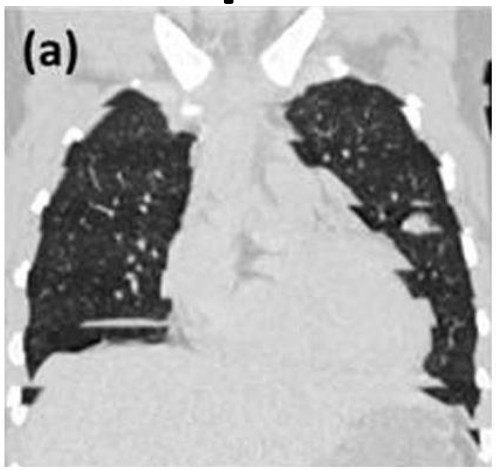
Modeling Breathing Motion

Daniel Low, Ph.D.

UCLA Radiation Oncology

Los Angeles, USA

Analytical and Clinical Technique



- Change approach to “4D”
- Employ motion model
  - Mathematical description of motion
  - First iteration
    - Based on breathing amplitude and rate (originally volume and flow)
    - Linear in amplitude and rate
- Use images to measure motion
  - Simultaneous amplitude measurement
  - Motion information provides model parameters

Motion Model

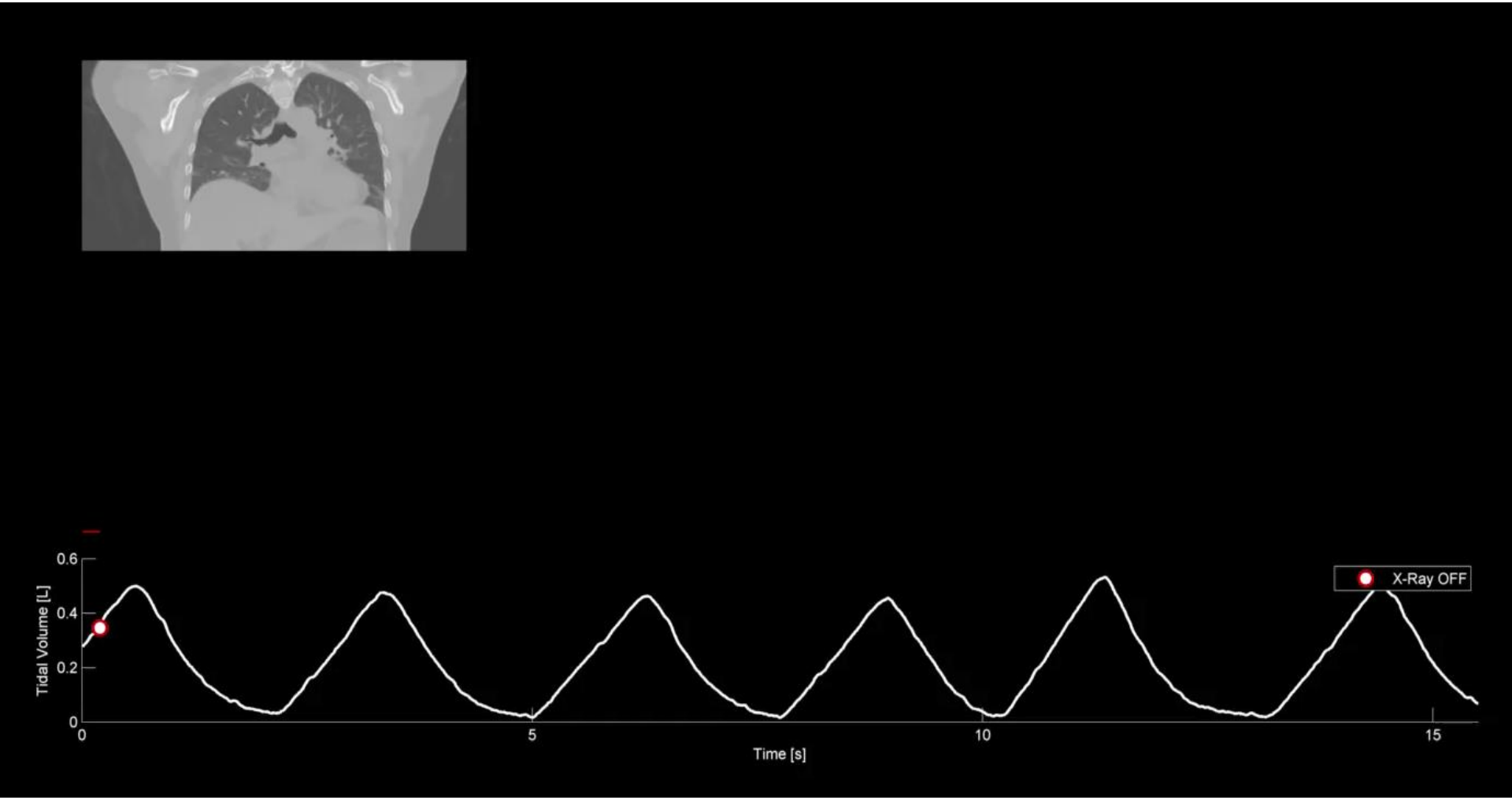
- Linear in amplitude (v) and rate (f)
  - Rate models pressure disequilibria that are hypothesized to cause hysteresis

$$\vec{X}(v, f) = \vec{X}_0 + \vec{\alpha}(\vec{X}_0)v + \vec{\beta}(\vec{X}_0) f$$

Imaging Requirements

- α and β are voxel and patient-specific parameters
- The model needs data
- Data = where are the structures (voxels) as a function of amplitude and rate???
- Old technique: low-pitch helical or cine
- Insight: The images aren't for humans, they provide voxel attenuation and location

5DCT Imaging



Free Breathing Fast Helical

- Fast helical CT scan, 32 or 64-slice CT
  - Pitch 1.2, fastest rotation (approx 0.26s), 40 mAs, approx 1.5-2.5s per scan
- Scan both directions, minimum pause, whole lungs
- 25 times (research protocol)
- Measure breathing cycle during image acquisition
  - Bellows

