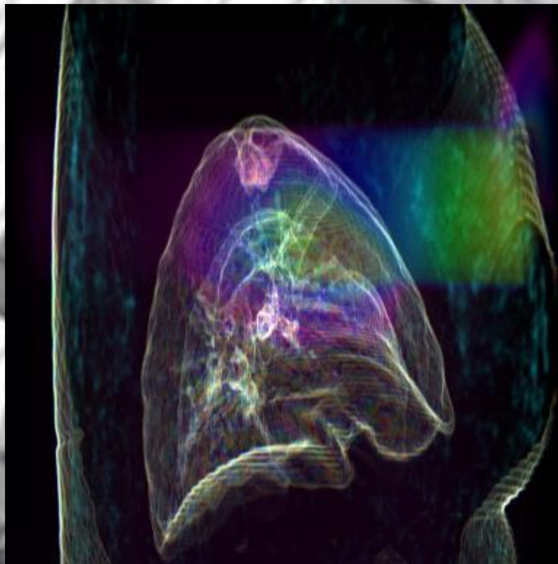

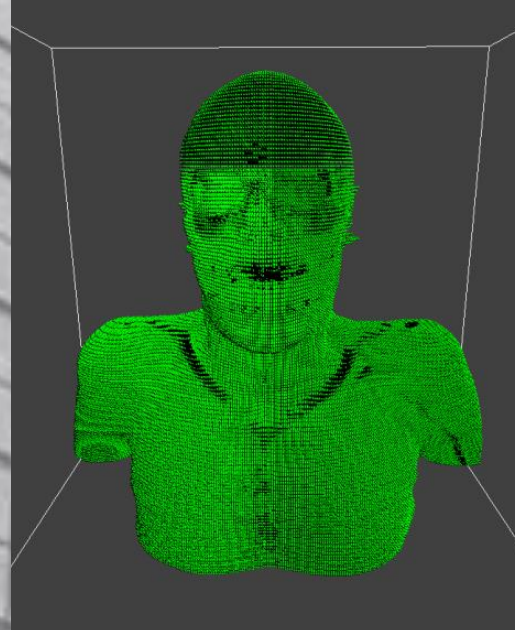

REAL-TIME ADAPTIVITY IN HEAD-AND-NECK AND LUNG CANCER RADIOTHERAPY IN A GPU ENVIRONMENT

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OUTLINE

- Adaptive radiotherapy for head and neck and lung cancer
- Key tools used for adaptive radiotherapy
  - 3D Deformable Image Registration (DIR)
    - Real-time 3D DIR
  - Physics-based modeling
    - Quantification of systematic errors in DIR
  - 3D Dose Calculation
    - Real-time non-voxel based dose calculation

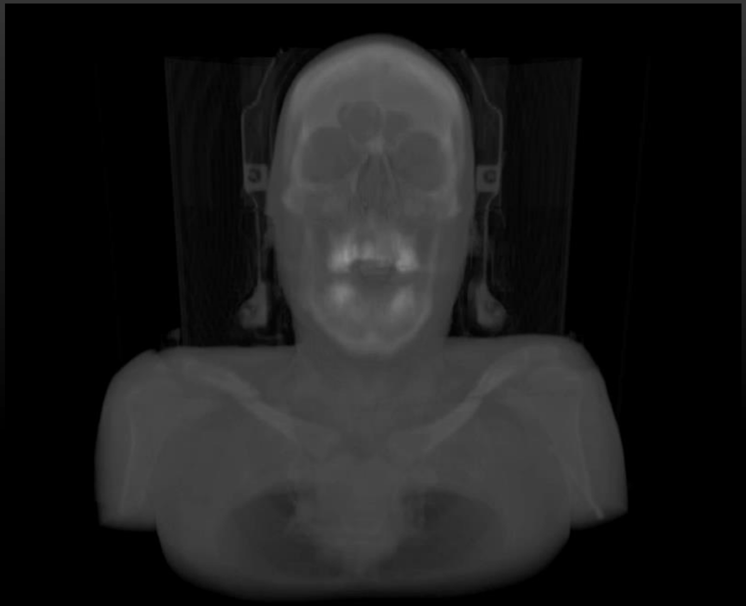
RADIOTHERAPY

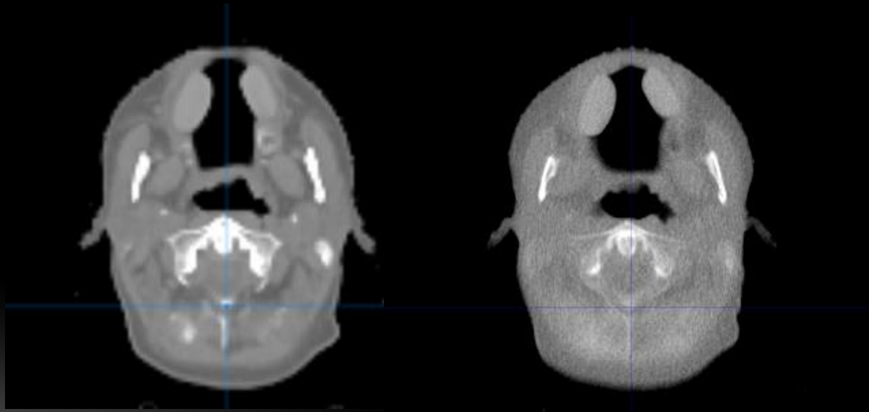
- Treatment for un-resectable tumors
- Procedure
  - Patient is already diagnosed with the type of cancer
  - A 3D/4D CT scan is acquired before the treatment
  - Clinical experts contour (or delineate) the tumor and surrounding critical organs
  - Appropriate radiation dose is planned
    - Max dose to the tumor
    - Min dose to the critical organs.
  - Patient is treated for sevaral days
    - 5-35 days

RESEARCH AIM & PURPOSE

Treatment Uncertainty

- Rigid Registration – neglects soft tissue changes
- Daily MVCT image quality - loss of detail and stratification
- Computational effort - accurate DIR is time consuming

