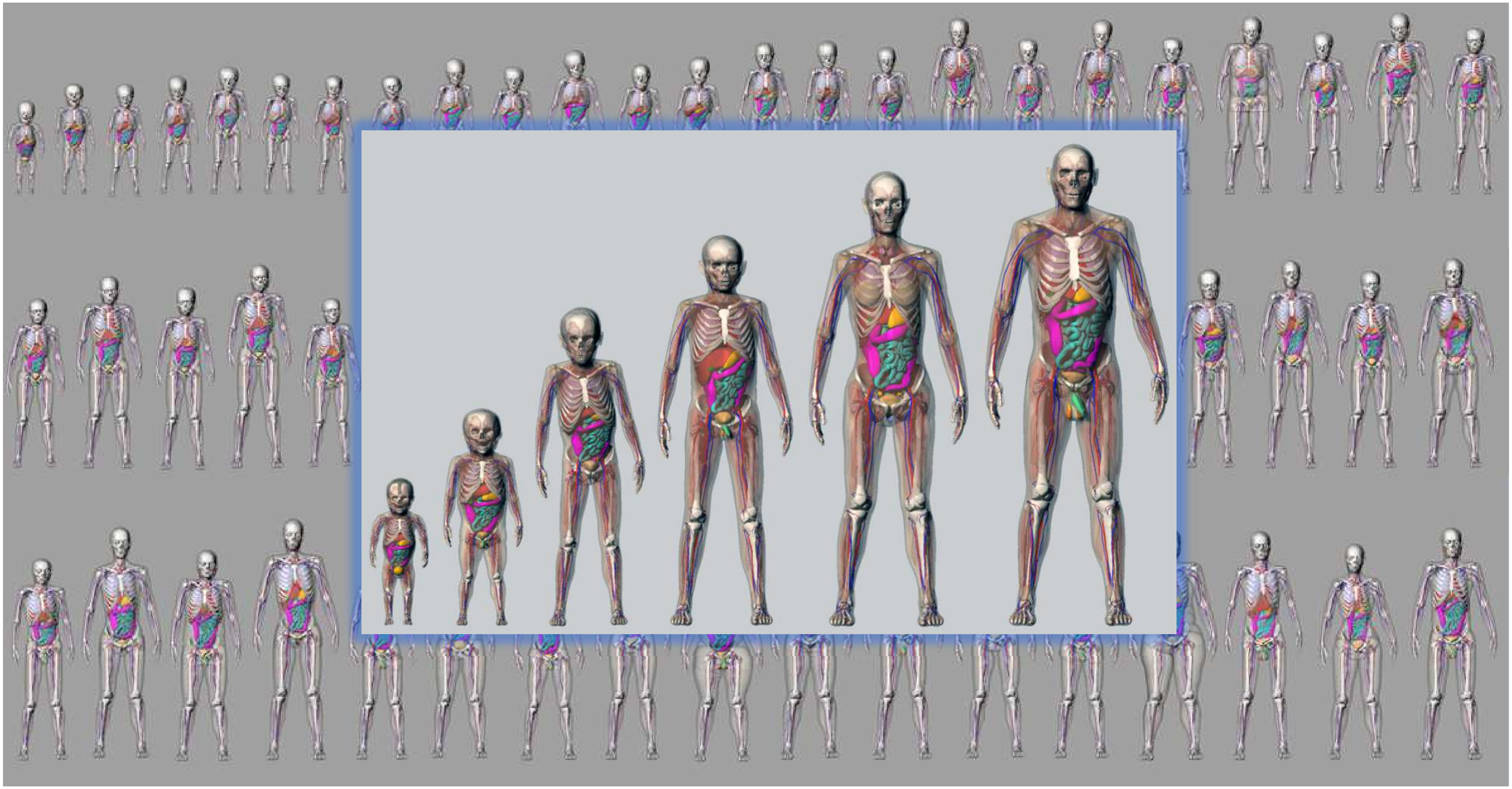


Template XCAT



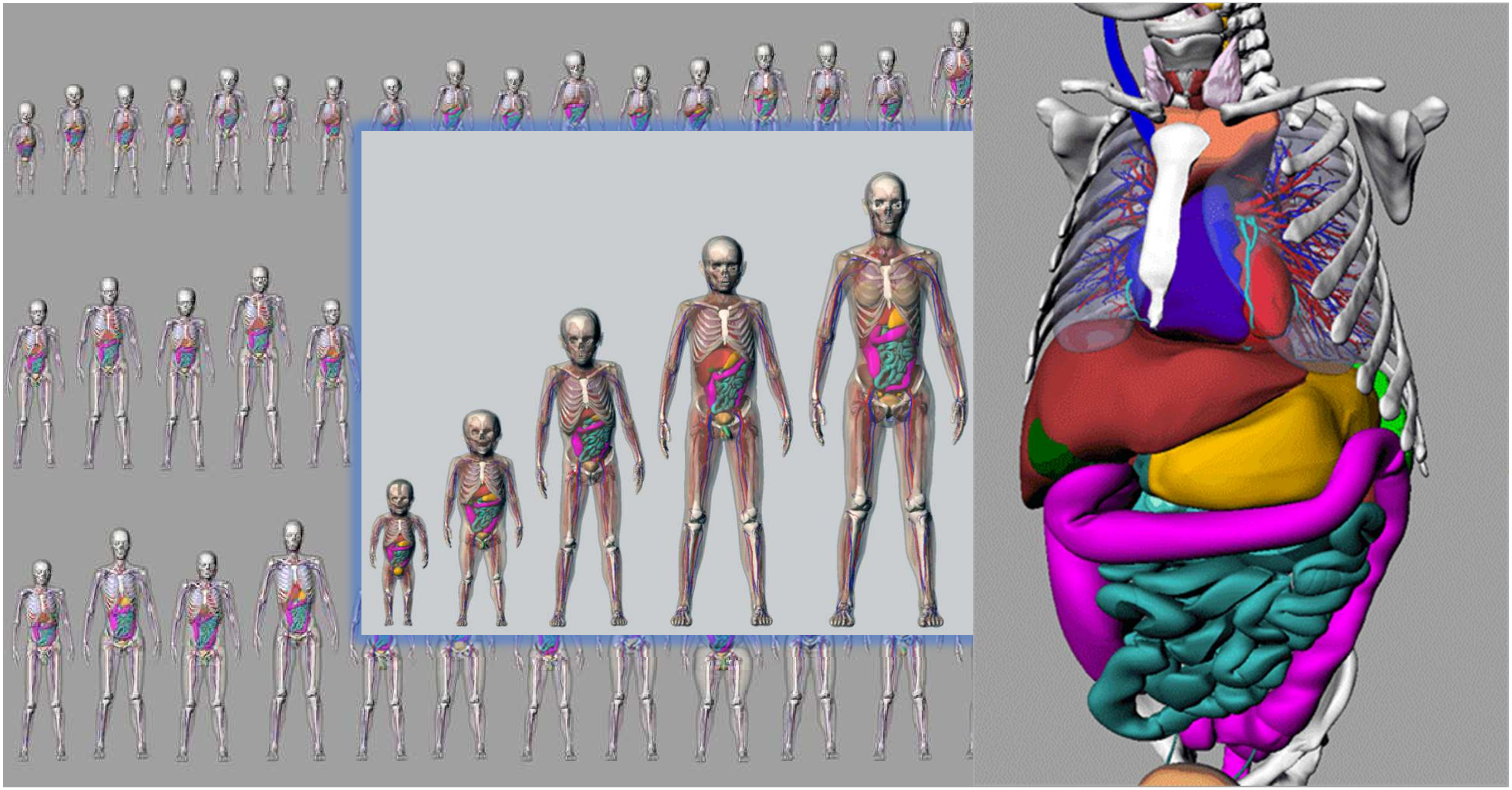
Patient Target

4D eXtended CArdiac-Torso (XCAT) Phantom



Segars el al, Population of anatomically variable 4D XCAT adult phantoms for imaging research and optimization, Med Phys, 40, (2013).
Segars el al, The development of a population of 4D pediatric XCAT phantoms for imaging research and optimization, Med Phys, (2015).

