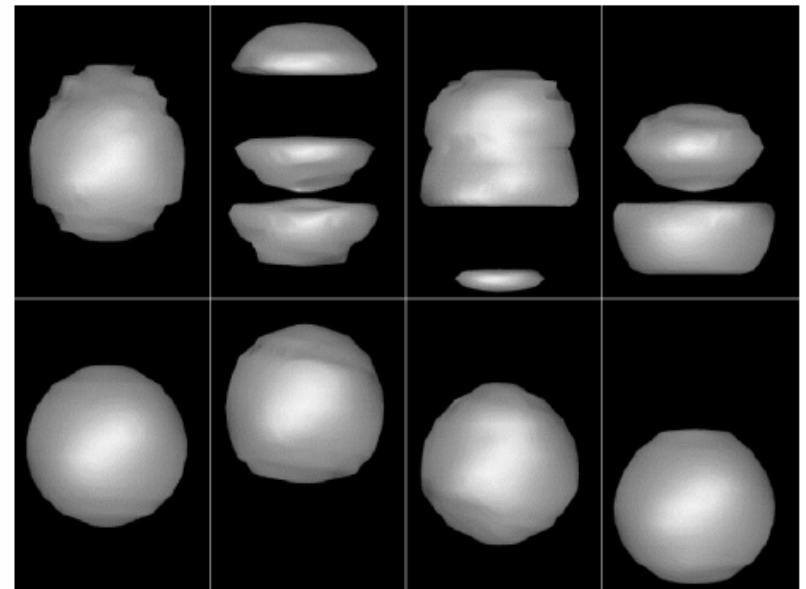


Issues in 4DRT

Daniel Low, Ph.D.
Director, Division of Medical Physics
Radiation Oncology
Washington University

4D RT

- For this discussion, limit definition to dealing with breathing motion
- Imaging
 - Removal of breathing motion artifacts
 - Measurement of motion
- Therapy
 - ITV
 - Gating
 - Tracking



4D Imaging

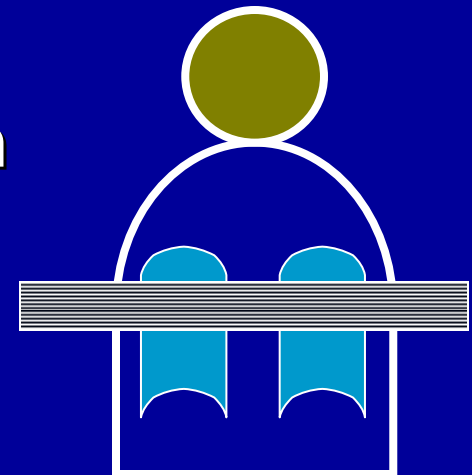
- CT remains the gold imaging standard
- 4D CT is a standard option for all of the CT sim vendors
 - Poorly defined process
 - Extension of cardiac gating software
- Research is ongoing for 4D MRI & PET

What is 4D CT?

- Process for obtaining image datasets
 - Images used to determine tumor/normal organ motion
 - Motion information used as inputs for treatment planning, delivery, verification
- Ultimate goal is NOT 4D CT image dataset
 - It is a model for breathing motion that can be used for planning, delivery, verification
- However, we are not “there yet”