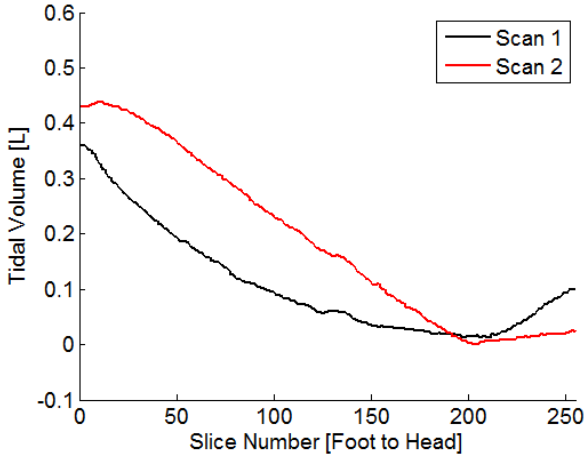
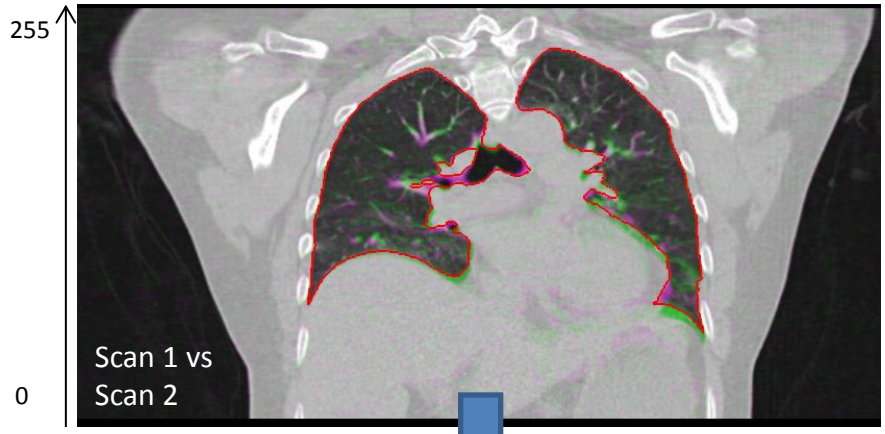
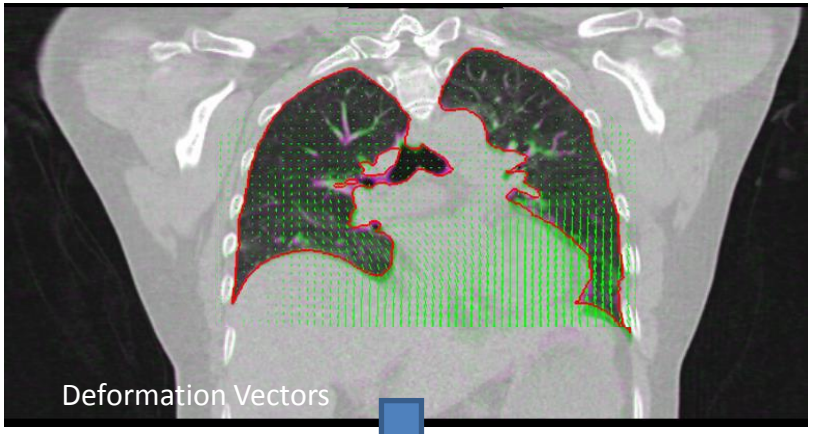
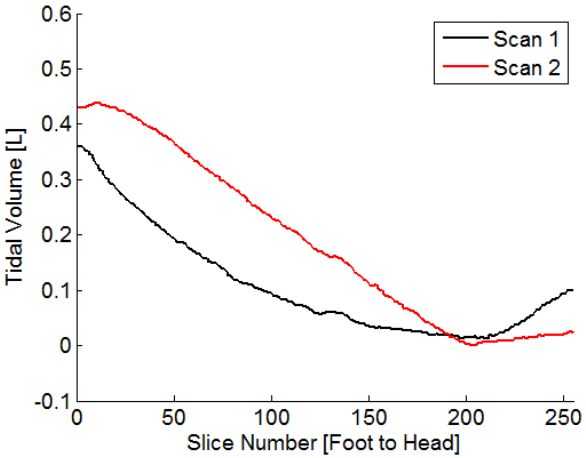


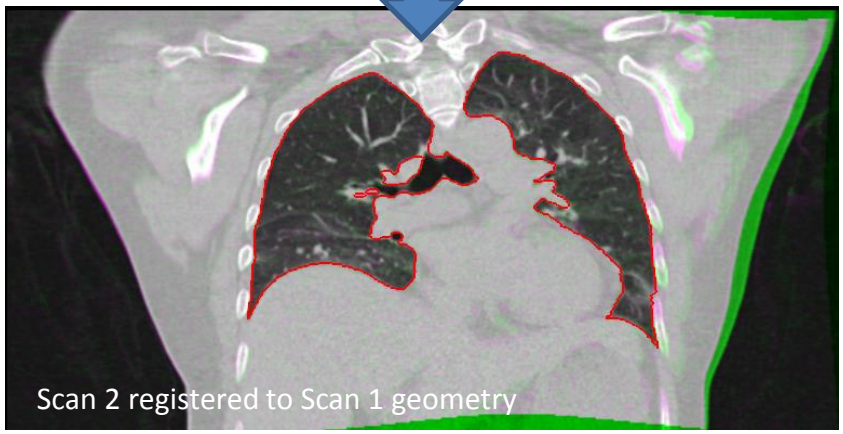
Image Analysis

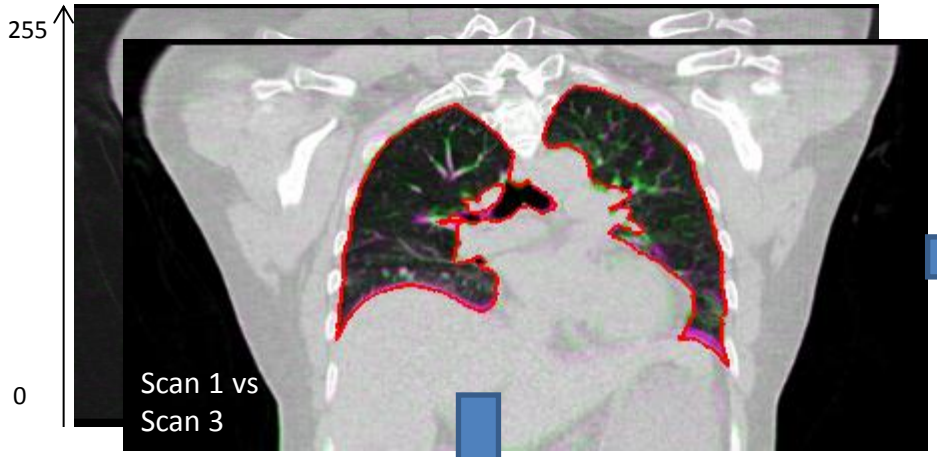
- Segment lungs (shear motion)
- Deformable image registration
- Select scan 1 as “reference” scan and measured distortions of other 24 scans relative to it