4D eXtended CArdiac-Torso (XCAT) Phantom



Segars el al, Population of anatomically variable 4D XCAT adult phantoms for imaging research and optimization, Med Phys, 40, (2013).
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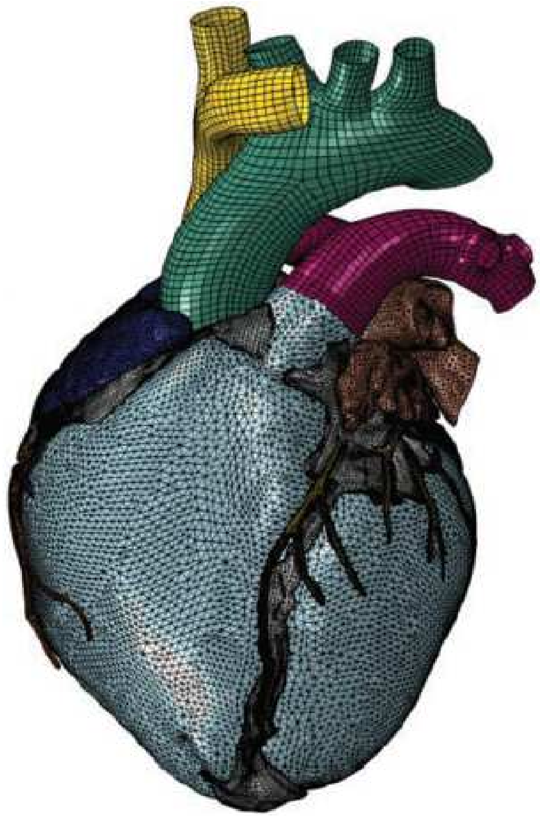
Limitations in the XCAT Cardiac Model

- Based on tagged MRI of a single normal subject
- Models one instance of the cardiac motion
- Does not have the ability to realistically simulate normal and abnormal variations in the cardiac anatomy or motion indicative of a patient population

Goal

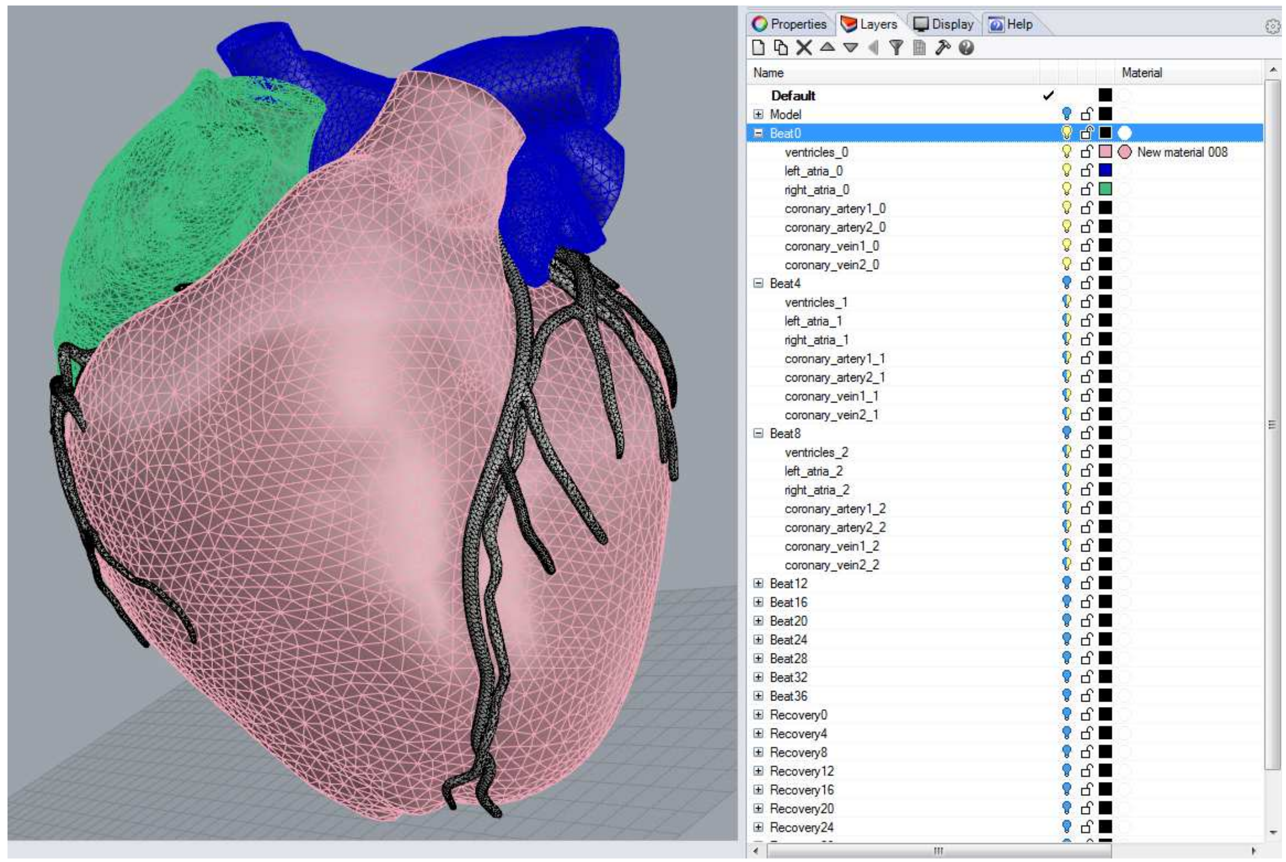
- To overcome these limitations, we incorporate into the XCAT anatomy, the physiologically based, four-chamber finite-element (FE) Living Heart Model (LHM)

- Plan to use the enhanced XCAT to simulate different anatomies and functions of the heart to evaluate and optimize 4D CT imaging techniques used in the diagnosis of coronary artery disease (plaque imaging)



Living Heart Model (LHM)

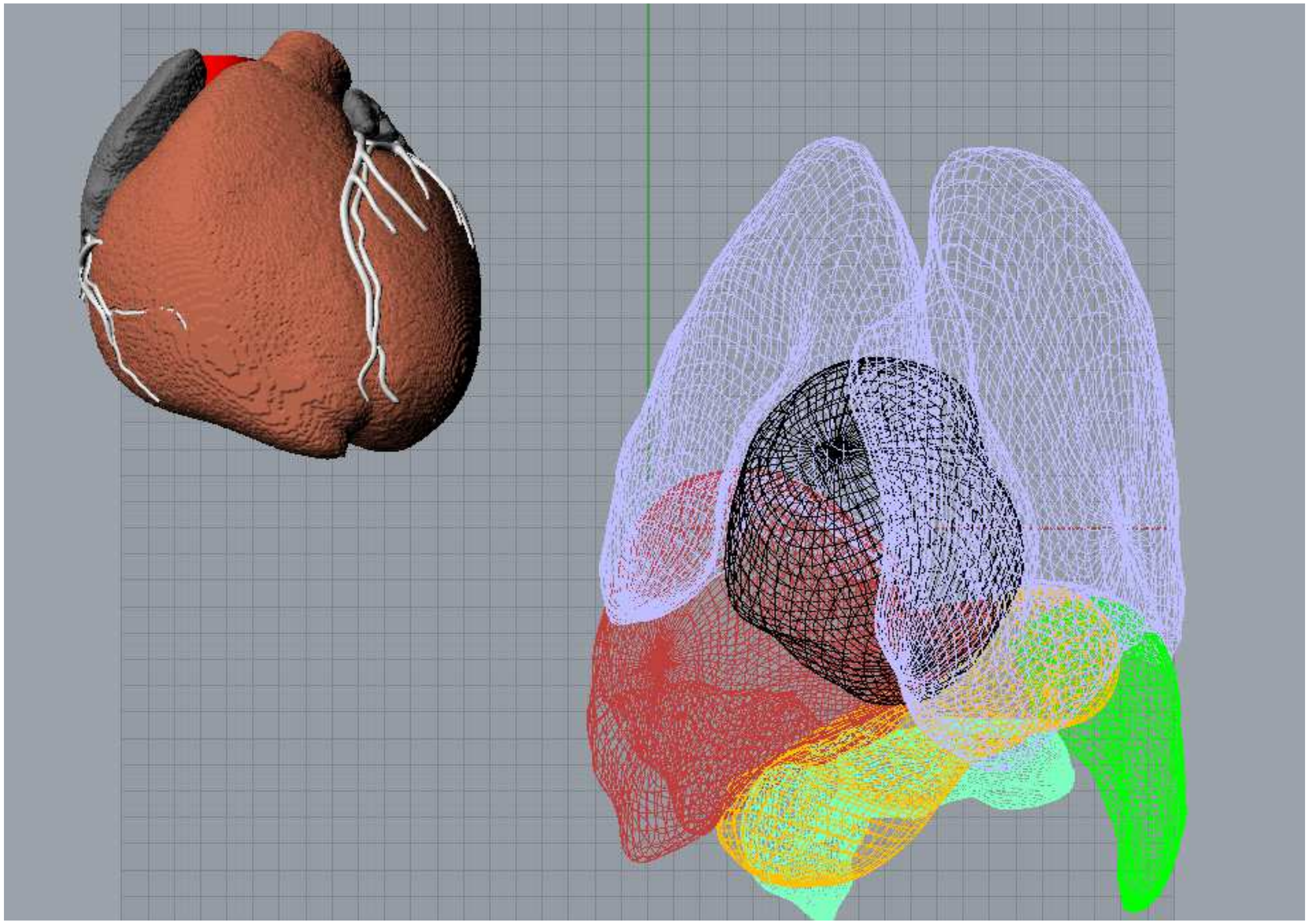
- Generated 80 times frames over the cardiac cycle
- Output the FE meshes at each time frame, saved as .obj files
- Wrote scripts to import and sort the meshes into the Rhinoceros modeling program (used to create the original XCAT)