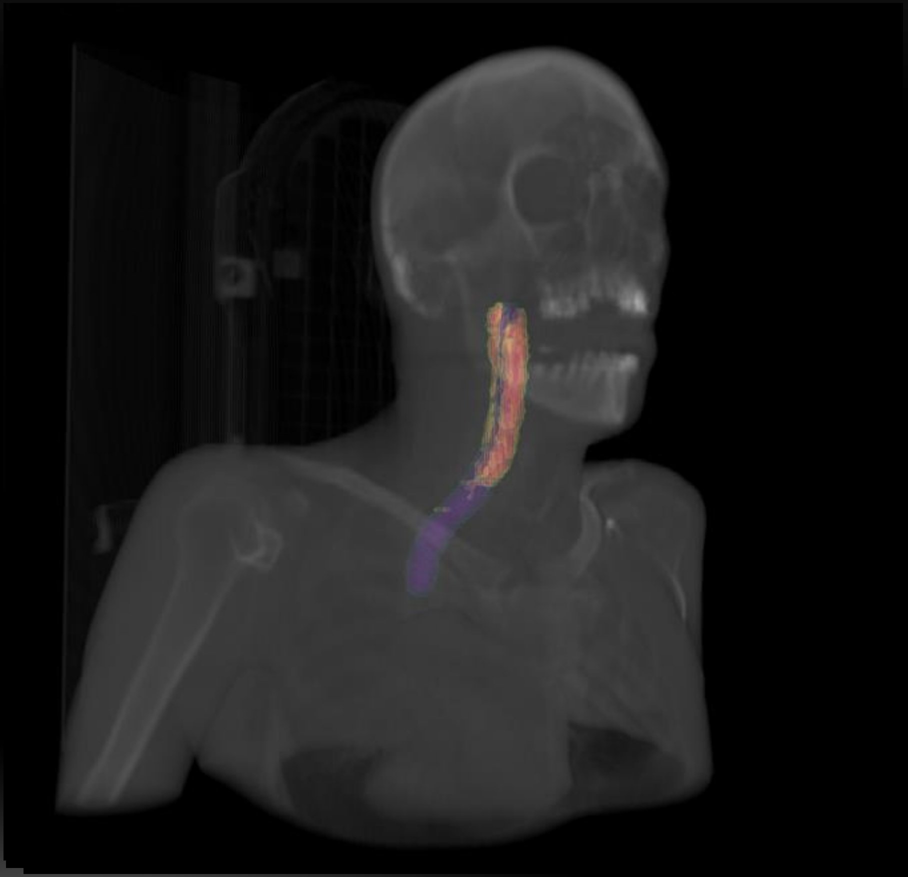




RESEARCH AIM & PURPOSE

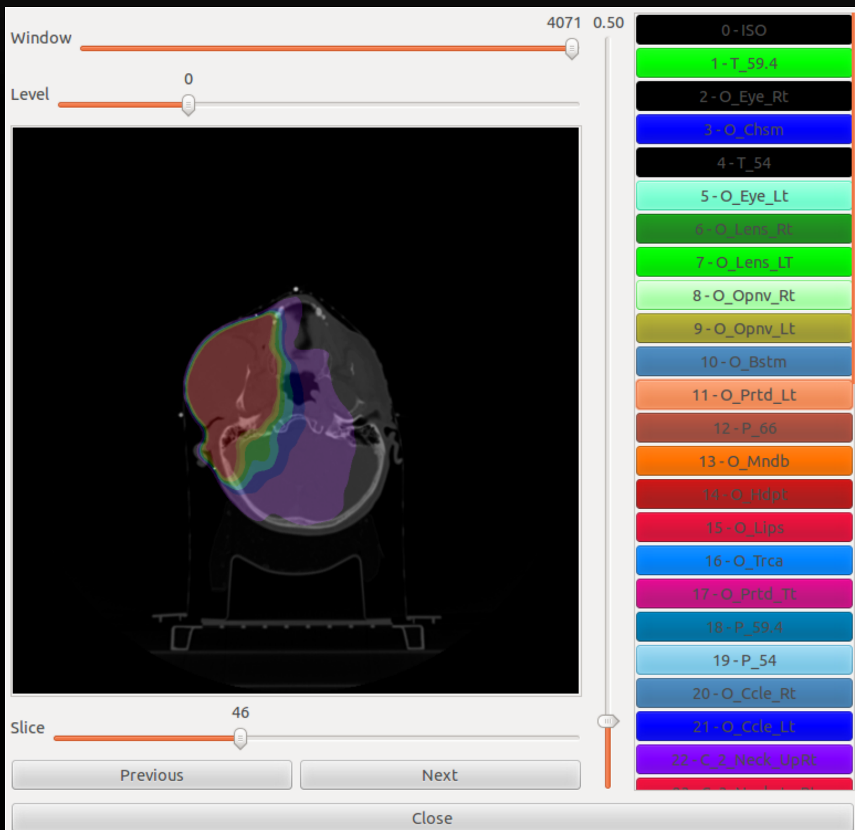
Adaptive Therapy

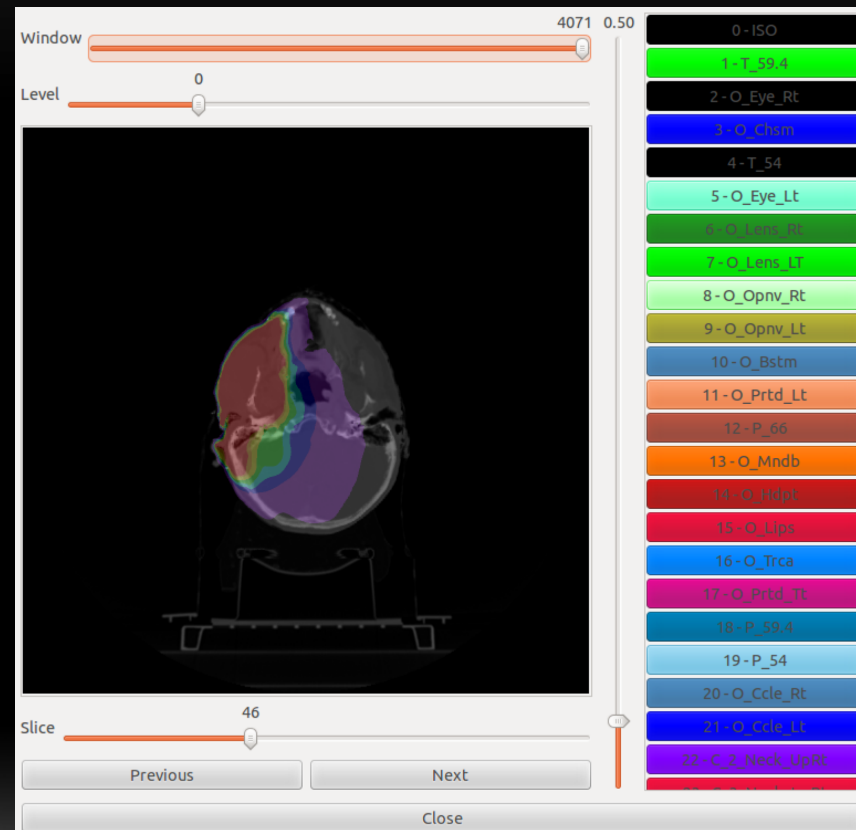
- Calculate the dose delivered on deforming normal and diseased organs.
- Facilitate 3D structures for deforming anatomy.
- Effectively spare normal organs and tissues.
- Modify the dose delivered on subsequent fractions