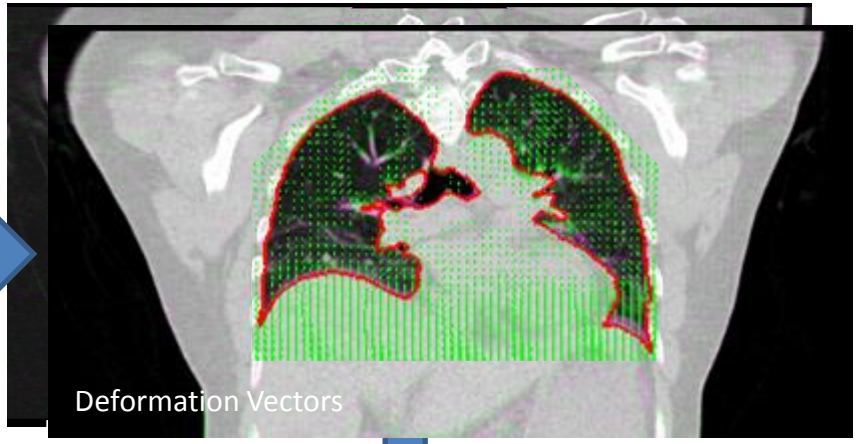

255
0
Scan 1 vs
Scan 2

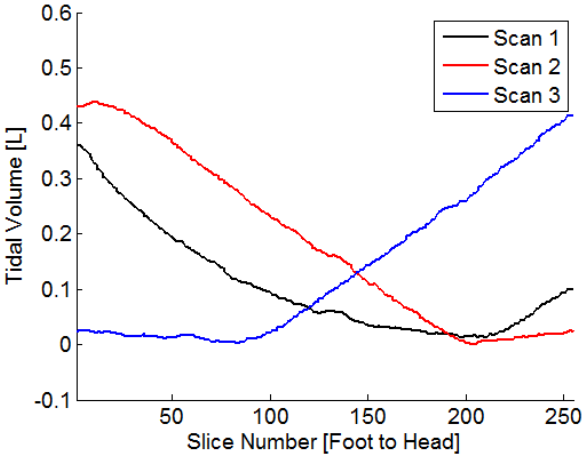

Deformation Vectors

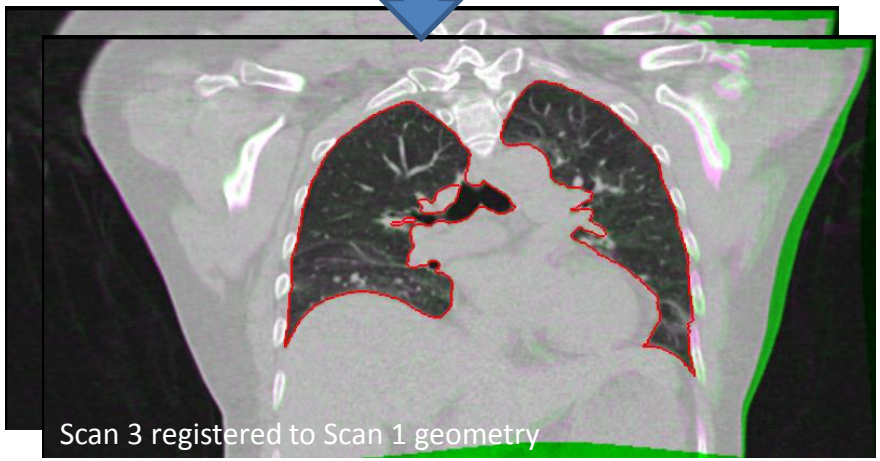

Scan 1
Scan 2
Tidal Volume [L]
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
50
100
150
200
250
Slice Number [Foot to Head]

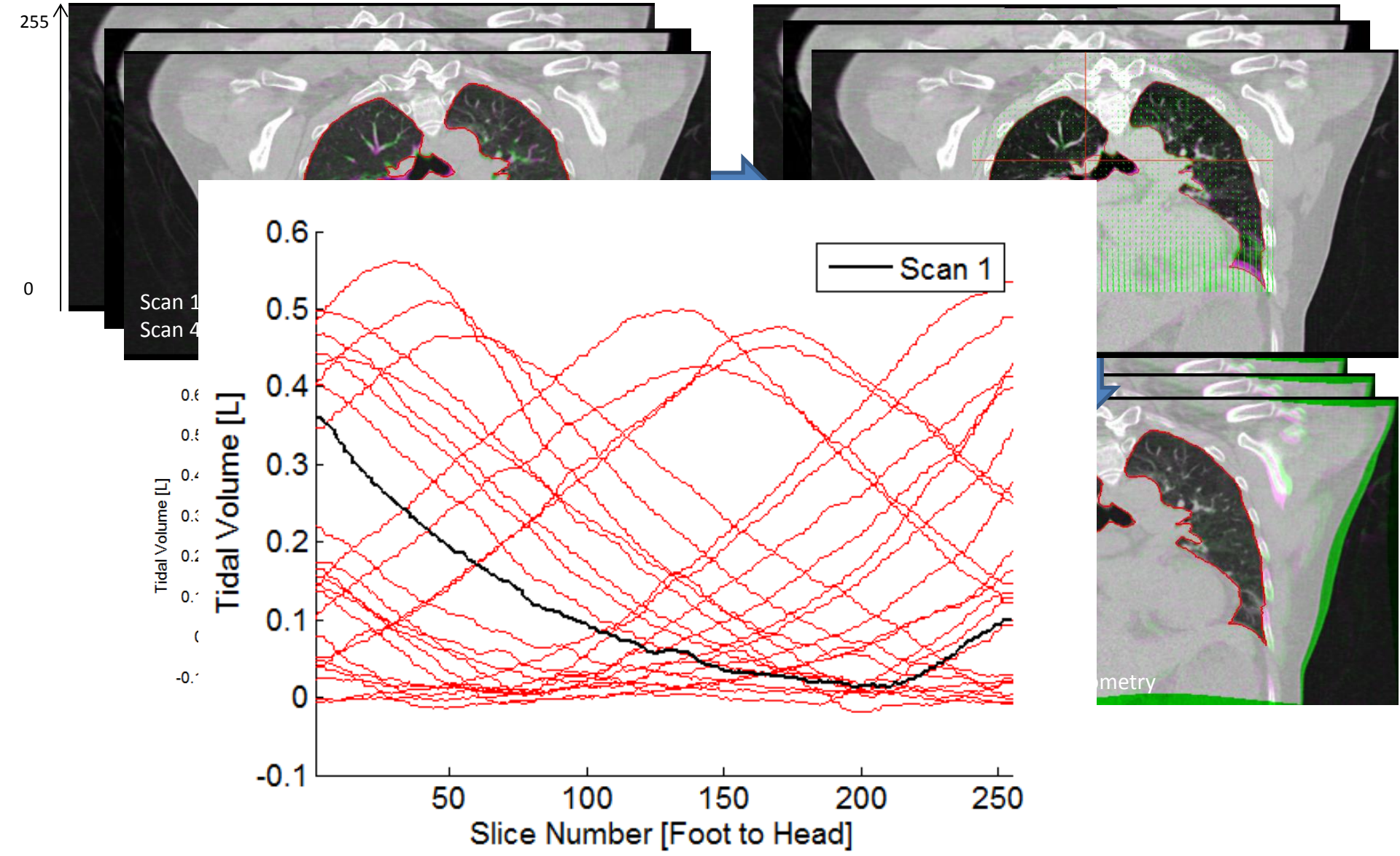

Scan 2 registered to Scan 1 geometry


255
0
Scan 1 vs
Scan 3


Deformation Vectors


Scan 1
Scan 2
Scan 3
Tidal Volume [L]
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
50
100
150
200
250
Slice Number [Foot to Head]