Screenshot from the Rhinoceros program

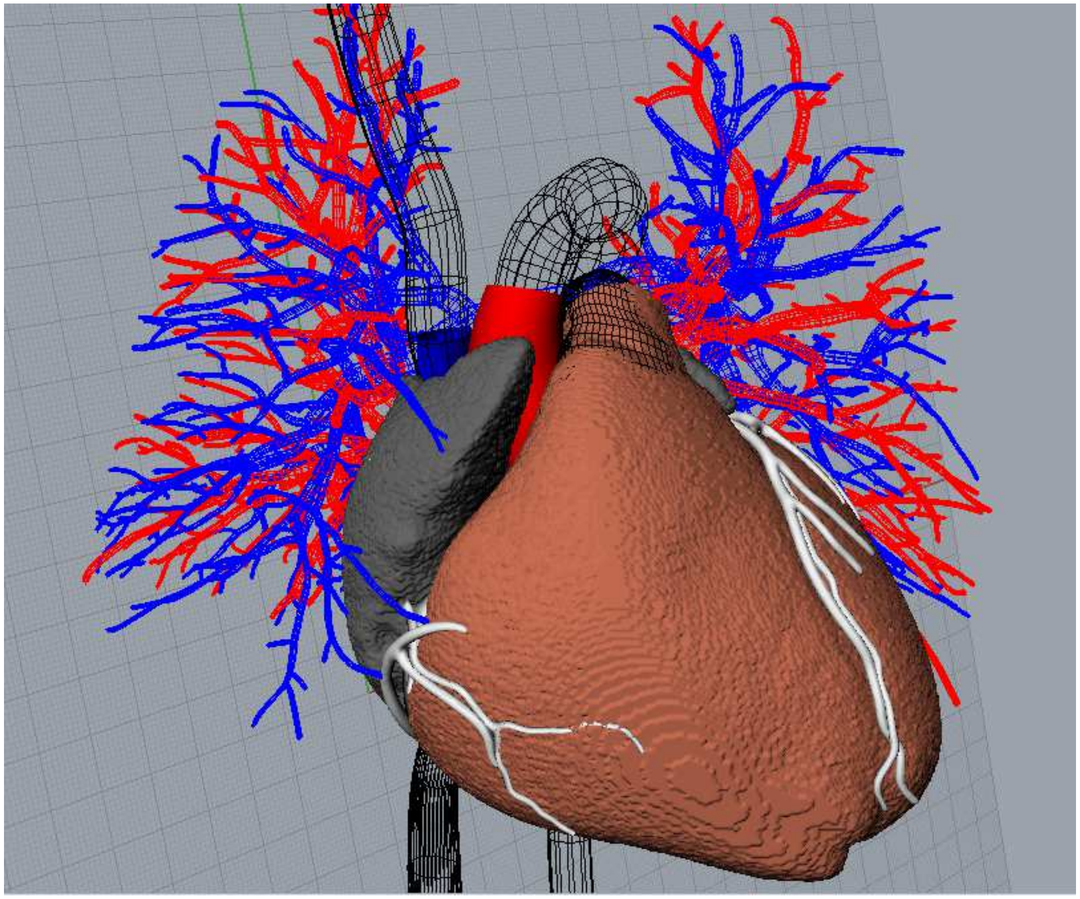
Insertion of the LHM into the XCAT Male Adult Anatomy

- Imported the XCAT adult male anatomy into the Rhinoceros modeling program along with the LHM



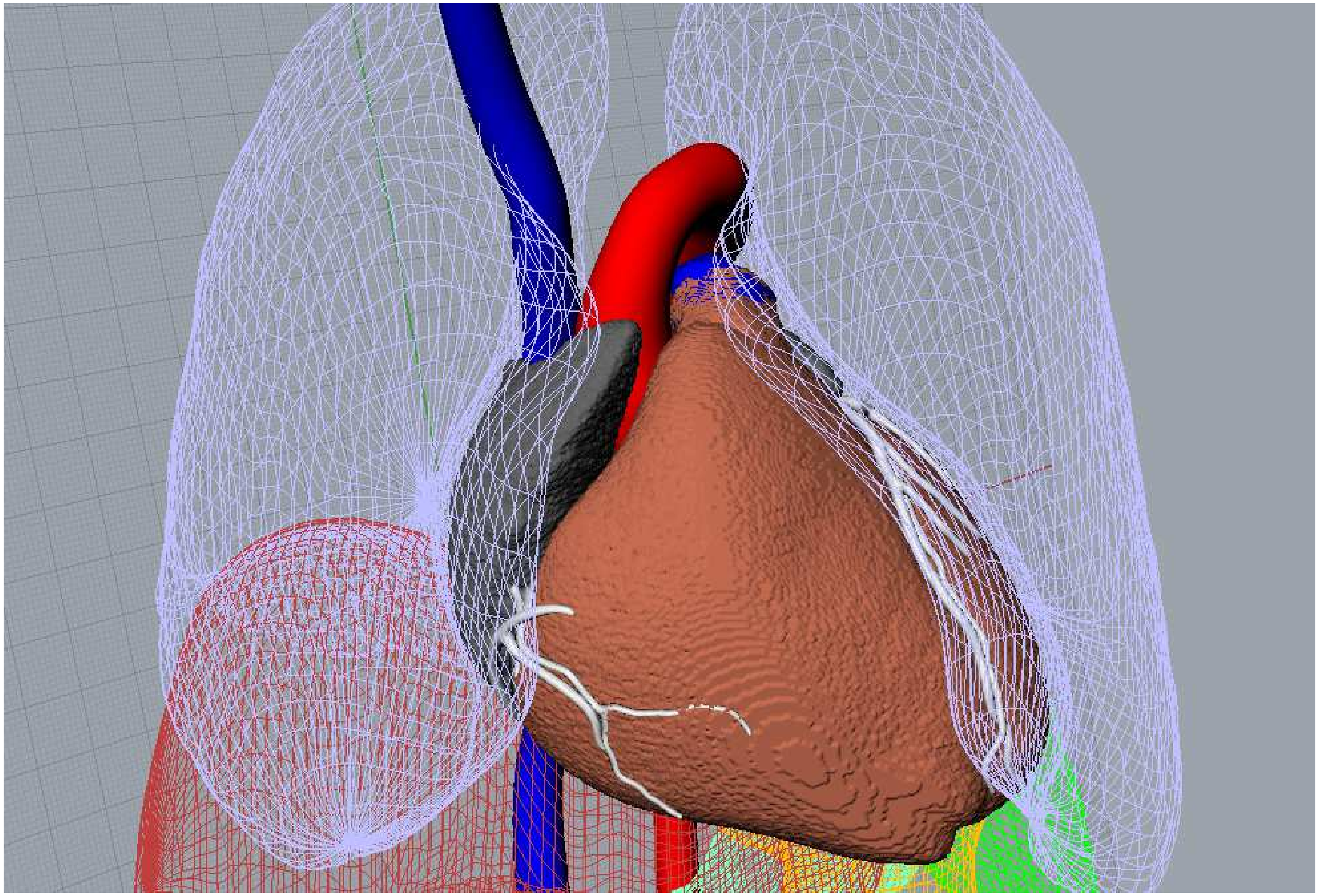
Insertion of the LHM into the XCAT Male Adult Anatomy

- Grouped all the LHM meshes (defined for each time point) together and manually translated and oriented them into the XCAT using the previous heart surfaces as a guide