ADAPTIVE RADIOTHERAPY

- Accumulate Dose over Deformed Volumes

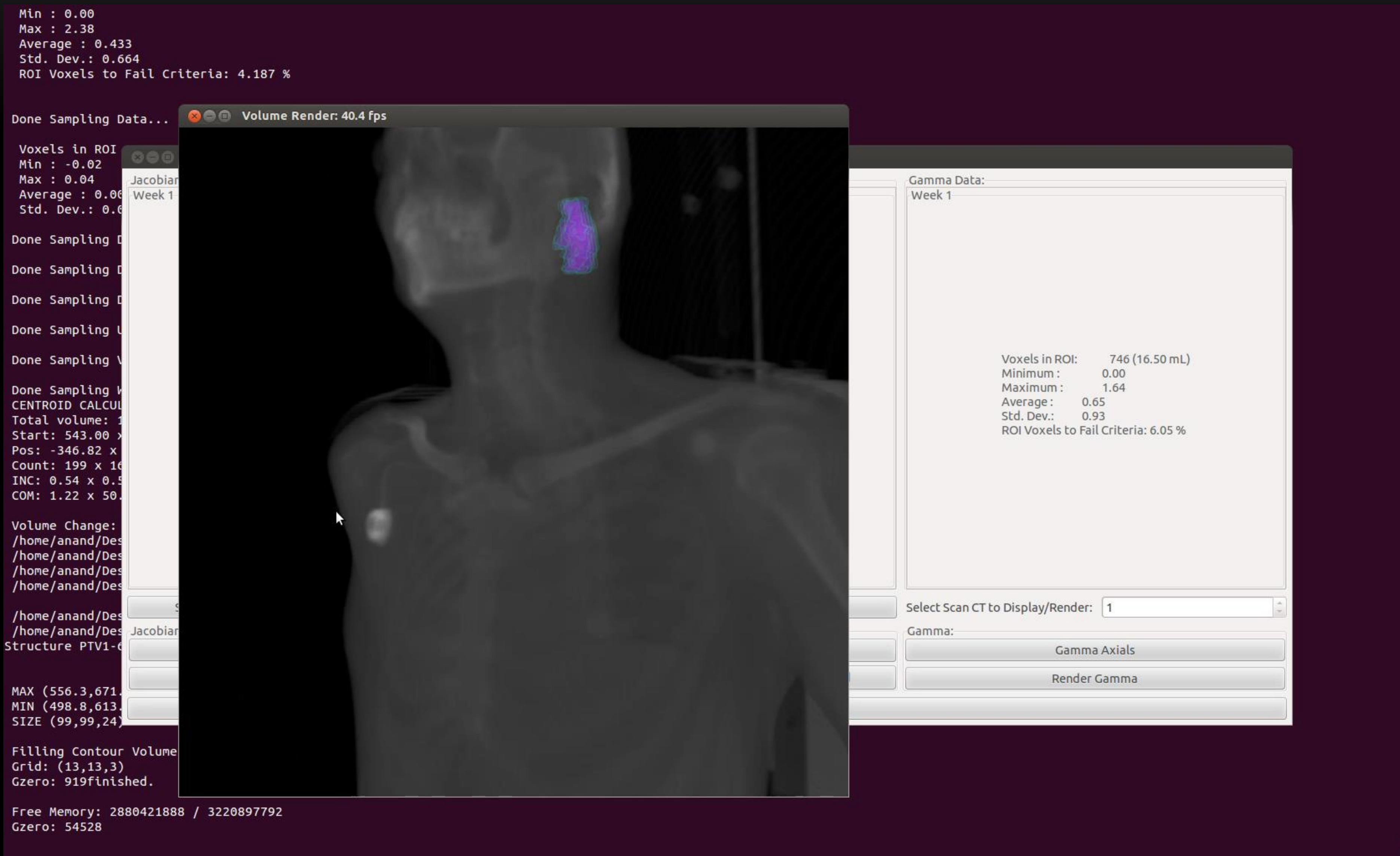




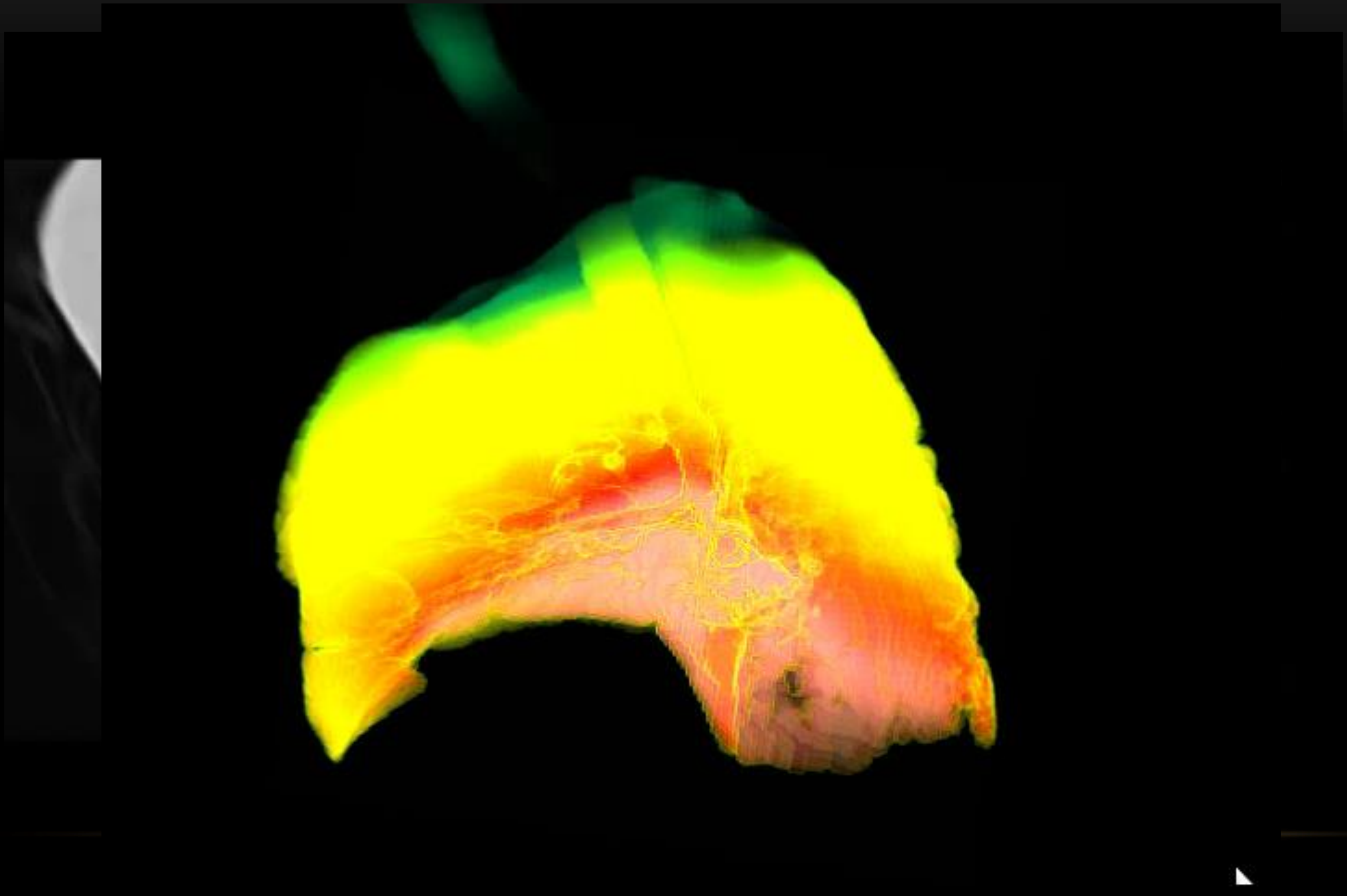
TOOLS FOR ADAPTIVE RADIOTHERAPY - 1

- 3D Image Registration
- 3D Biomechanical modeling
- 3D Dose Calculation

GPU BASED IMAGE REGISTRATION FOR ADAPTIVE RADIOTHERAPY



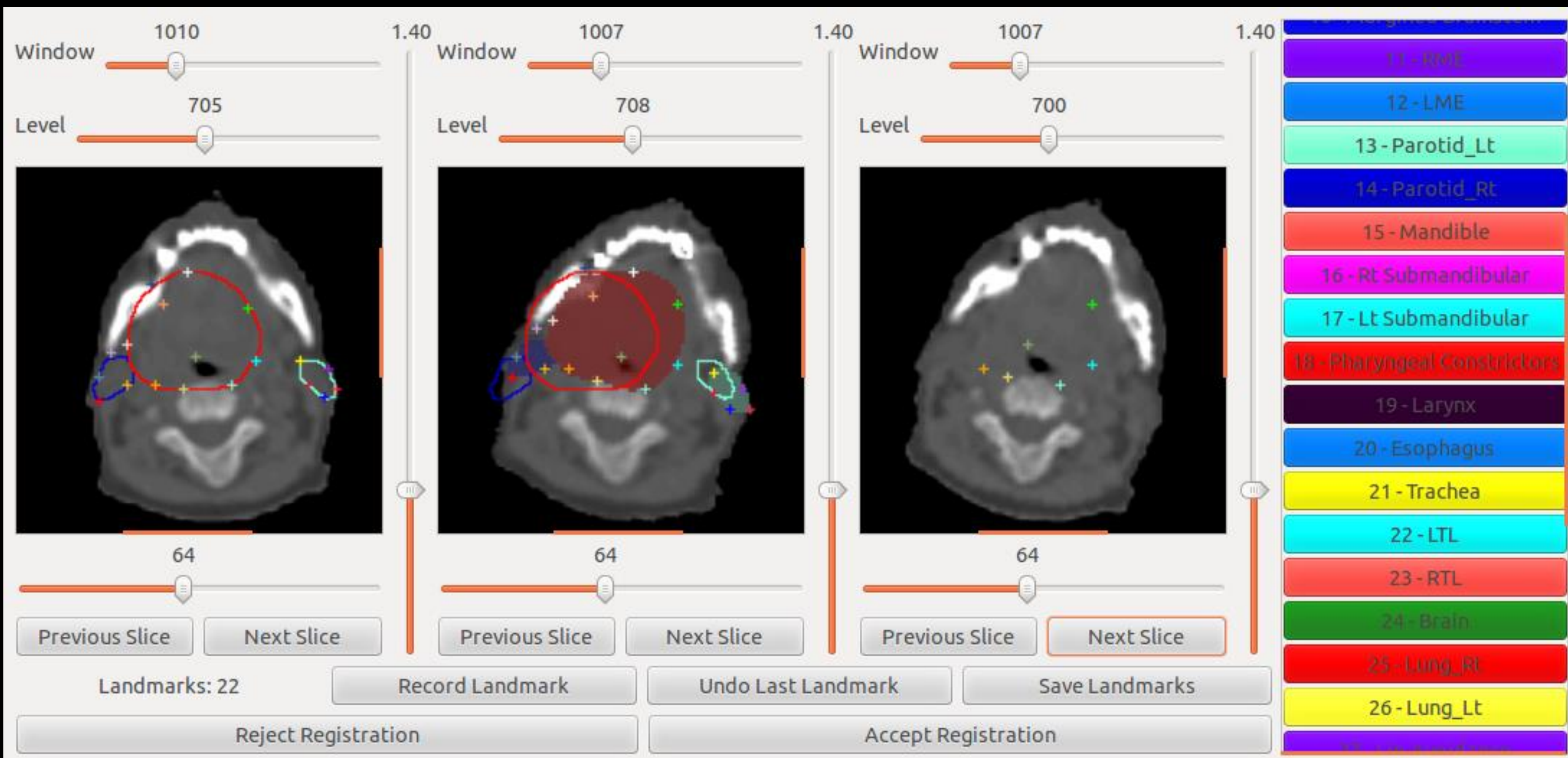
4D CT LUNG REGISTRATION



D. Thomas, *et al.*, "A Novel Fast Helical 4D-CT Acquisition Technique …," *International Journal of Radiation Oncology*Biology*Physics*. 2014

DEFORMABLE IMAGE REGISTRATION ACCURACY

- Registration error is typically quantified using manually placed landmarks
- Validation hampered by lack of ground truth data

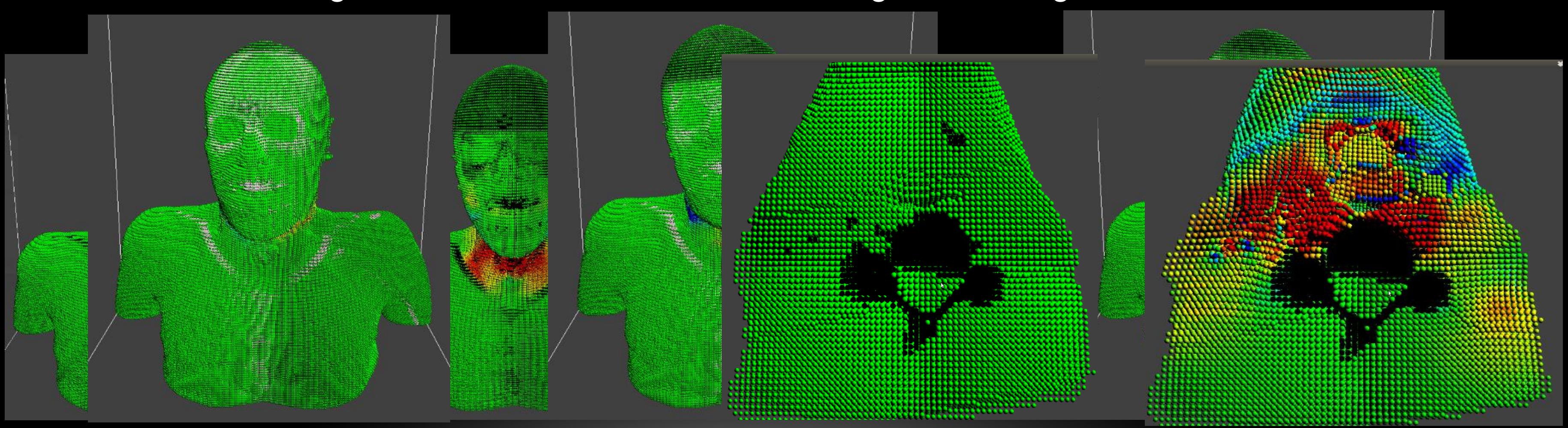


SYSTEMATIC STUDY FOR DIR VALIDATION

- Registration parameters determined through exhaustive search.
- Validation:
  - Landmark based metric
    - Target Registration Error
  - Image based metrics
    - Mutual Information, Correlation Coefficient, Entropy Correlation Coefficient, DICE