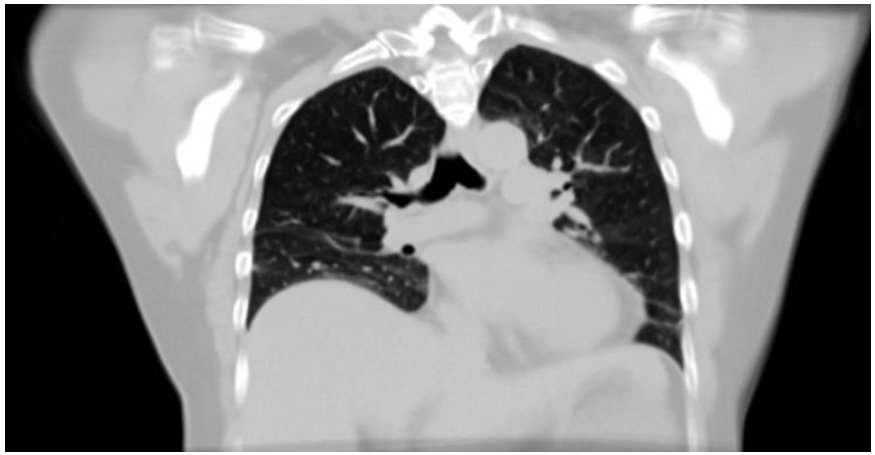

Scan 3 registered to Scan 1 geometry


255
0
Scan 1
Scan 4
Scan 1
Tidal Volume [L]
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
50
100
150
200
250
Slice Number [Foot to Head]
metry

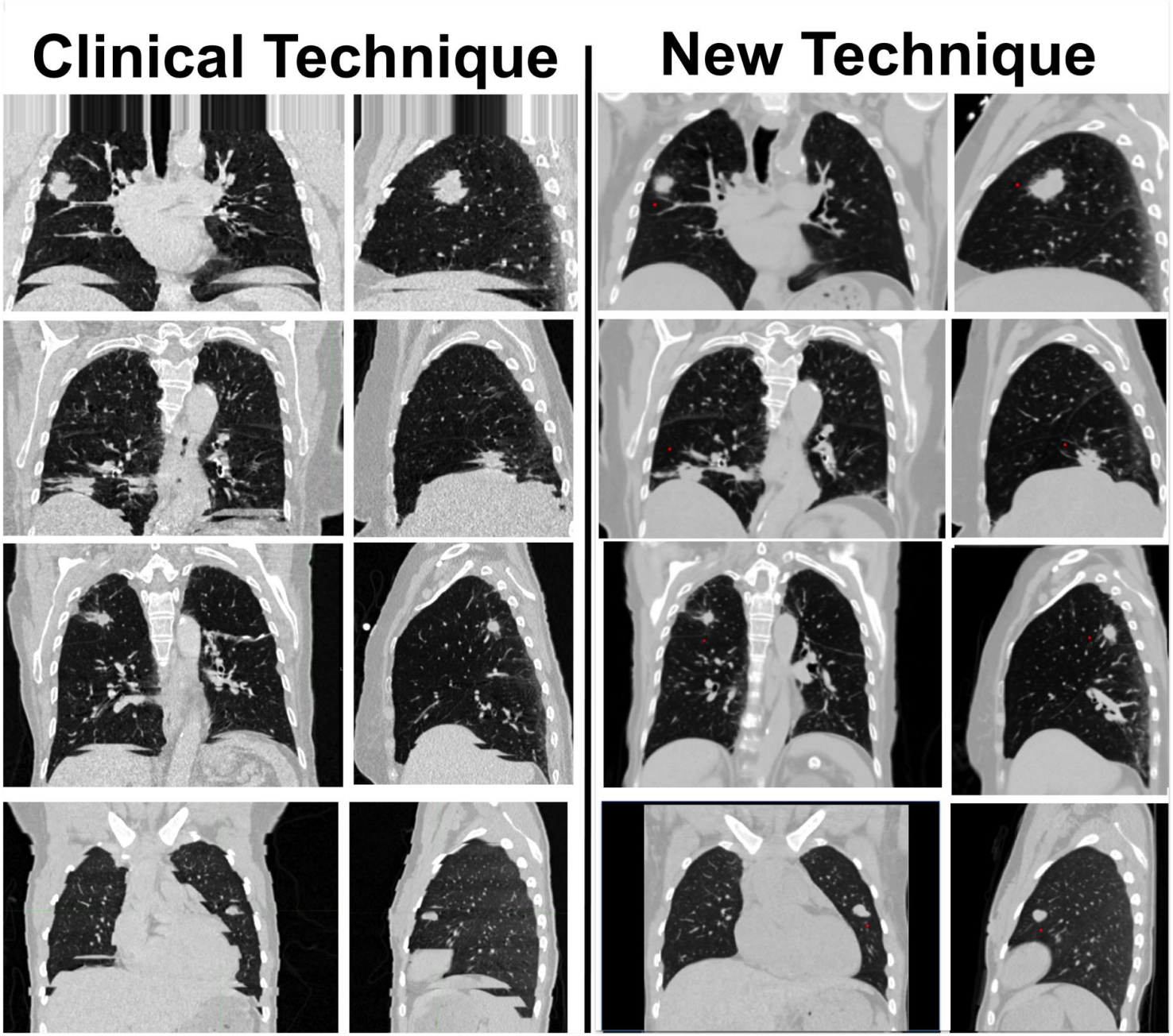
- 25 Scans registered to Scan 1 geometry
- Average HU values
- Fit HU to bellows signal (v)

$$+ \quad \vec{X}(v, f) = \vec{X}_0 + \vec{\alpha}\left(\vec{X}_0\right)v + \vec{\beta}\left(\vec{X}_0\right)f$$