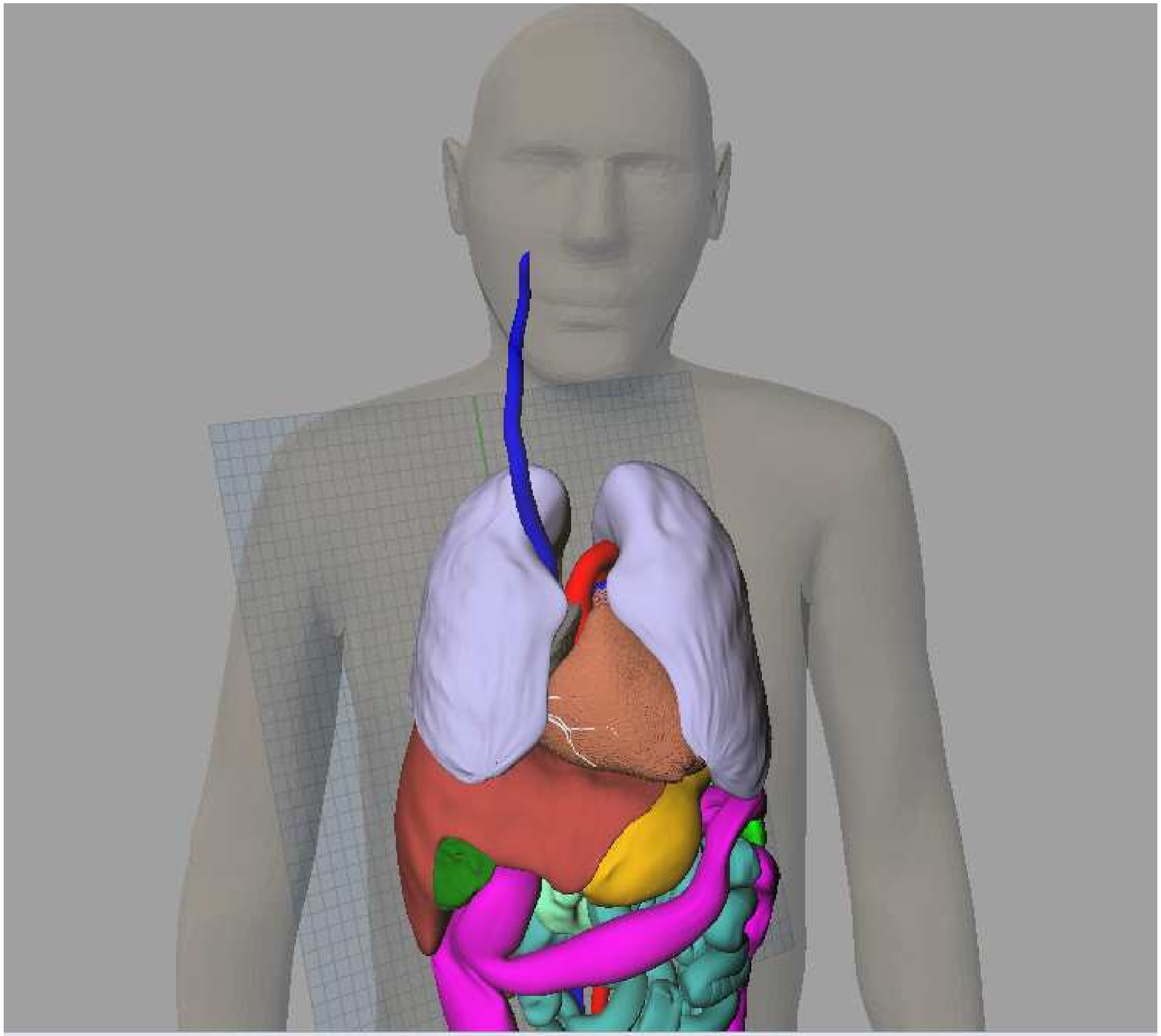


Insertion of the LHM into the XCAT Male Adult Anatomy

- Joined vessels together and reshaped lung surfaces to accommodate the new cardiac geometry

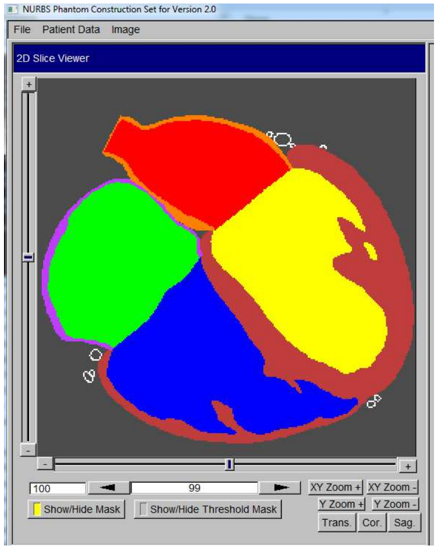


Insertion of the LHM into the XCAT Male Adult Anatomy

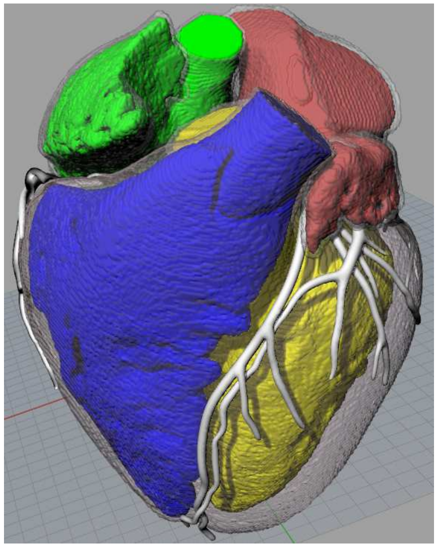


Defining the Heart Motion within the XCAT Software

- XCAT heart is currently defined by reading in heart surfaces defined at multiple points over the cardiac cycle then fitting time curves to the points defining each surface
- LHM FE meshes would not plug directly into the XCAT software (volumetric meshes)
- To create a set of surface files for the XCAT, we first voxelized the FE meshes defined for frame 1
- We then segmented the inner and outer walls for the chambers as well as the coronary vessels
- We used the marching cubes algorithm to create polygon surfaces for the heart structures