SYSTEMATIC DEFORMATION

- 11 Head and Neck Patients were used in the study
- 6 levels of target volume reduction were examined
  - 0, 5, 10, 15, 20, and 30%
- 45 postures were created systematically at each volume reduction level
  - rotating the skull between 4 and -4 degrees along each axis.

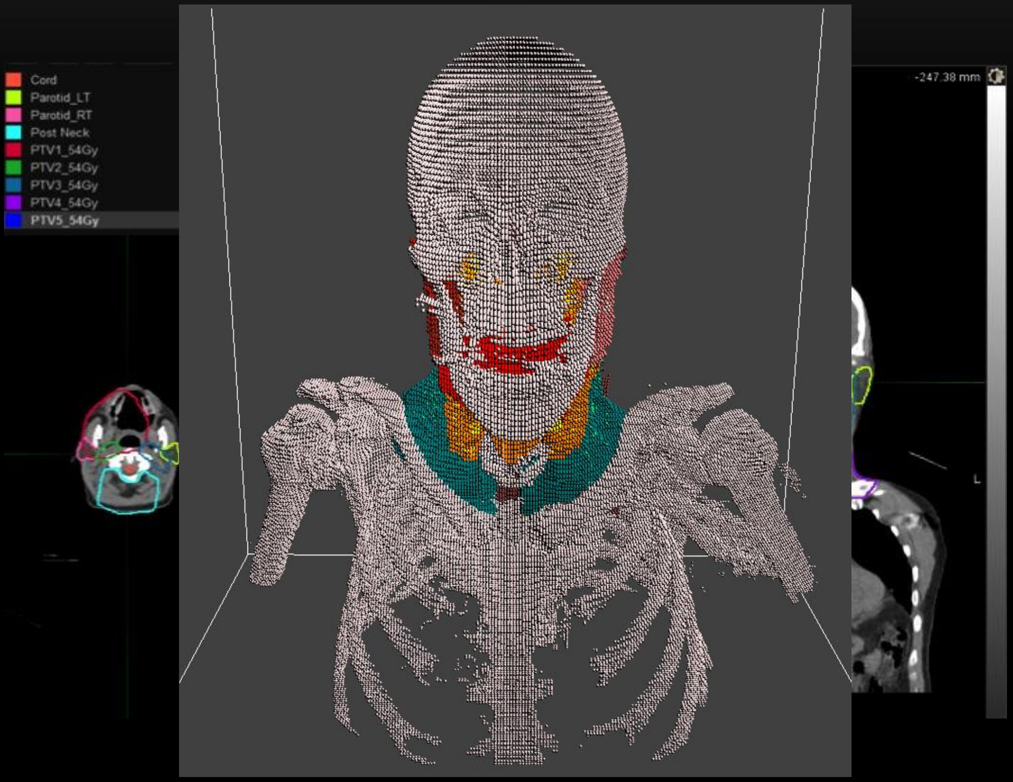


Neylon J and Santhanam AP et al Medical Physics 2015

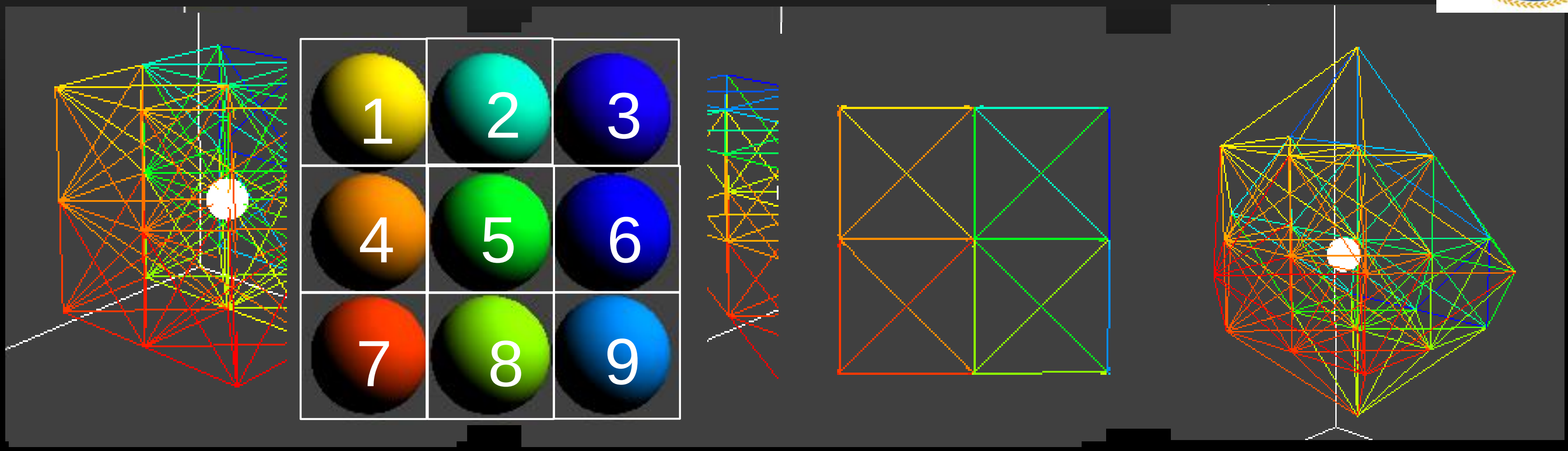
PATIENT SPECIFIC MODEL GENERATION

Initializing the mass-springs

- Load DICOM CT
- Load DICOM RTSTRUCT
- Volume Filling Algorithm
- Assign elements to structures
- Establish spring-damper connections
- Set material properties