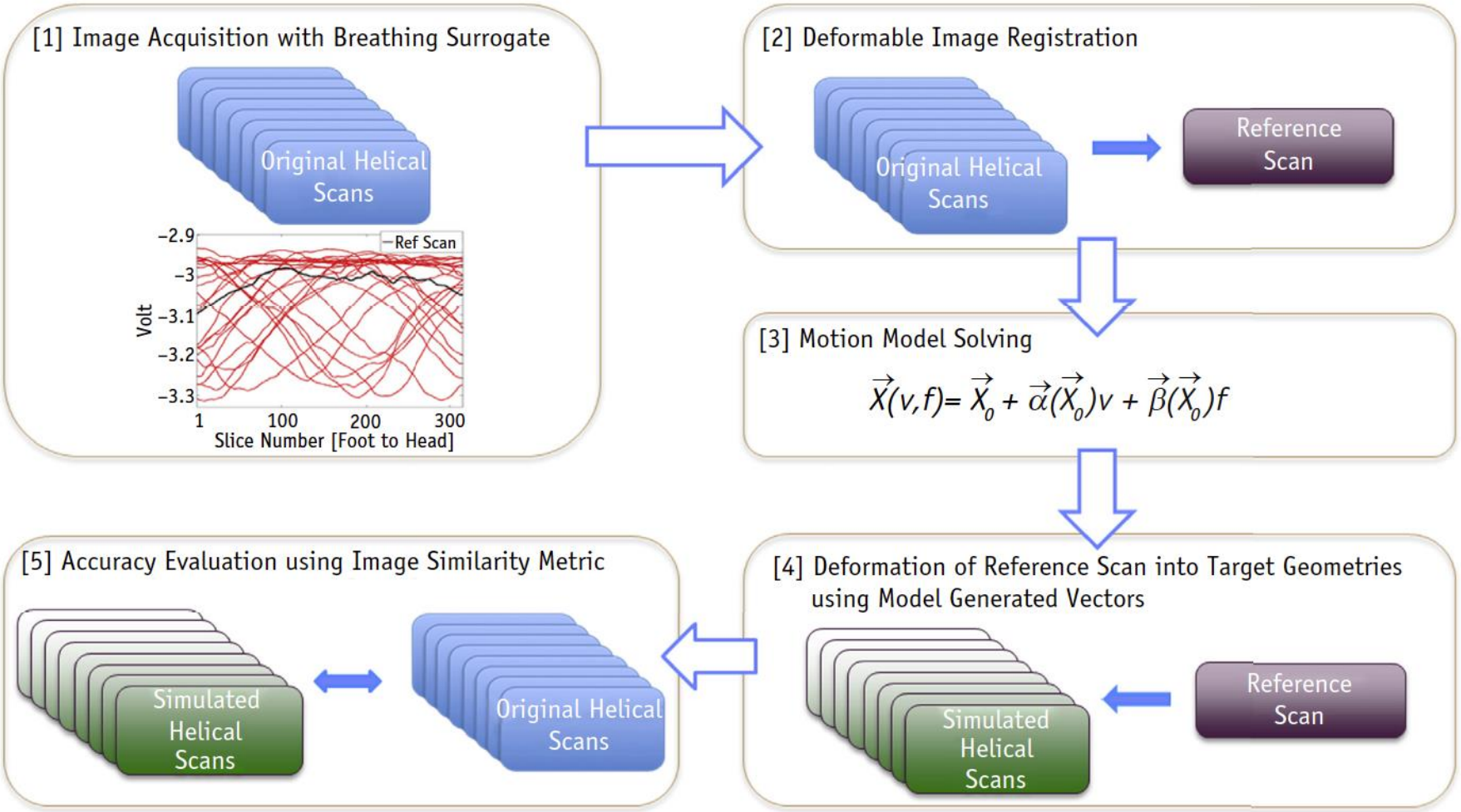
- Deform the low-noise scan from scan 1 geometry to user-selected phase (*v* and *f*)
- Assign accurate HU values each voxel in the reconstructed images



- Psuedo Static Scan 85%ile Inhale

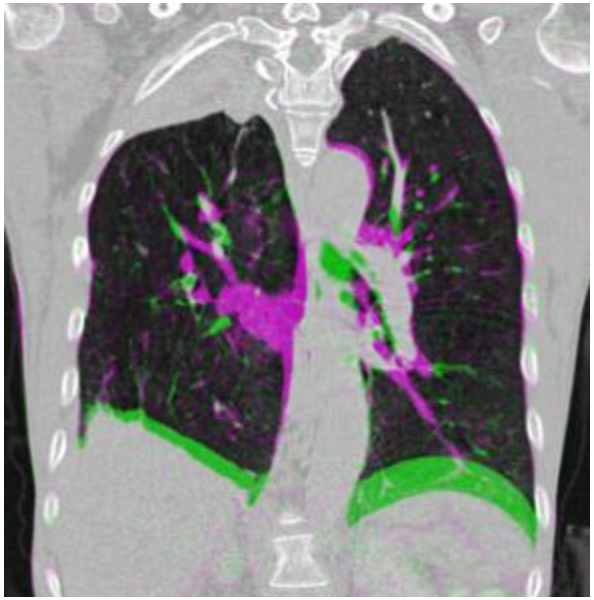

Clinical Technique
New Technique

Pretty, But is it Right?

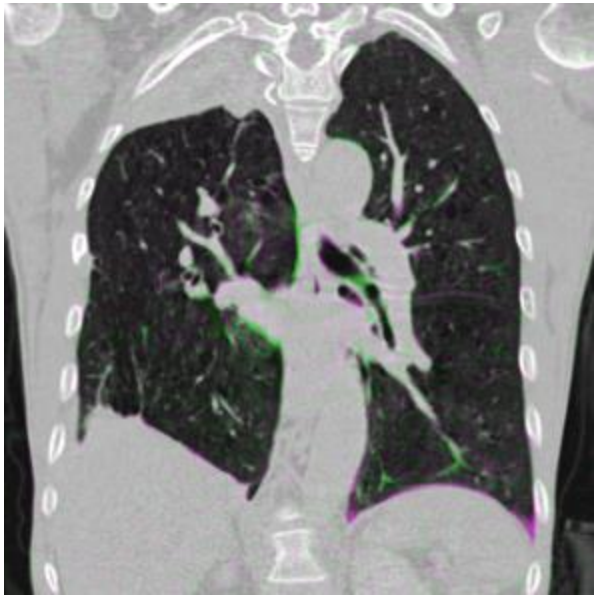


Overlay – Reconstructed Scan vs. Original Scan

[scan 3] vs. [Reference]



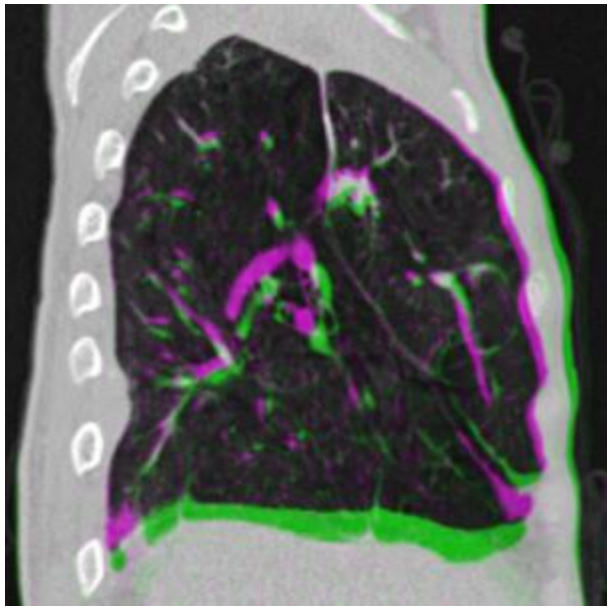
[scan 3] vs. [Reference deformed to scan 3]