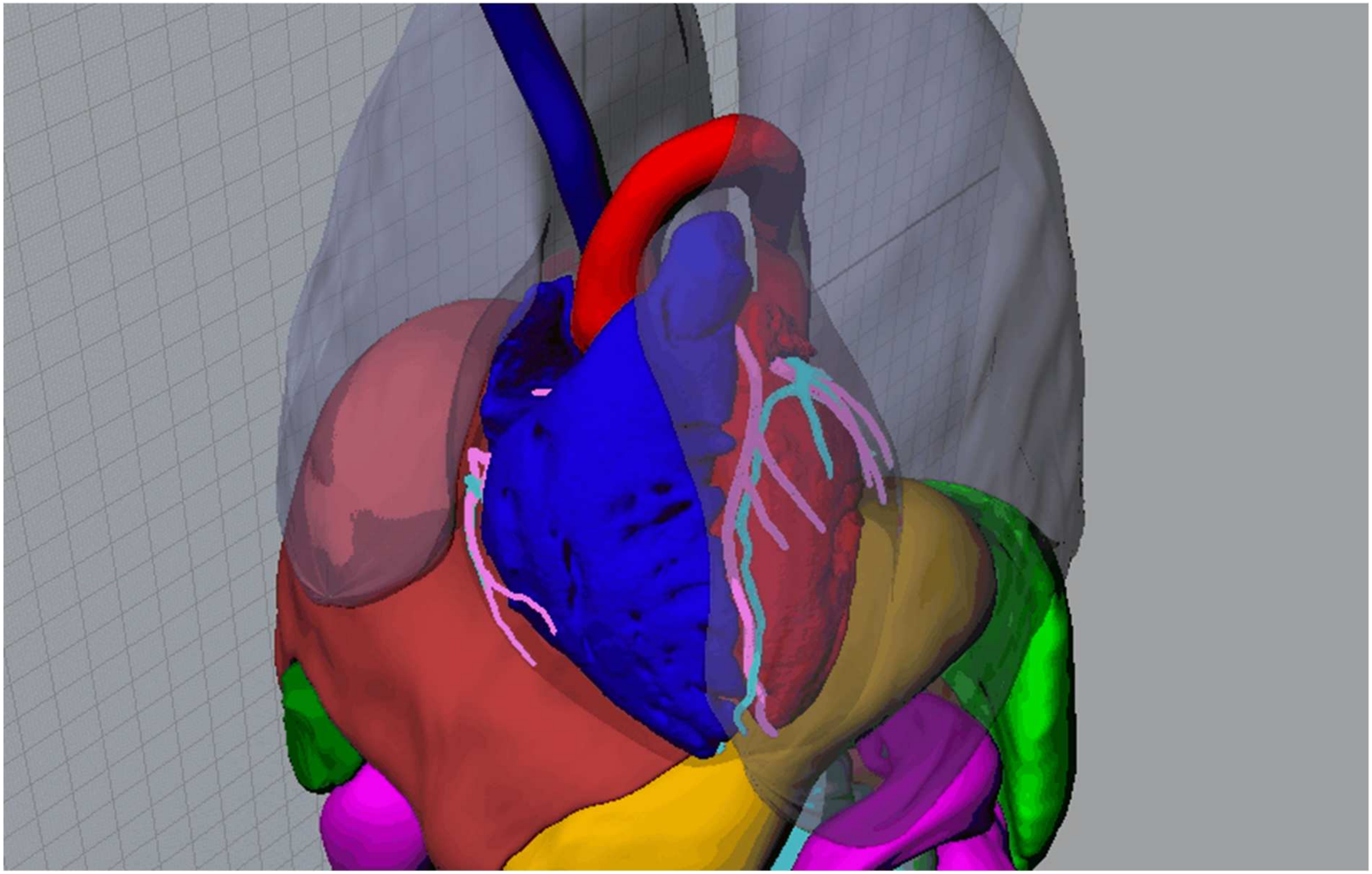
Segmentation


Polygon surfaces

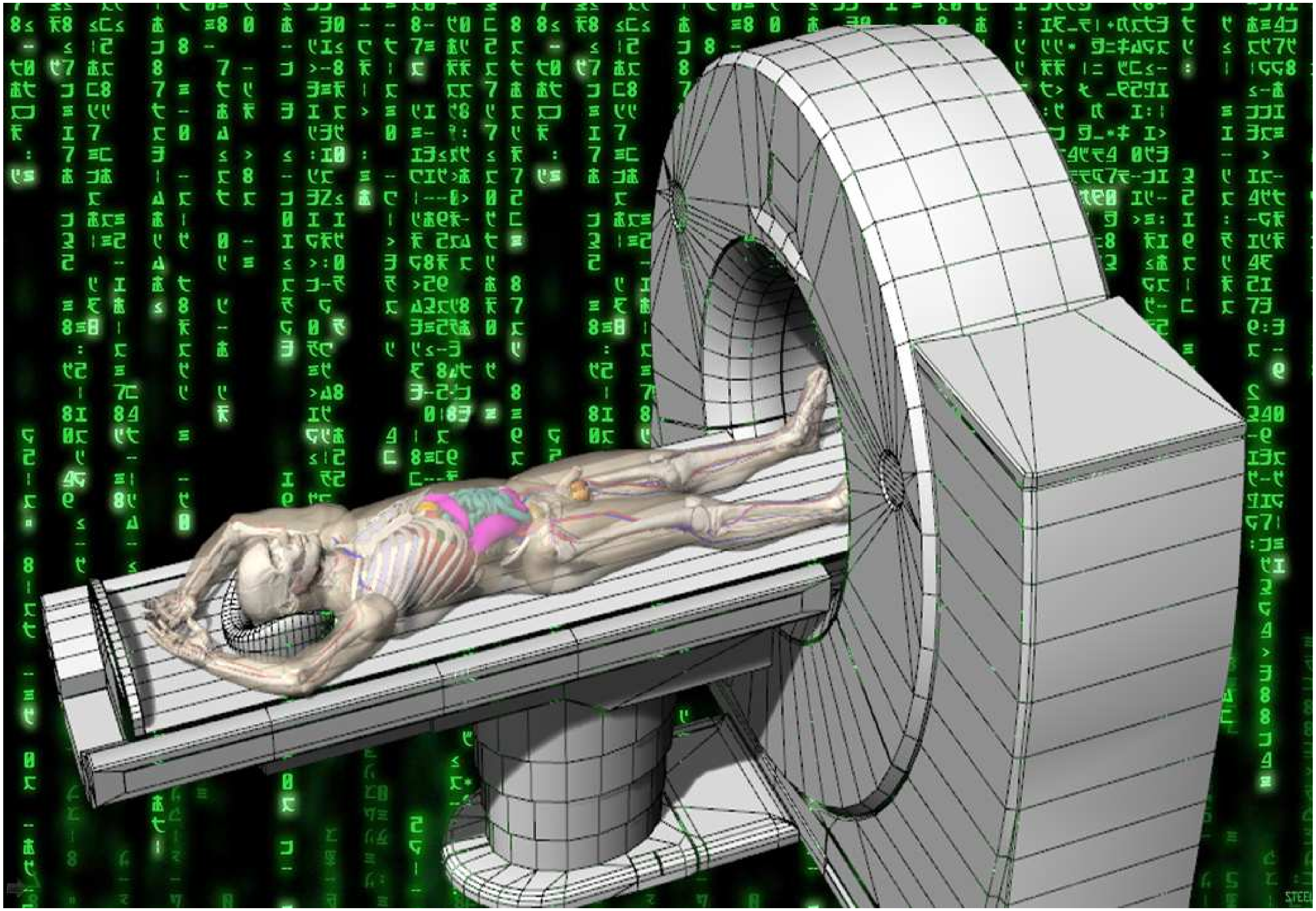
Defining the Heart Motion within the XCAT Software

- We analyzed the motion of the heart from the FE meshes defined at the 80 time points
  - The vectors for the mesh points were used to create a 3D motion vector field (interpolation was used to fill in the blanks)
- Motion field was applied to the surfaces created for the XCAT to define them at each of the 80 time points, creating a surface file for each
- XCAT software was setup to read the new surface files
  - 80 time points are read in and time curves are fit to the 3D location of each vertex point of each structure
  - The time curves can be sampled to create any number of frames over the cardiac cycle