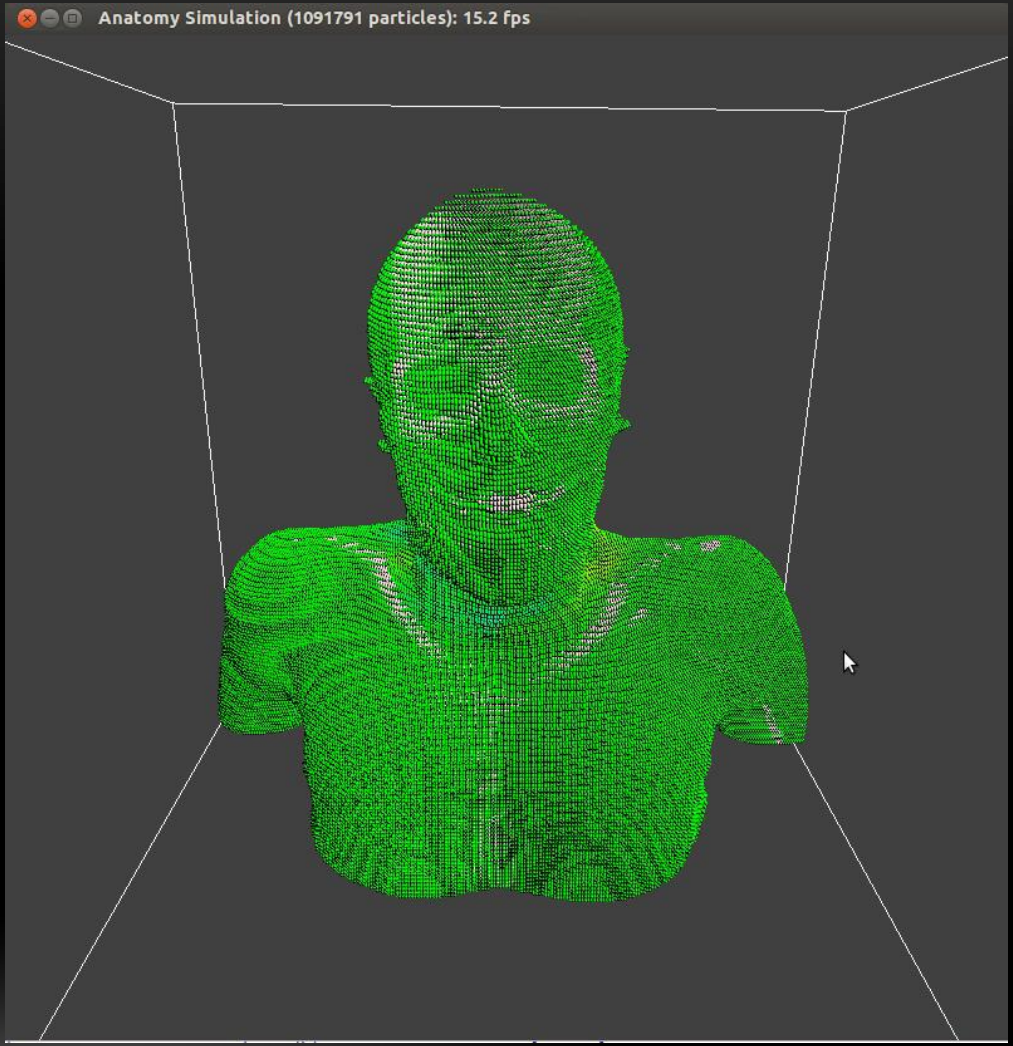
GPU BASED MASS-SPRING SYSTEM



- Create a uniform cell grid, assign each element a hash value based on cell ID
- Sort by hash using a fast radix algorithm
- Search a 5x5x5 cell neighborhood and establish connections as a 3x3x3 cube, creating 26 ‘springs’ per element
- Record the rest lengths and orientations

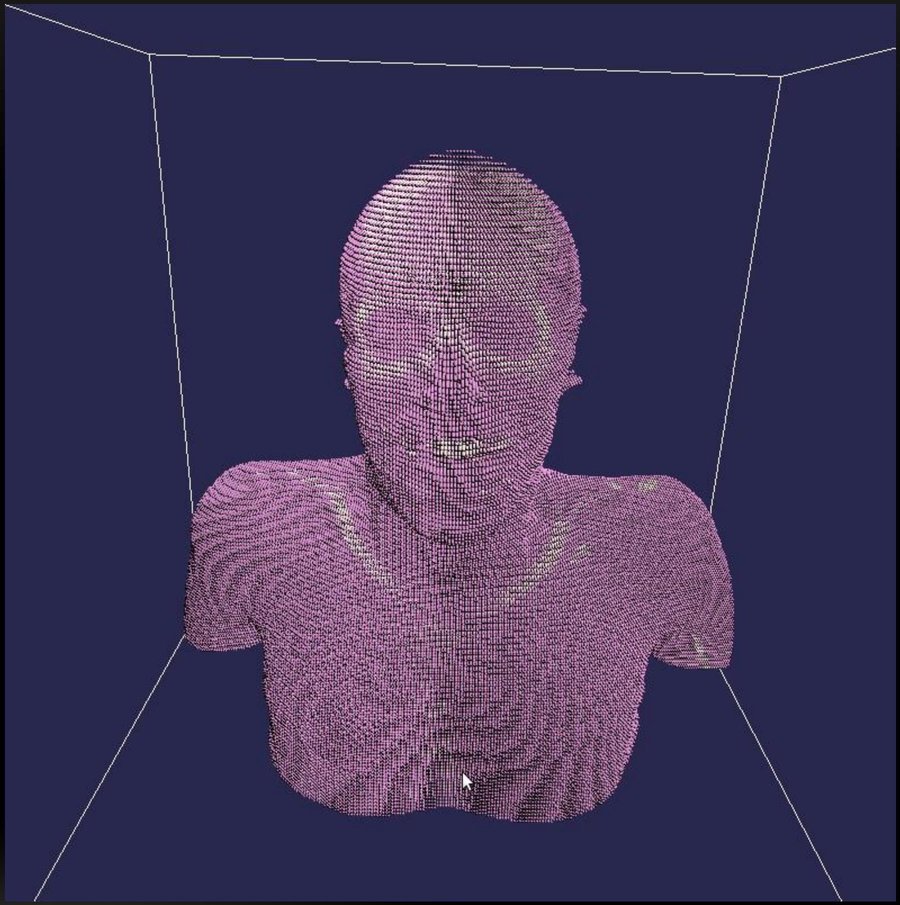
MODEL ACTUATION

- Control the skeletal anatomy
  - 1 degree rotations about each axis
- Soft Tissue deforms due to elastic forces
- The color map illustrates areas of compression (blue) and strain (red)



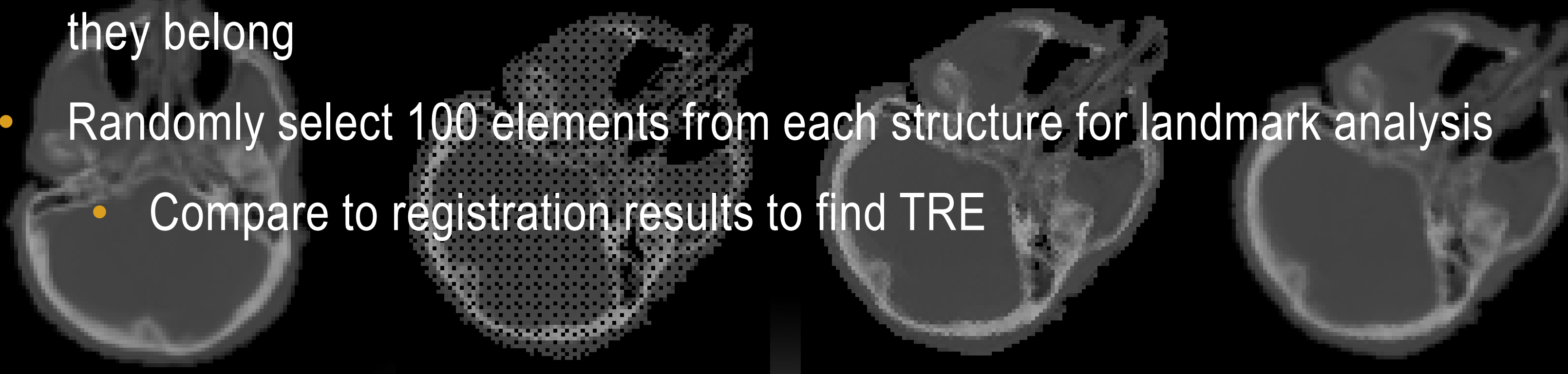
VOLUME CHANGES – WEIGHT LOSS

- Volume can be adjusted manually by increasing or decreasing the rest length of the internal connections of a structure
- The update loop uses a two-pass system
  - First - apply the internal structure forces
  - Second - propagate changes to surrounding tissues



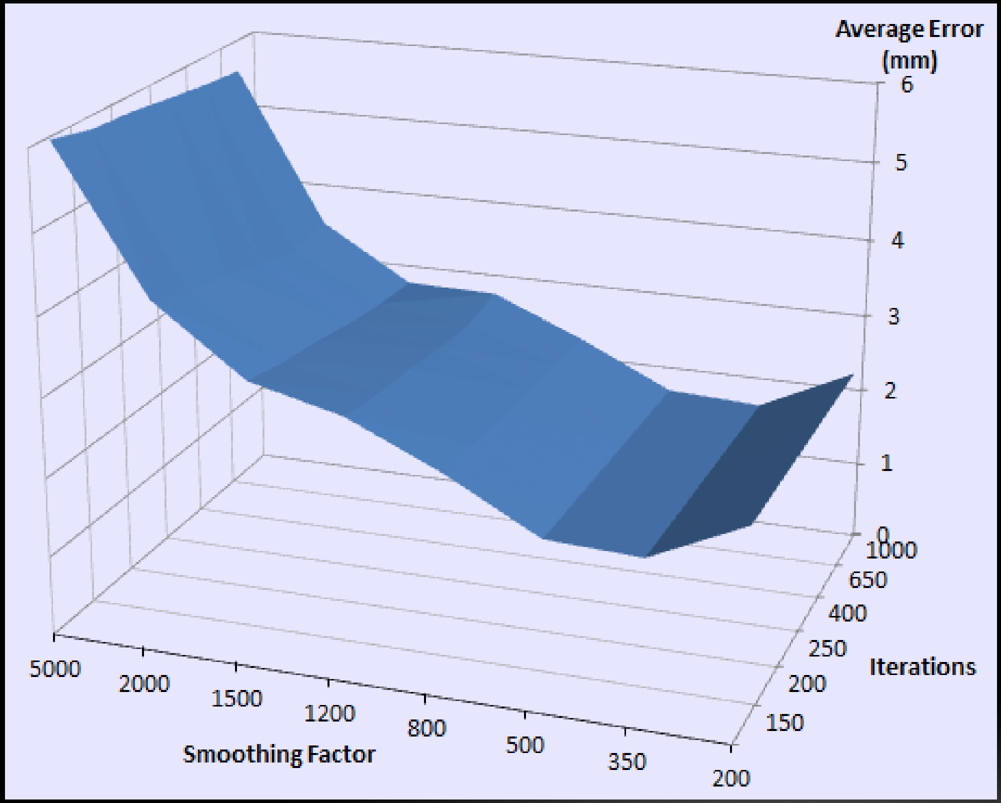
SYNTHETIC DATA CREATION

- Find the voxelized coordinates of each element after deformation
- Rotation and regression causes hole and aliasing artifacts
- Holes are addressed by ray-casting along each spring connection to fill holes
- Aliasing is addressed using a GPU based texture smoothing on edges
- Record the vector displacement of each element and the structure to which they belong
- Randomly select 100 elements from each structure for landmark analysis
  - Compare to registration results to find TRE



PARAMETER SEARCH

- From a set of manually placed landmarks, calculated the target registration error (TRE) for a spectrum of registration parameters.