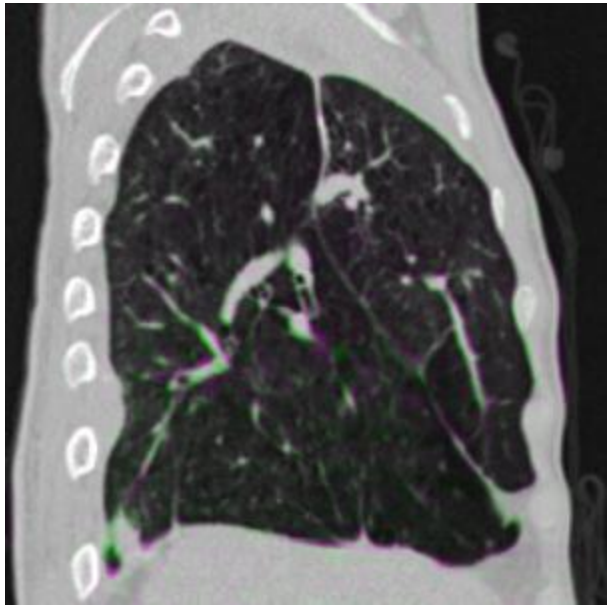


Overlay – Reconstructed Scan vs. Original Scan

[scan 3] vs. [Reference]

[scan 3] vs. [Reference deformed to scan

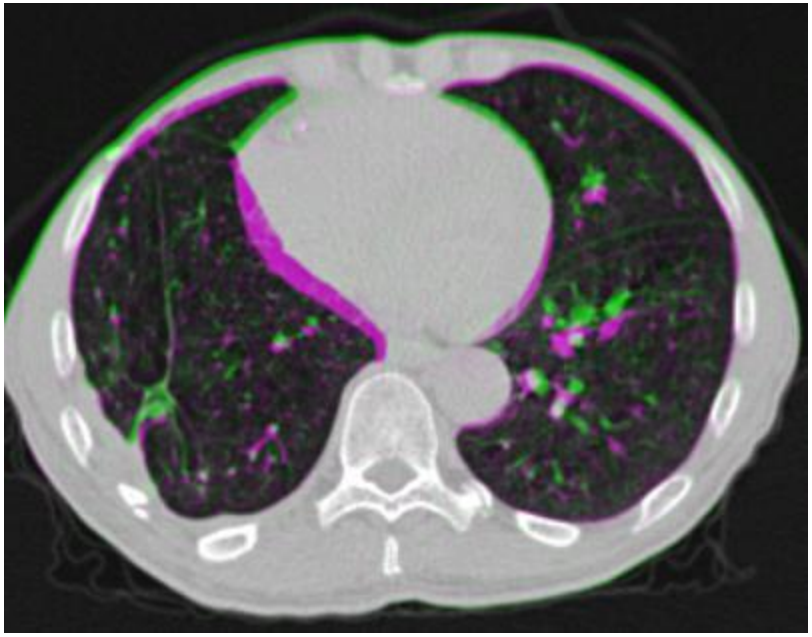


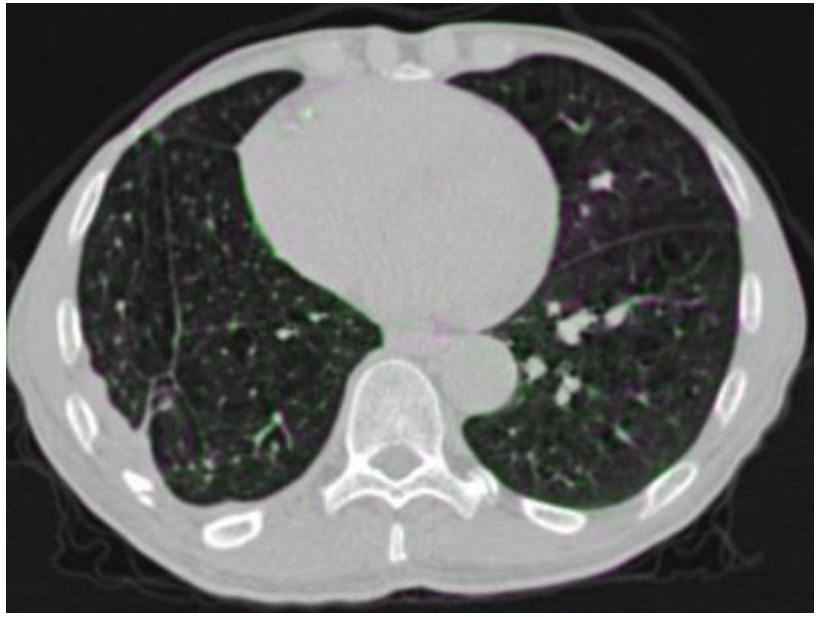


Overlay – Reconstructed Scan vs. Original Scan

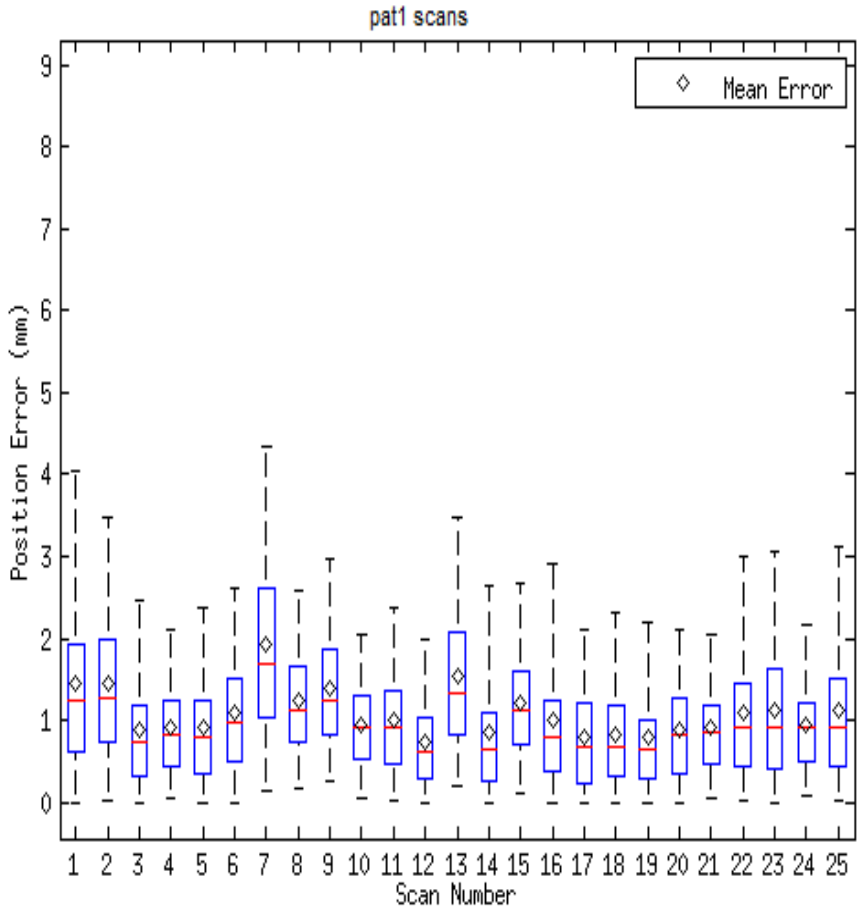
[scan 3] vs. [Reference]