Enhanced XCAT Cardiac Motion



Simulated 4D CT from Enhanced XCAT



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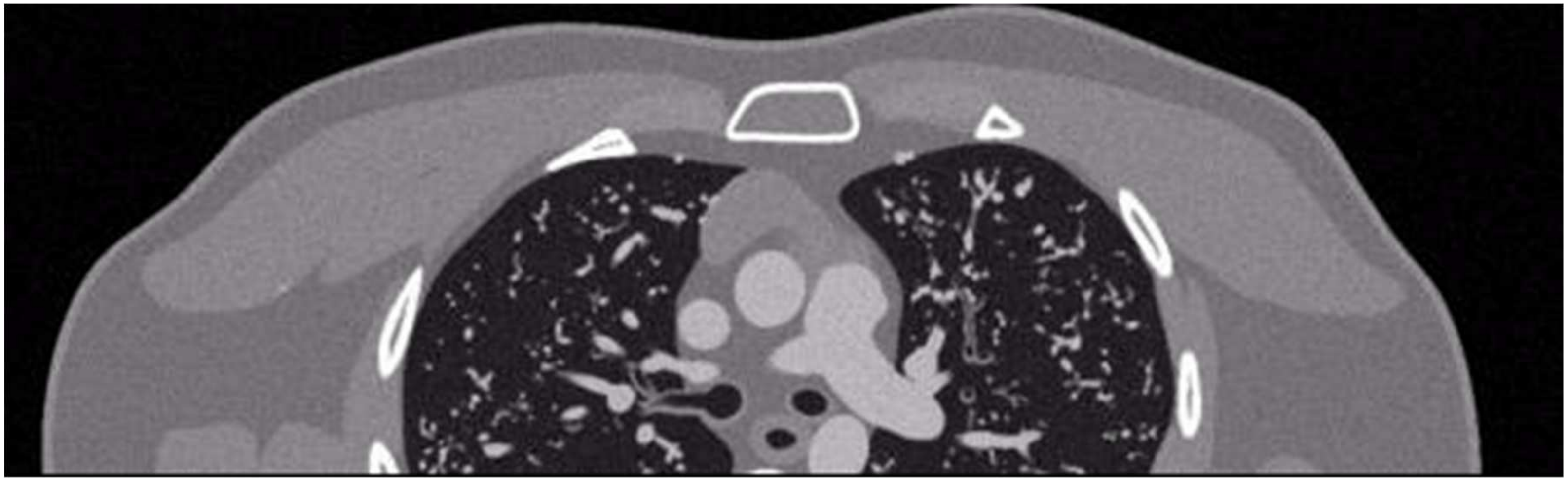
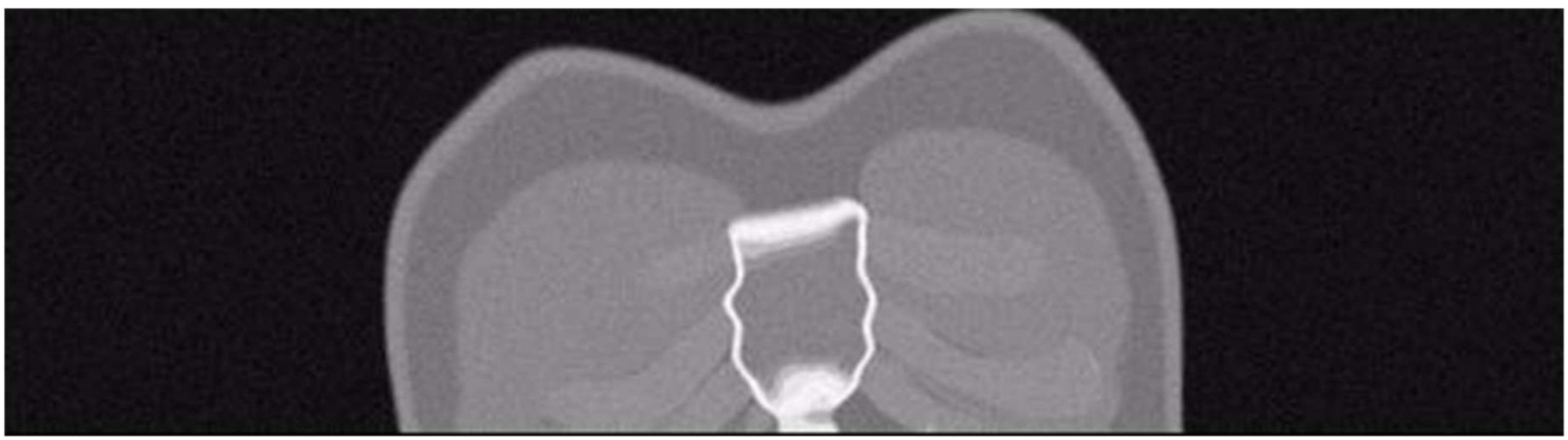
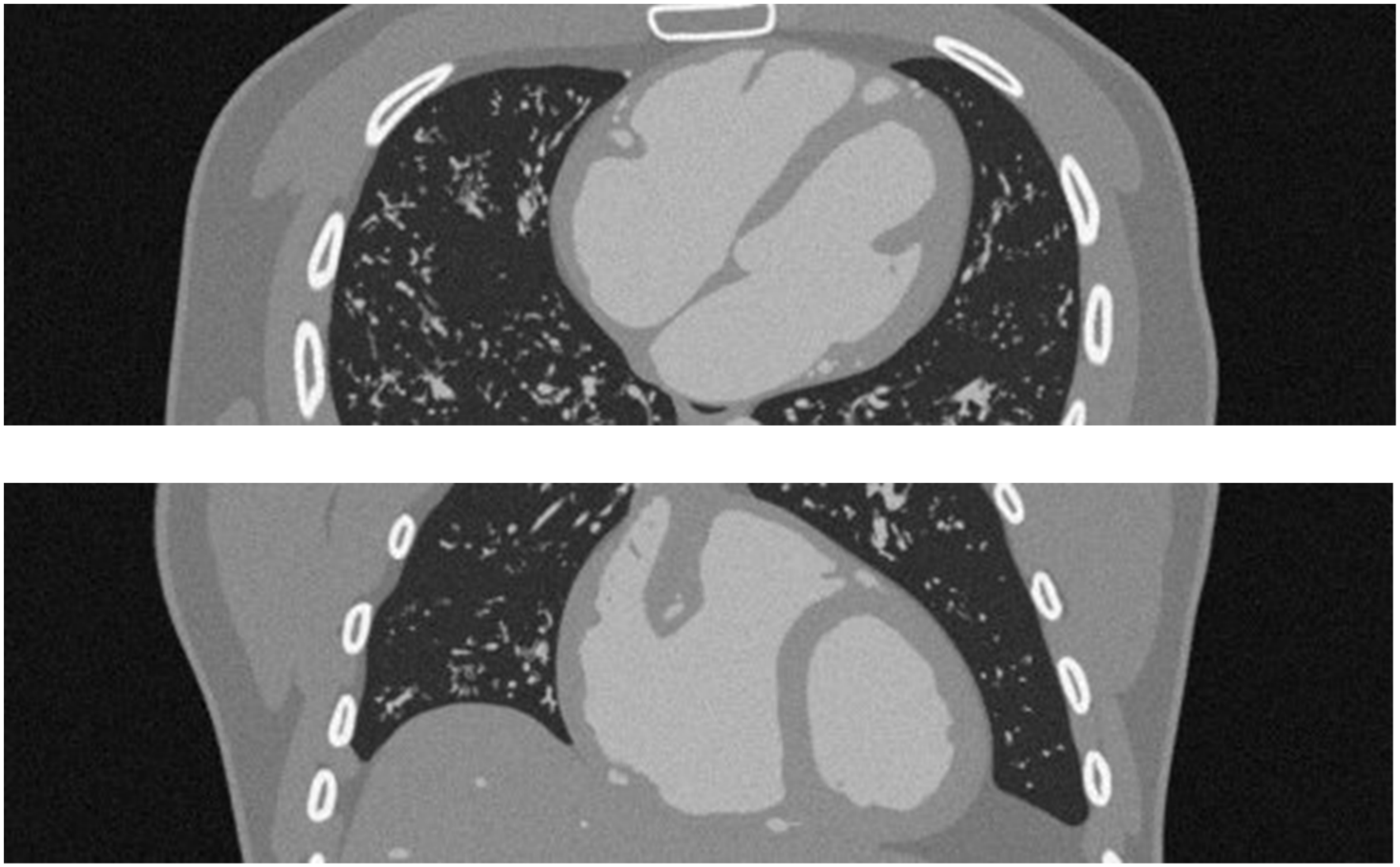
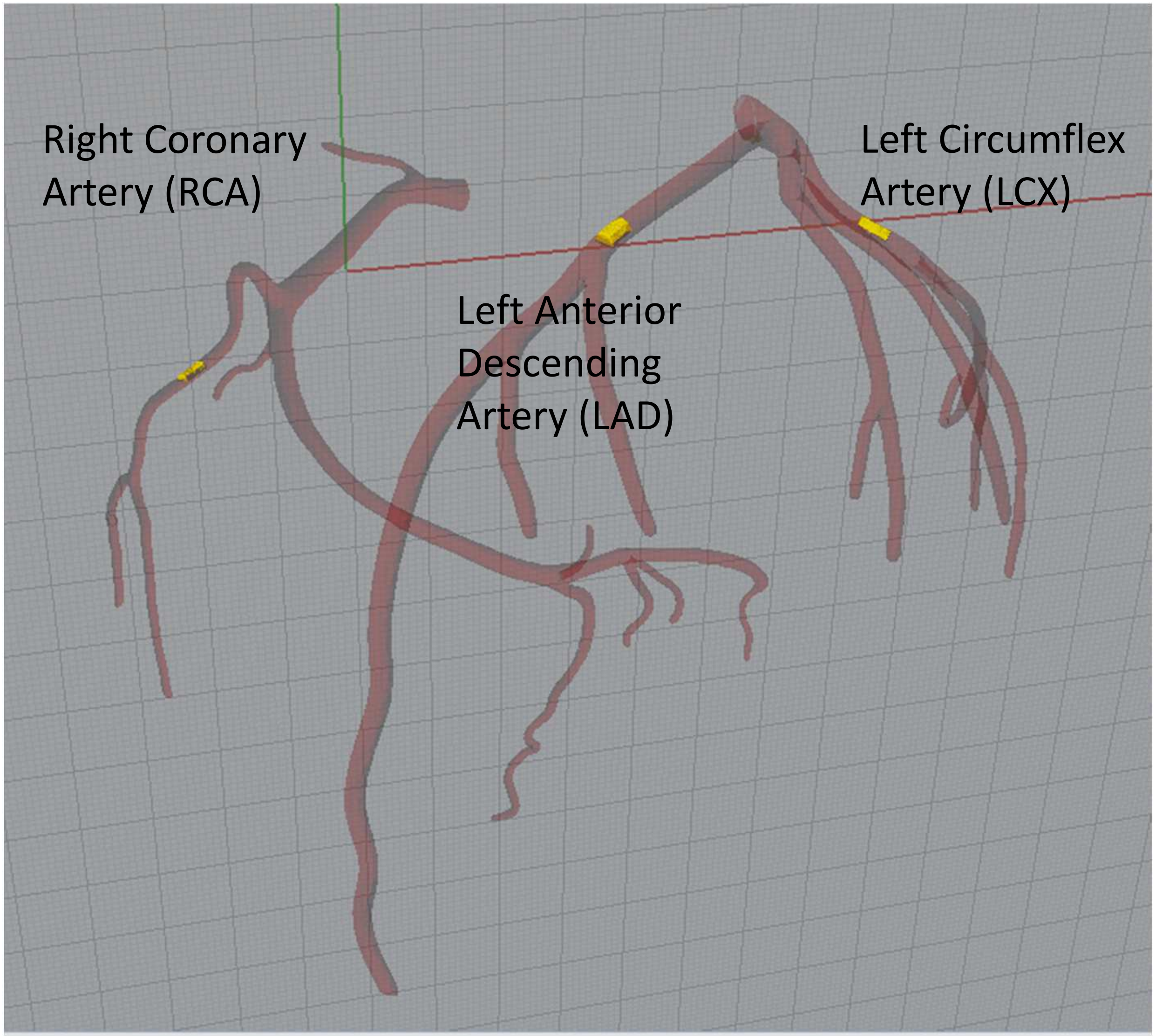