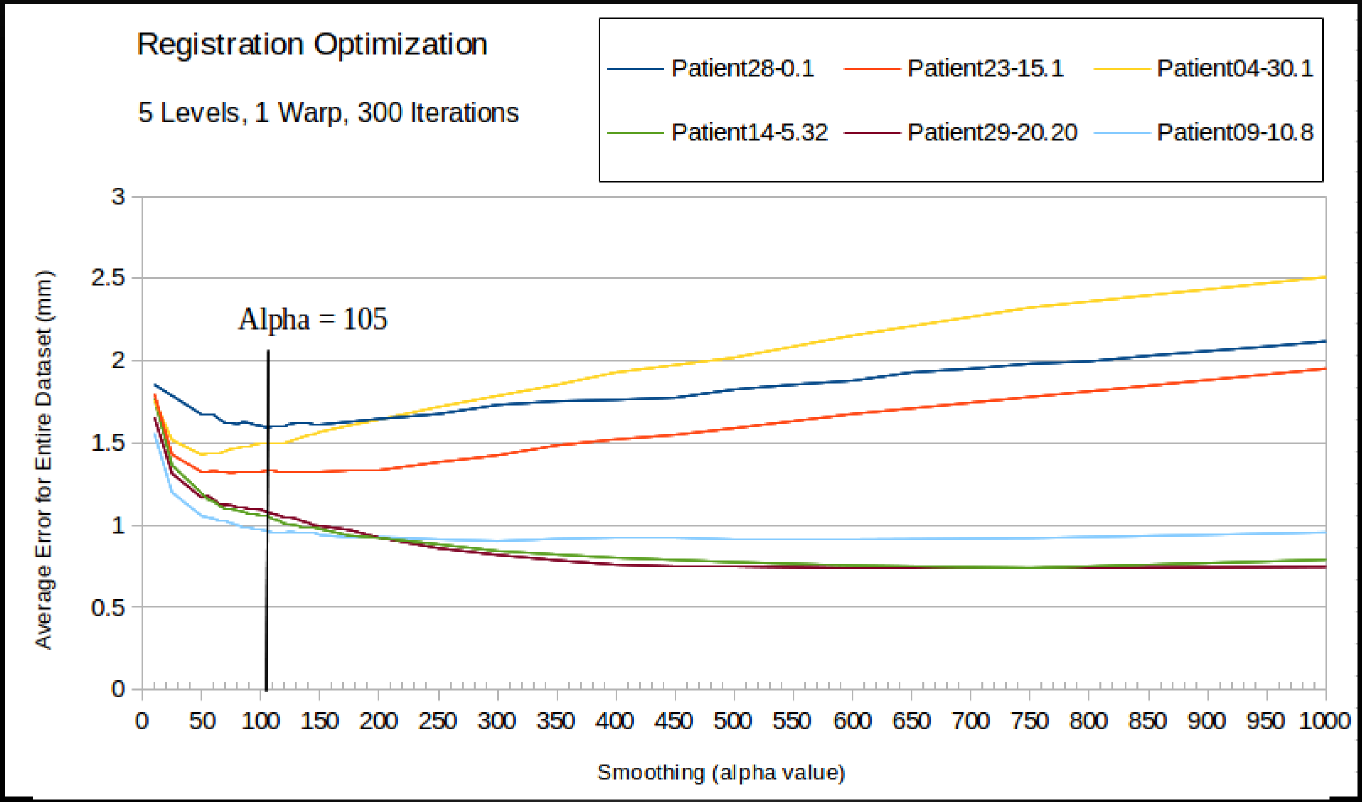


- Error for kV->MV registration with 5 Levels, 1 Warp

- Default parameters:
  - Smoothing: 500
  - Levels: 5
  - Warps: 2
  - Iterations: 150