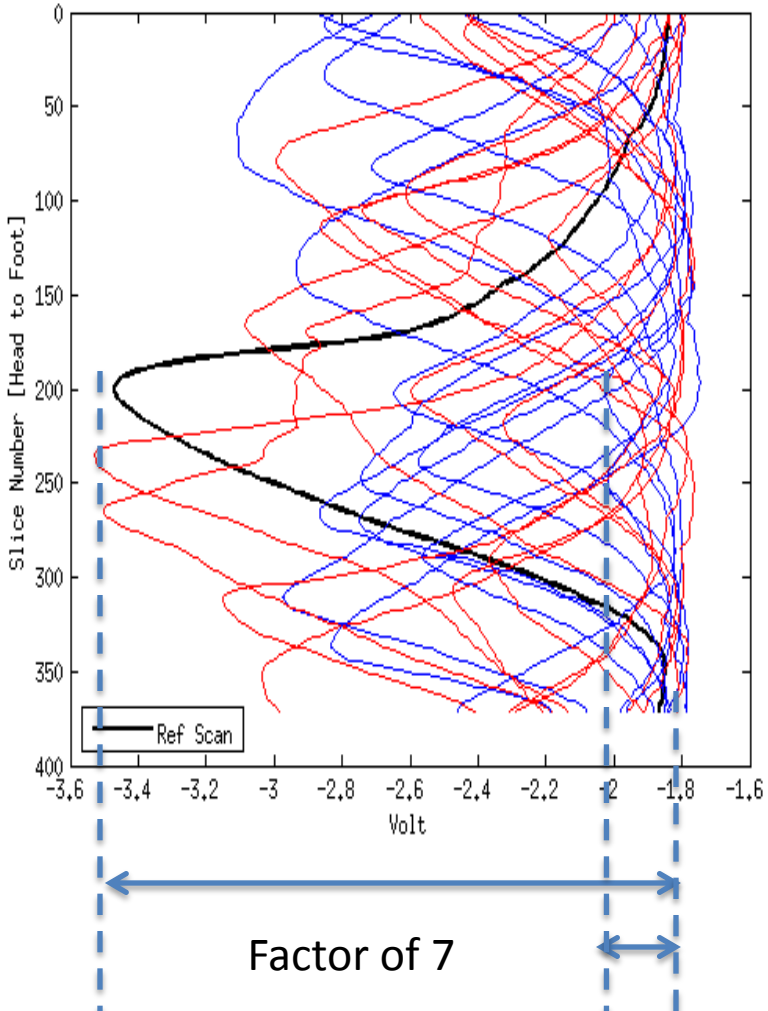
[scan 3] vs. [Reference deformed to scan 3]



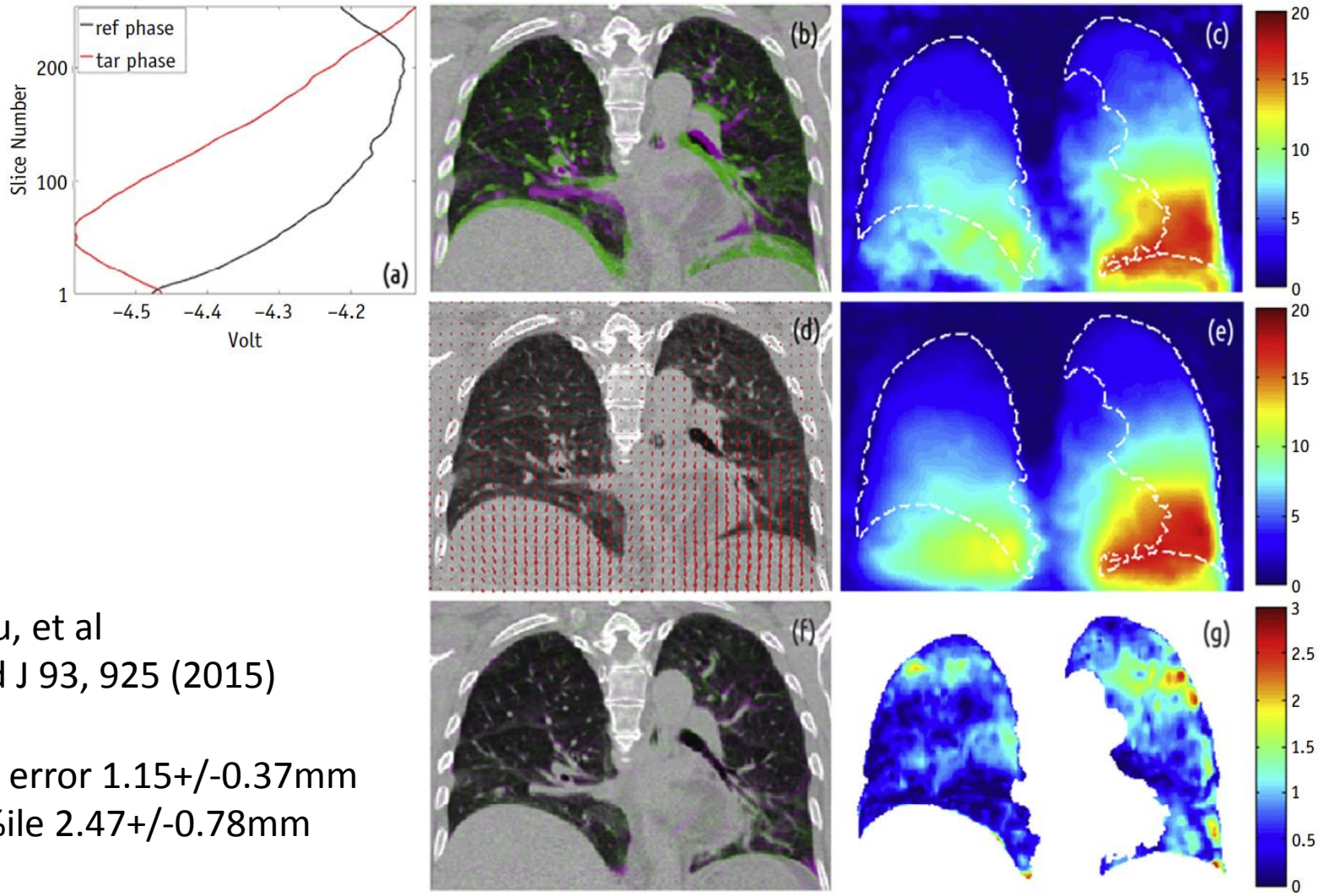


Error Distribution by the Scans





Published Results



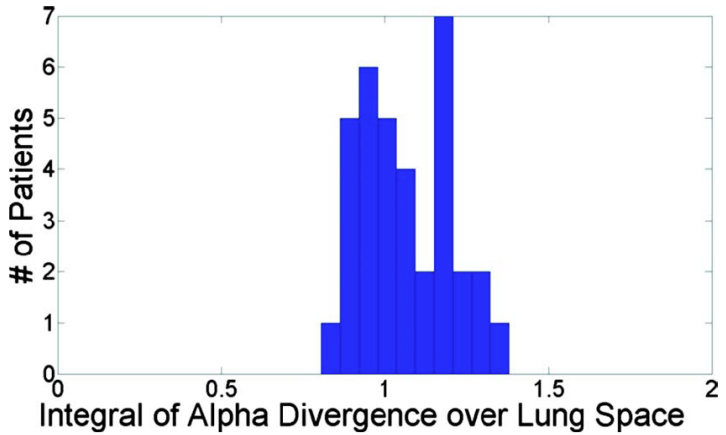
Dou, et al
Red J 93, 925 (2015)