Simulated 4D CT from Enhanced XCAT



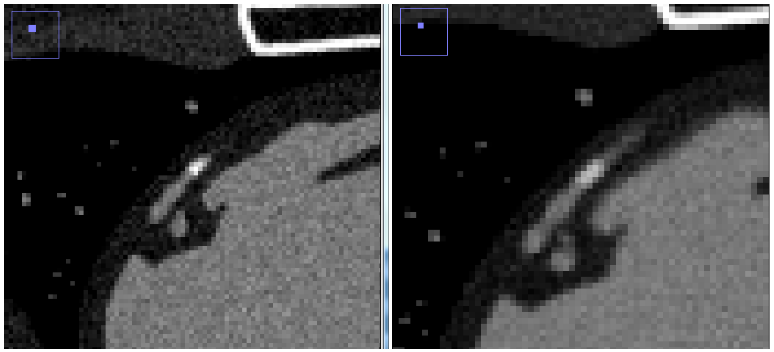
Simulation of Coronary Plaques

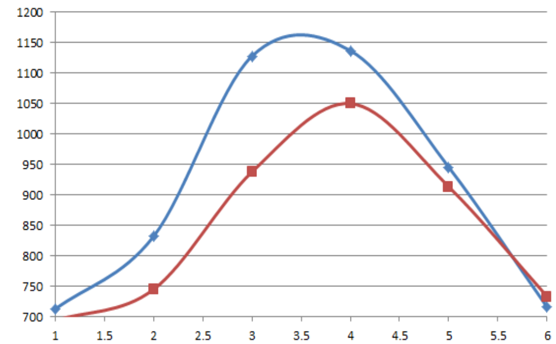


Simulated 4D CT Data with Plaques

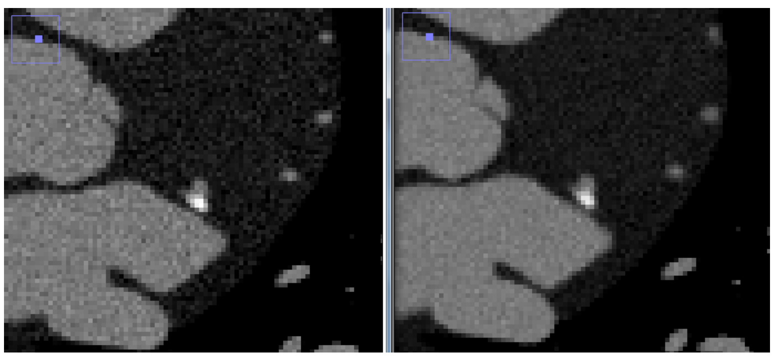
No motion   Motion (quiet phase)