PARAMETER SEARCH

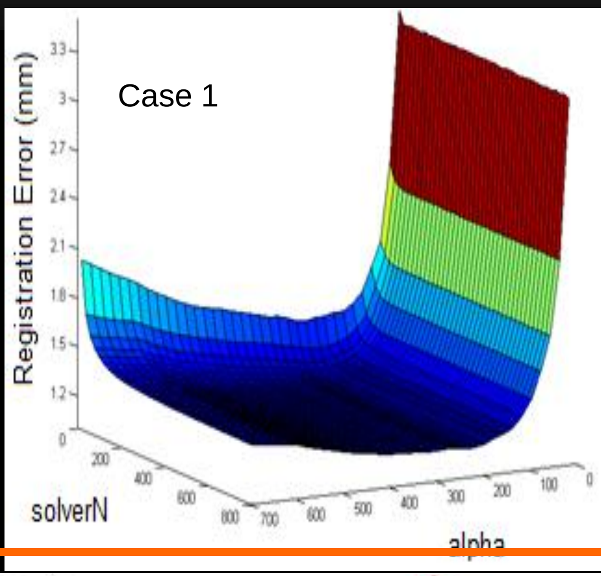
- Similarly for kV->kV registrations

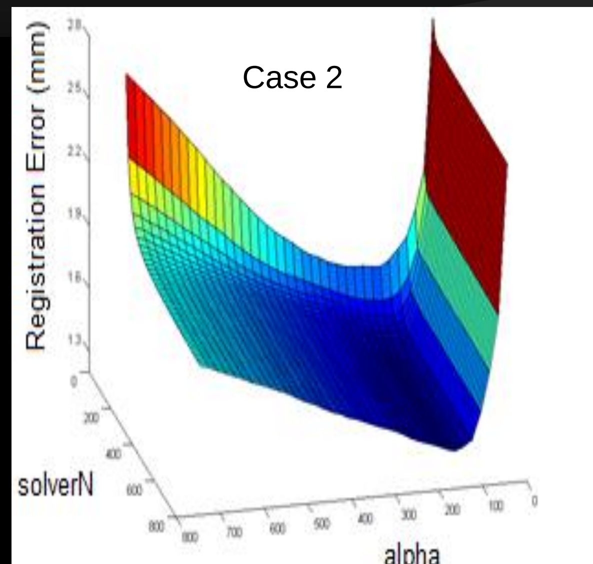


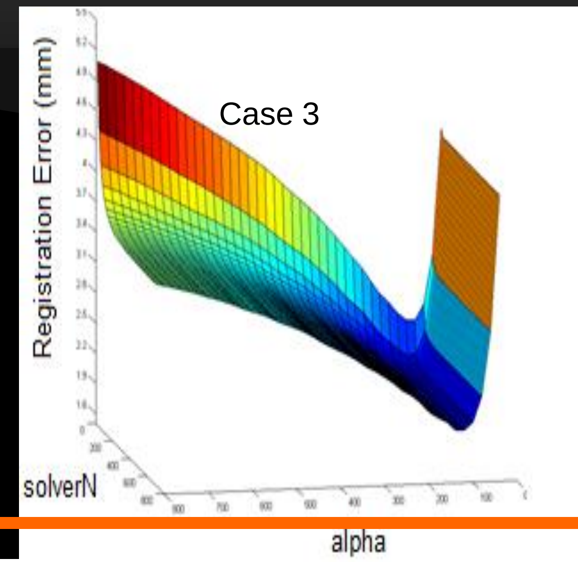
GROUND TRUTH REGISTRATION ACCURACY

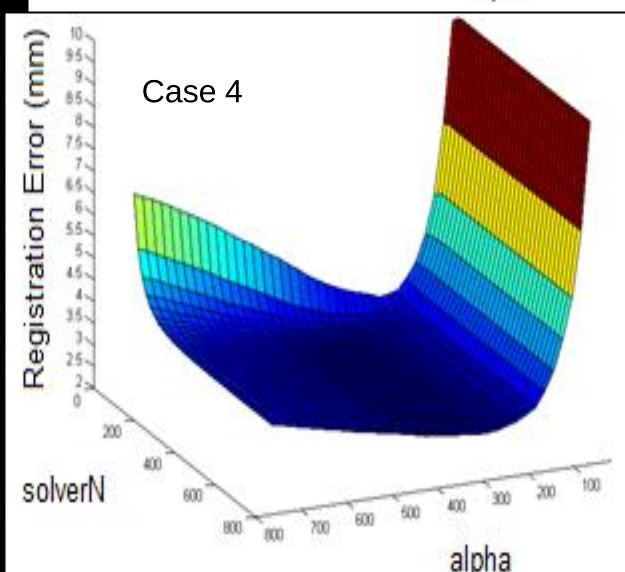
2 Parameter optimization is convex

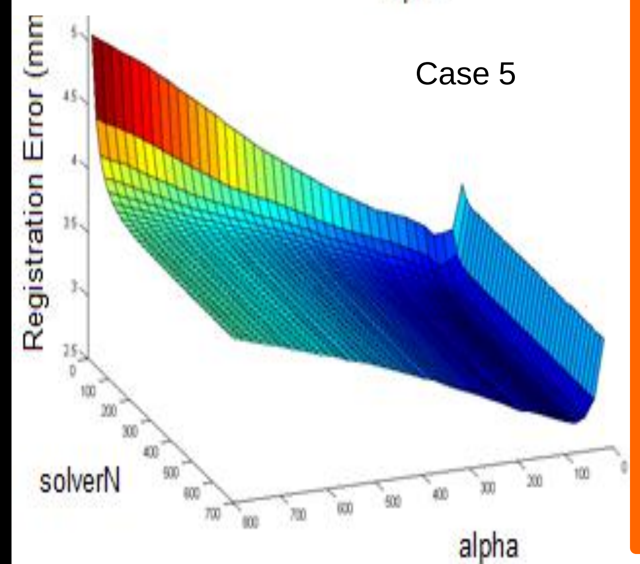
3 Parameter optimization is non-convex

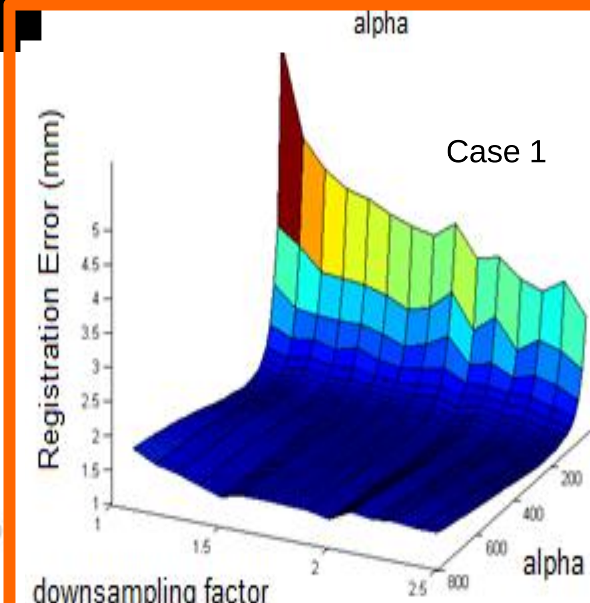




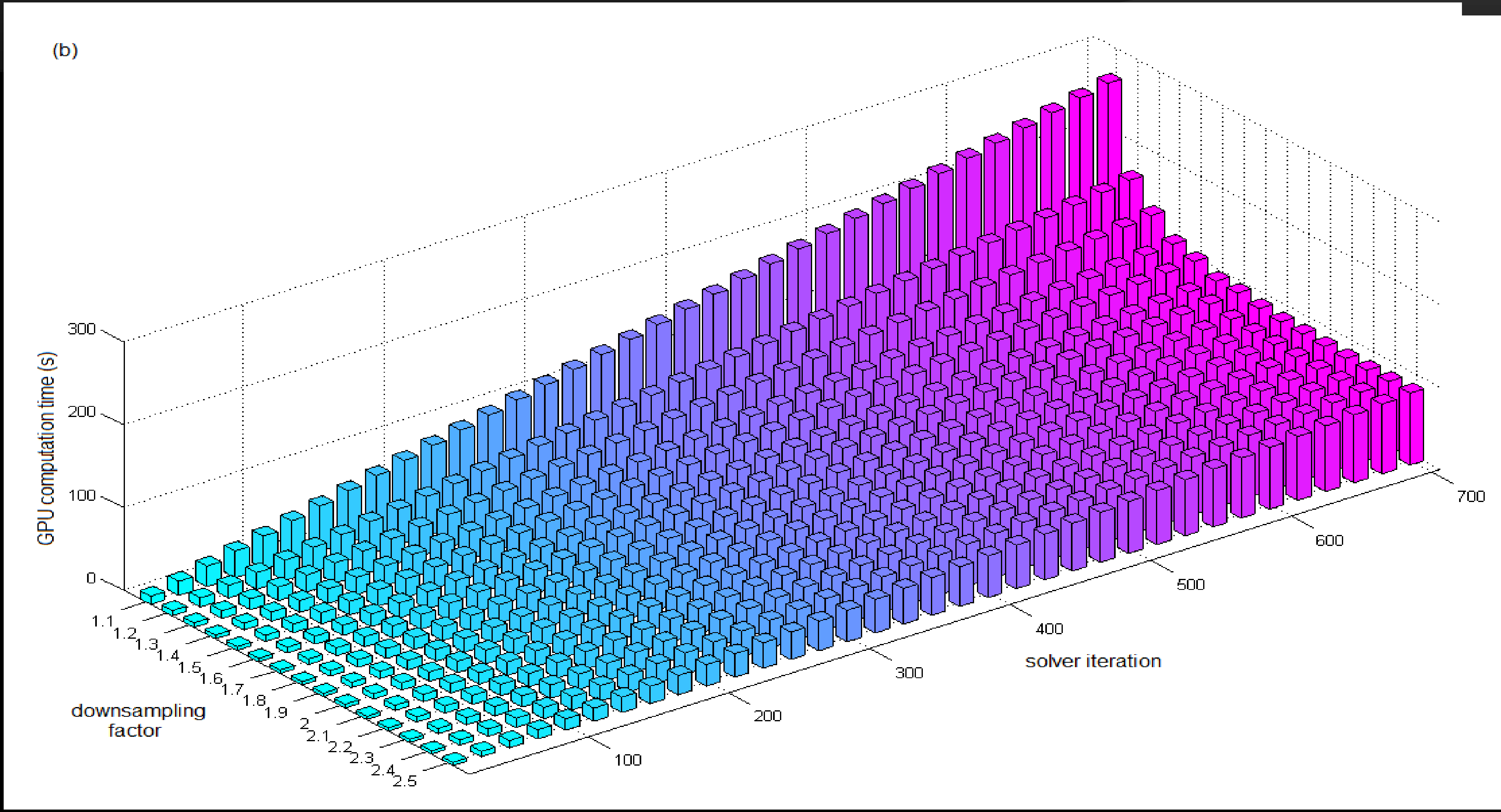








GPU BASED COMPUTATIONS



GPU run time in dependence of the resolution levels and the solver iterations for a whole lung data (a) and separate lung data (b) on a NVIDIA GTX 680 GPU.

LANDMARK BASED DIR VALIDATION

Registration error by patient for head rotation of -4°, -2°, and -2° about the x, y, and z axes, respectively.				
Error (mm)	PTV 1	Parotids	Mandible	Total
Patient 1	0.902	0.906	1.348	0.640
Patient 2	0.743	1.022	1.262	0.779
Patient 3	0.845	2.227	2.615	0.926
Patient 4	0.674	1.375	1.465	0.872
Patient 5	0.925	1.843	1.923	1.094
Patient 6	1.124	0.827	1.135	0.927
Patient 7	0.873	0.936	1.254	0.861
Patient 8	0.925	1.124	1.345	0.951
Patient 9	1.132	1.334	1.659	1.296
Patient 10	0.887	1.473	1.726	0.881