Mean error 1.15+/-0.37mm
95th %ile 2.47+/-0.78mm

Model Verification

- Model is tied to breathing amplitude
- If amplitude is tidal volume, can use mass conservation to develop quantitation validation

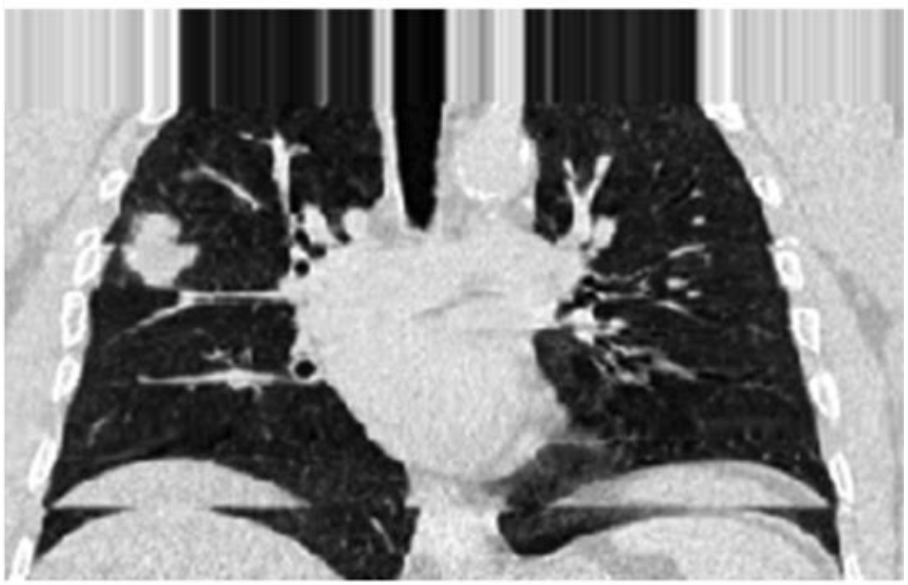
$$\int_V \vec{\nabla} \cdot \vec{\alpha}\, dV = 1.11.$$

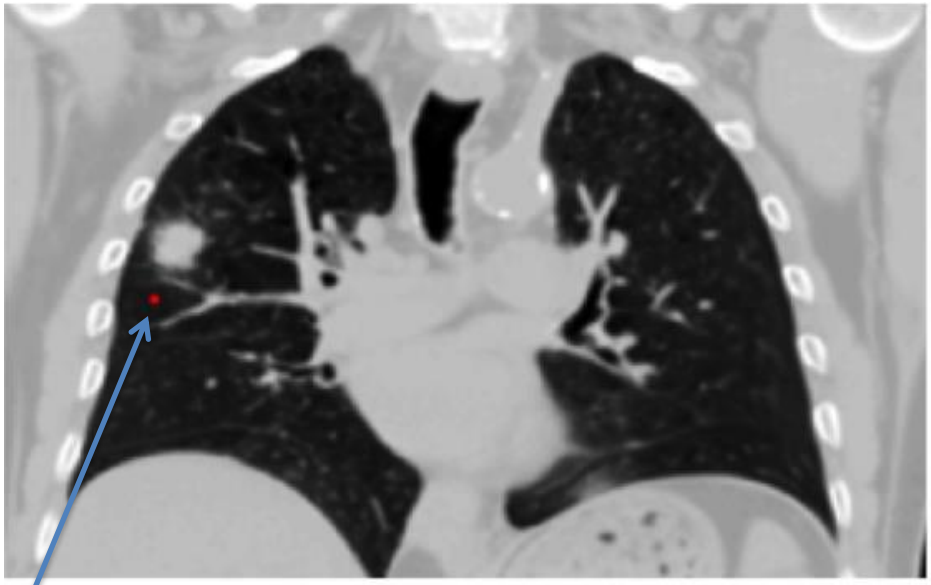


1.06 +/- 0.14

Med Phys 37, 1360 (2010)

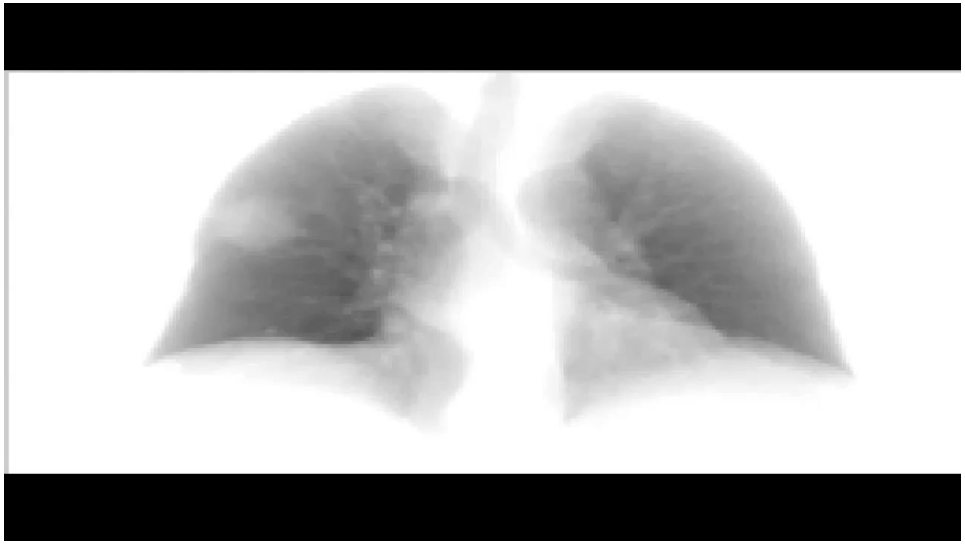
Results: Interpretation





2mm Diameter Circle

Benefits of new 4D Approach



- Fast scans, no modification to acquisition
- Average images to allow full use of all irradiated dose
- No sorting artifacts
- User-selected phases (1 image for contouring)
- Deformation maps that can be sent to TPS
- Quantitative
  - Accuracy evaluations
- First Clinical implementation: November 2015!

Thank You!

- 5D Research Group
  - Daniel A. Low, Ph.D.
  - James Lamb, Ph.D.
  - John Lewis, Ph.D.
  - Dan Ruan, Ph.D.
  - Tai Dou
  - Dylan O'Connell
  - David Thomas, Ph.D.
  - Shyam Jani
  - Xiao Wu
  - Anand Santhanam, Ph.D.
  - Jiulong Liu
  - Lisa Yang
  - Percy Lee, M.D.