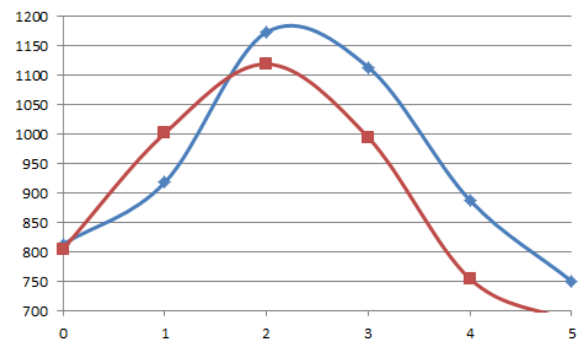
RCA



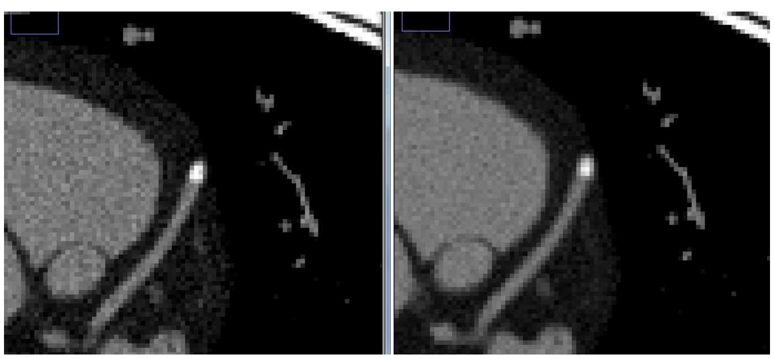


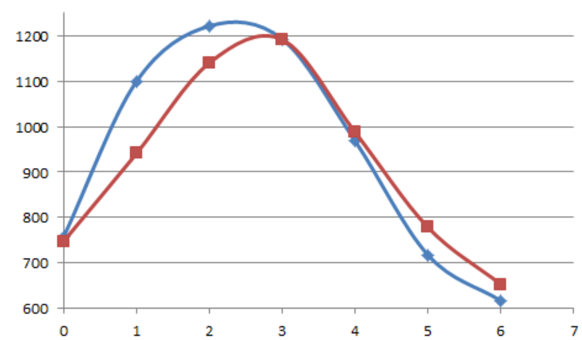
LCX





LAD

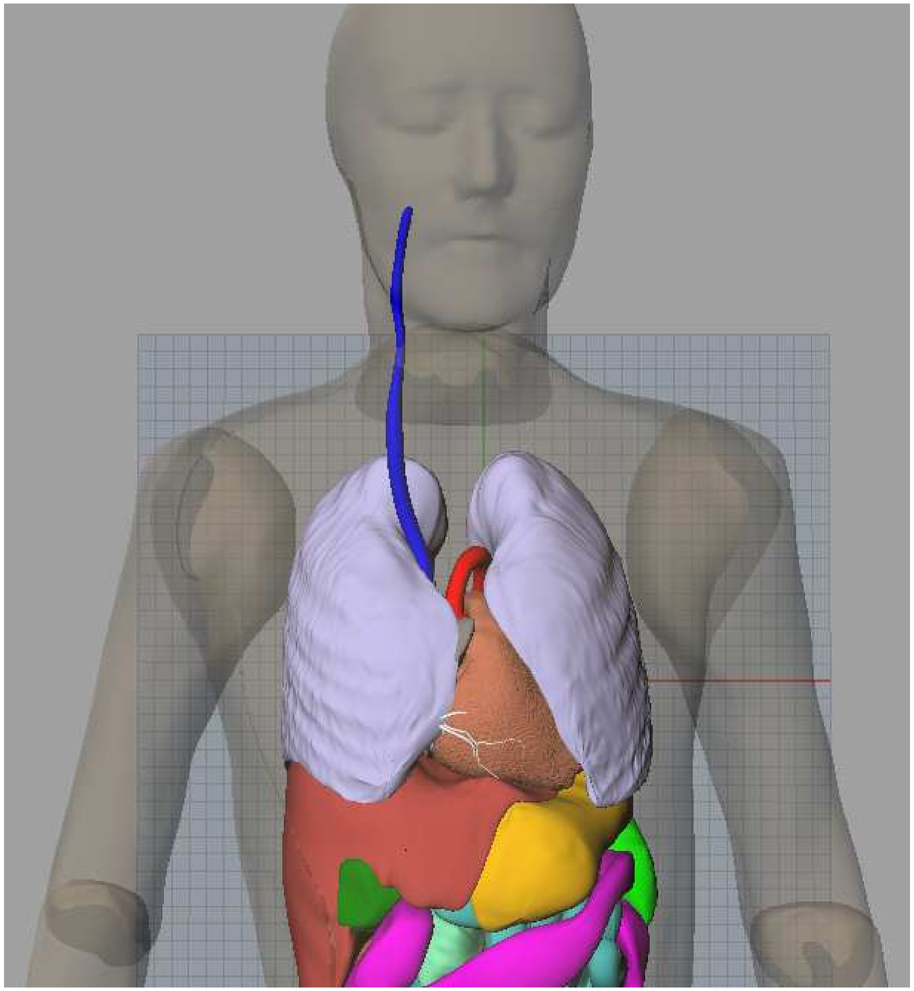




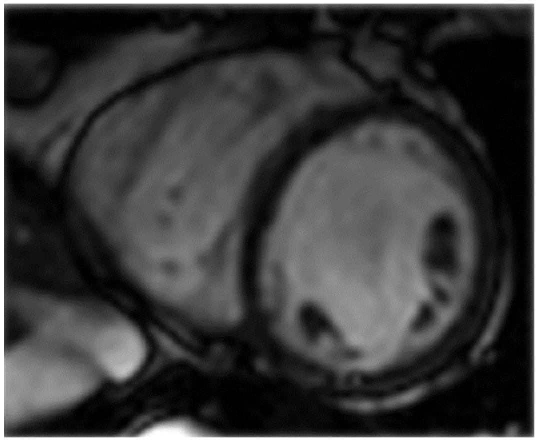
Our Goal and Future Needs

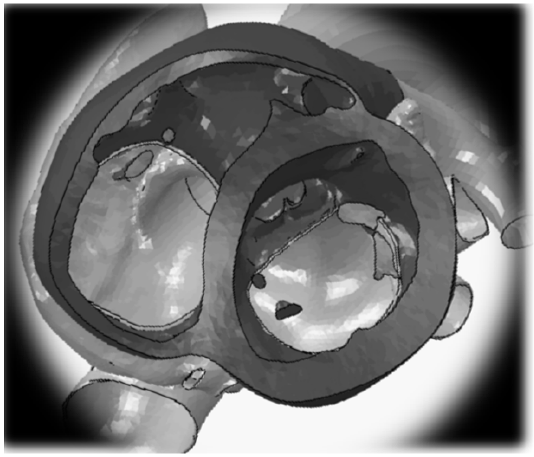
- Our goal is to investigate the effective optimization of CT for the assessment of coronary artery disease
- For this we need to:
  - Create a series of anatomically variable cardiac models fit to various patient anatomies
  - Manipulate FE parameters to simulate different functions of the heart

Anatomical Variations

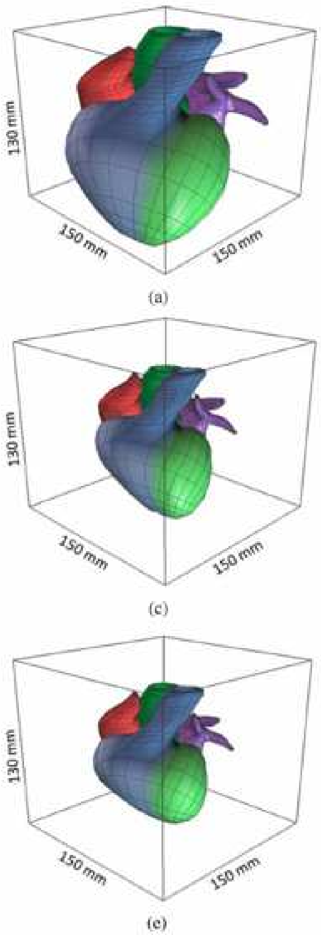


Rigid transformations as done with the adult male XCAT





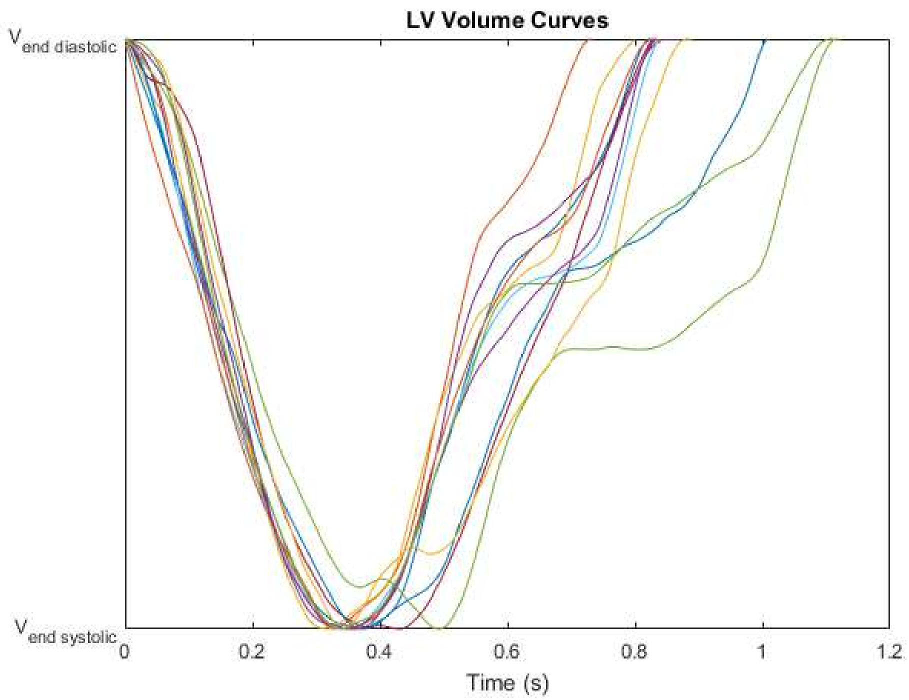
Morph the FE mesh non-rigidly to match patient imaging data (Major challenge)



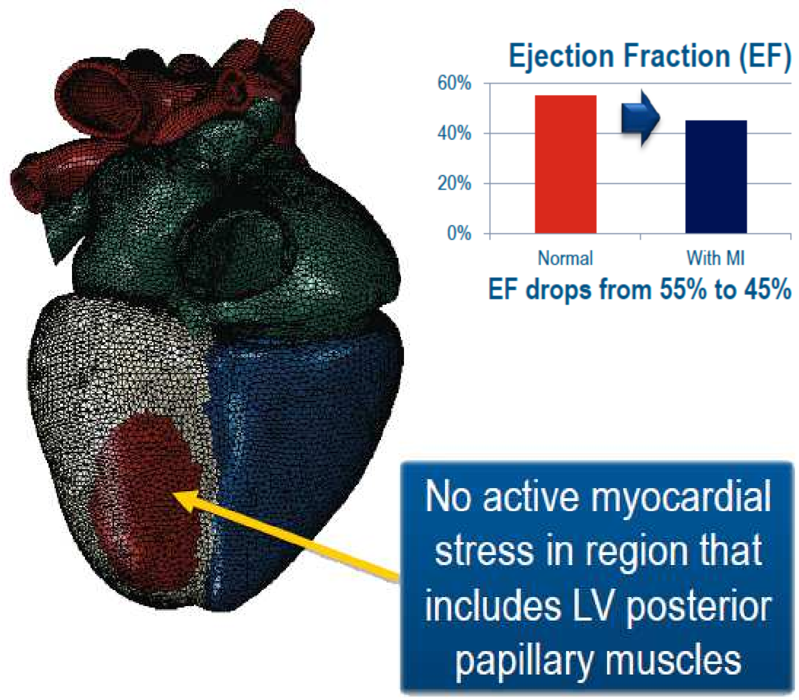
Additional FE models, Andrew McCulloch, UCSD

Functional Variations

- For our purposes, we would like to simulate different LV volume curves as well as heart rates
- In the future for other studies, we would like to manipulate parameters to simulate ischemia and infarction



Fitting FE heart to LV volume curves obtained from patients (echocardiography)



Modeling ischemia and infarction through manipulation of material properties

Summary

- We combined the XCAT phantom with the FE Living Heart Model
- The LHM provides a physiological basis with which to realistically simulate normal and abnormal functions of the heart
- We are developing models for different types of plaques to insert into the FE-enhanced XCAT
- We are working to simulate different cardiac geometries and incorporate them into various patient anatomies
- We are working on simulating different heart functions (LV volume curves, heart rate)

Summary

- The XCAT phantoms combined with FE models like the Living Heart have great potential to simulate realistic, predictive, patient quality 4D imaging data essential to conduct studies to investigate cardiac CT imaging methods

Thank You! | paul.segars@duke.edu

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