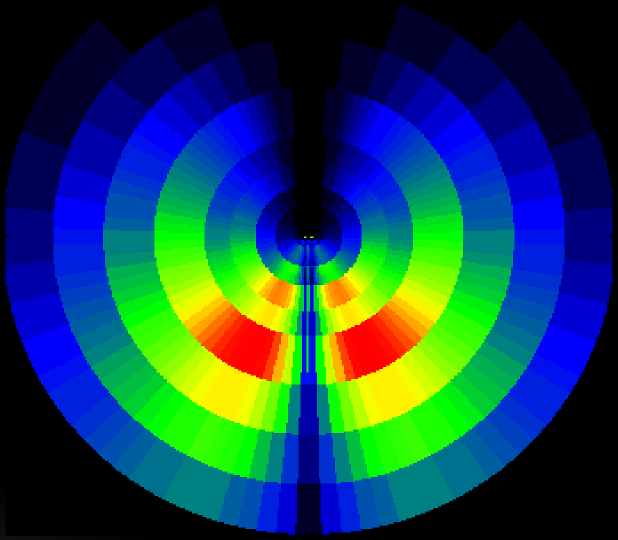
Santhanam AP and Neylon J, ASTRO 2014

GPU BASED DOSE CALCULATION

- Convolution/Superposition

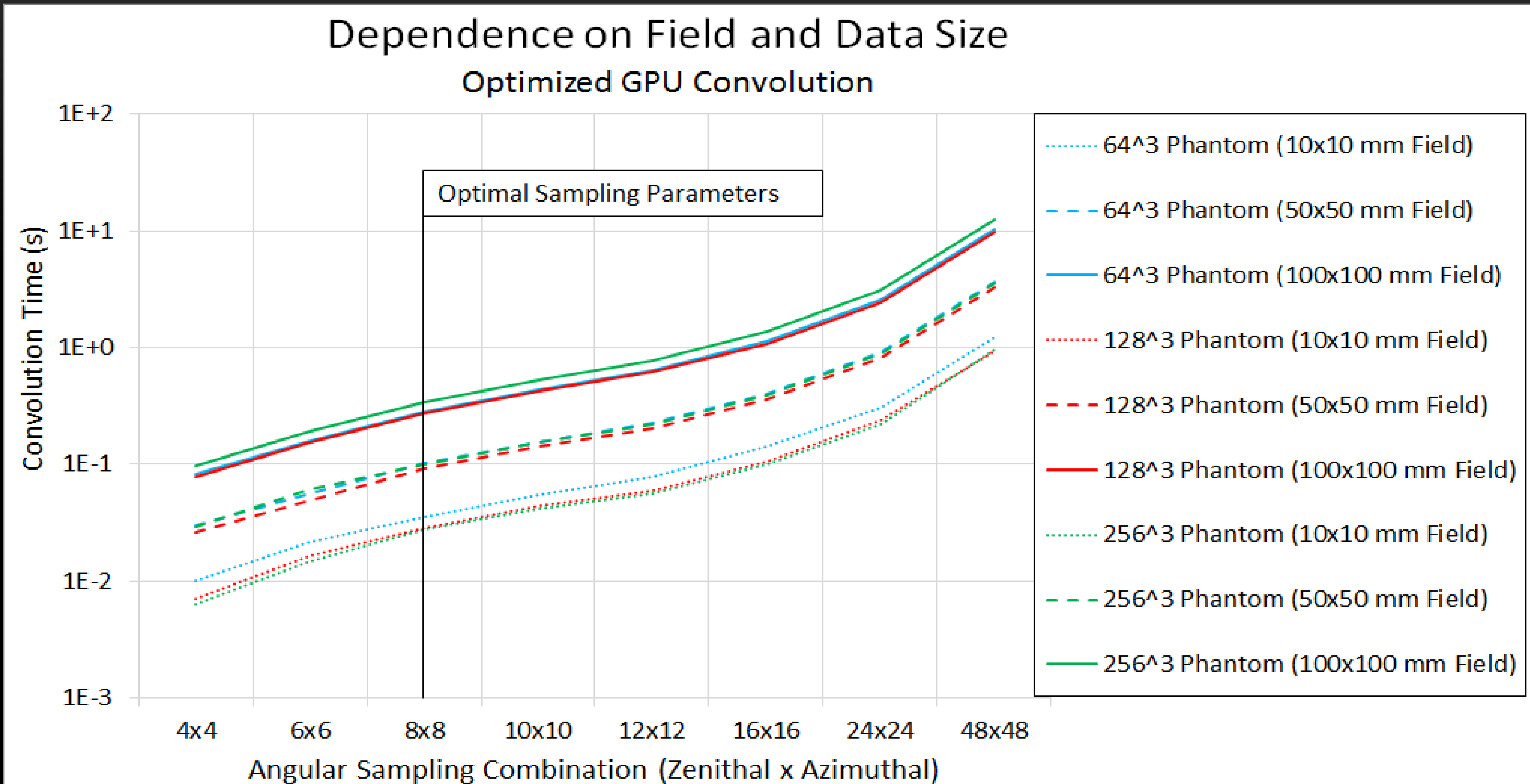
$$Dose(v) = \int T'(v')H(\bar{\rho}_{v-v'}(v - v'))d^3v'$$

- Naïve Implementation
  - Port CPU algorithm directly
  - Calculate every voxel simultaneously
- Optimized Implementation
  - Coalesced Global memory - data size invariability
  - Texture memory caching - intrinsic linear interpolation
  - Shared memory utilization – 20x to 30x shorter latencies than Global memory



Neylon J and Santhanam A.P Medical Physics 2014

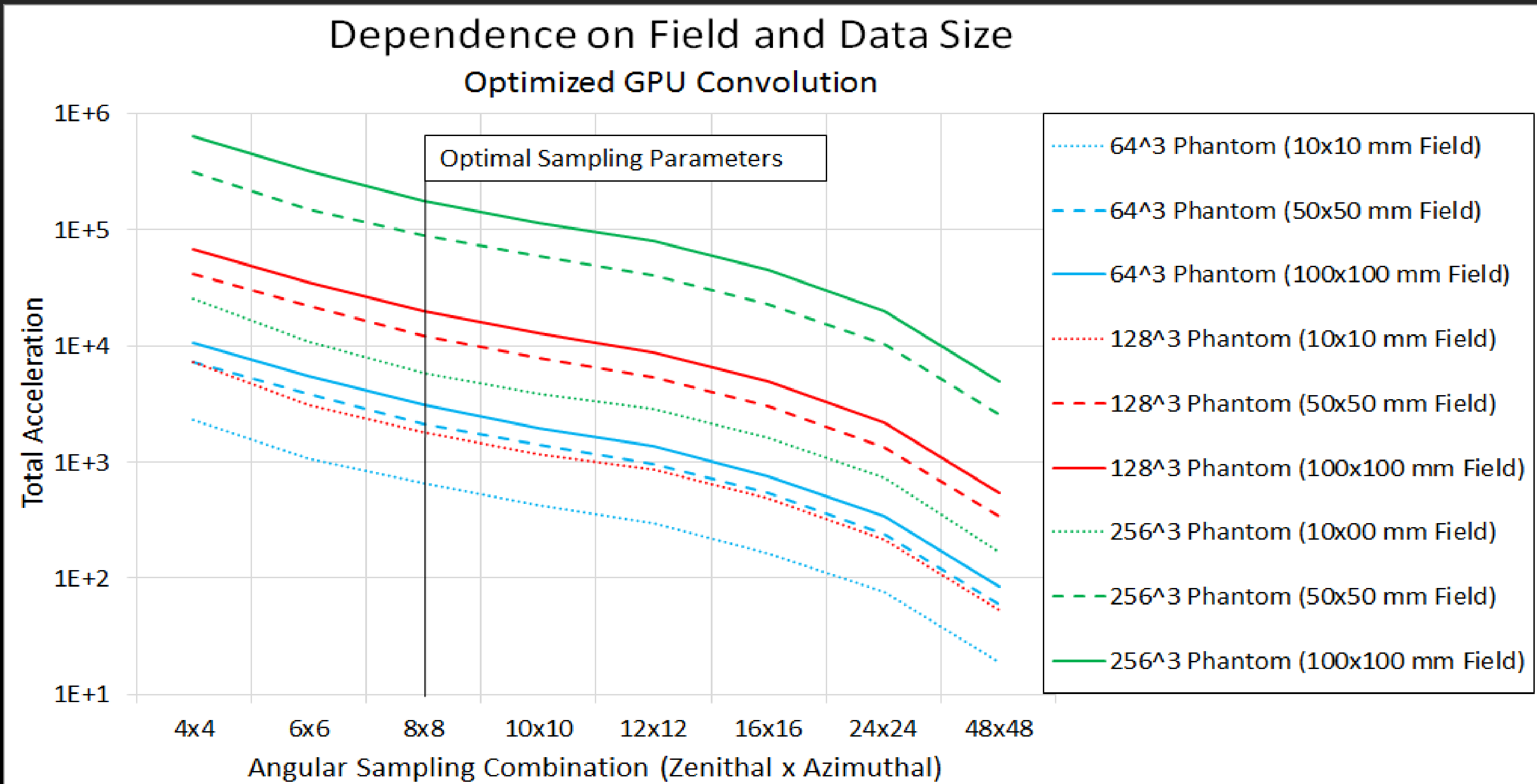
PERFORMANCE – GPU PARALLELIZATION



100x100 mm Field	64^3 Phantom 4 mm voxels	128^3 Phantom 2 mm voxels	256^3 Phantom 1 mm voxels
CPU / Naïve	59.26 1.66	113.2 1.75	193.7 12.76
Naïve / Optimized	1.46 0.04	4.82 0.135	21.6 0.576
CPU / Optimized	86.63 3.49	546.4 20.3	4,175.5 354.96

UCLA Health

PERFORMANCE – SAMPLING + GPU



100x100 mm Field	64^3 Phantom 4 mm voxels	128^3 Phantom 2 mm voxels	256^3 Phantom 1 mm voxels
CPU / Naïve	2,100	4,100	8,200
CPU / Optimized	3,100	19,500	176,000

CONCLUSION

- Adaptive radiotherapy is made possible by GPU based algorithms.
  - 3D Deformable image registration
    - Head and neck – X50 speed-up
    - Lungs - X200 speed-up
  - 3D Biomechanical modeling for motion tracking
    - Head and neck – No comparison
    - Lungs - X200 speed-up
  - 3D Dose calculation
    - X4200 speed-up

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