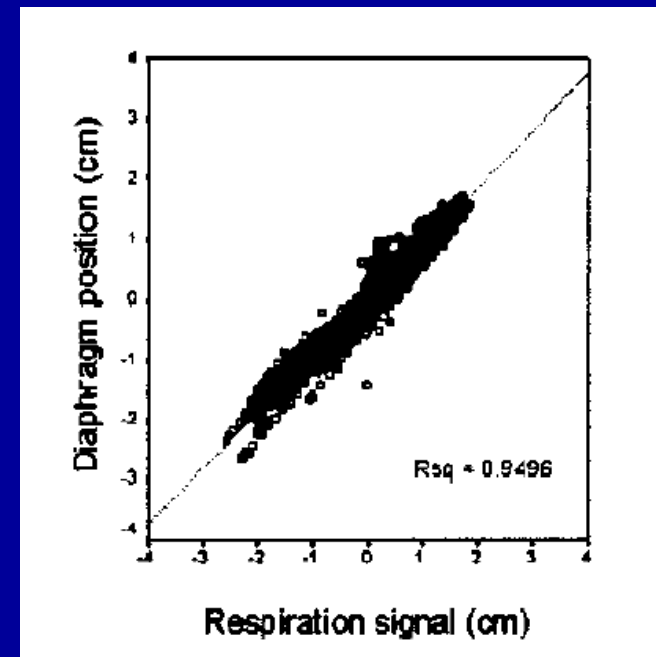
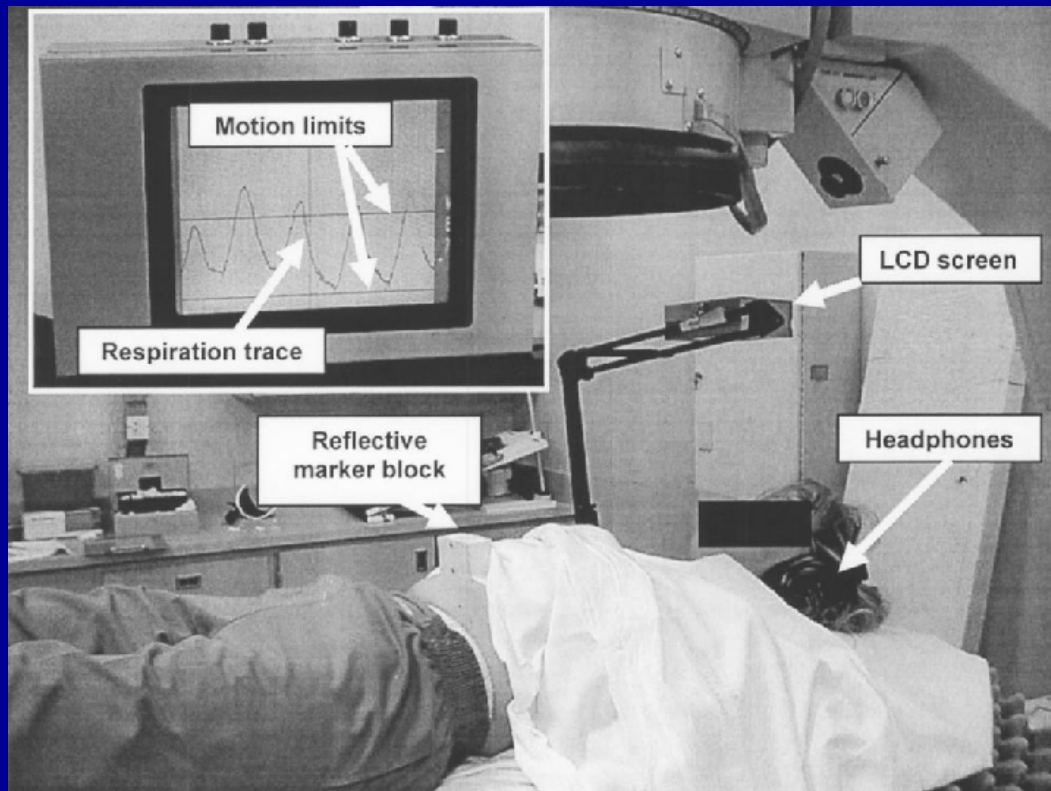
Some Issues to Address

- Breathing is not perfectly periodic
- No electronic monitorable surrogate (metric) such as with cardiac gating
- CT images are acquired throughout breathing cycle
 - Not in the same physical location
- How do we register images acquired at different times?



Metric – Chest Height

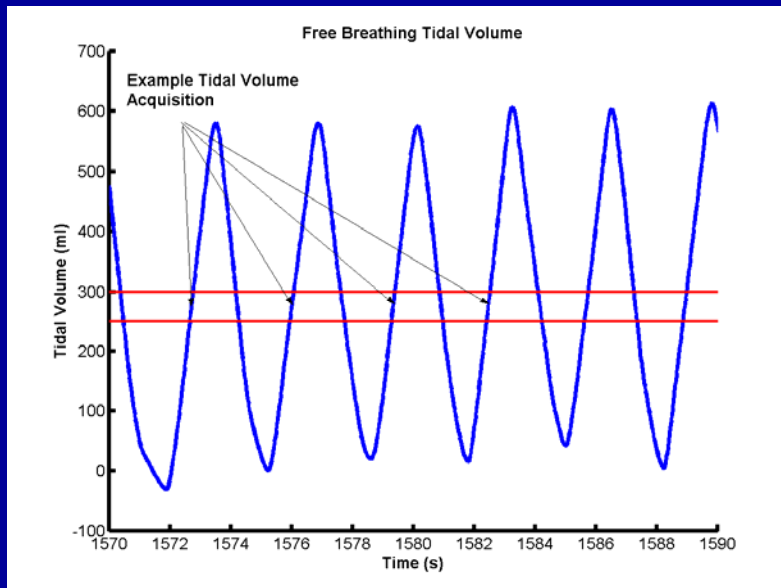
- Chest Height (Varian RPM)
- Infrared reflective marker placed on abdomen



Vedam et al Med Phys 30, 505 (2003)

Metric - Spirometry

- Turbine-shaped fan encased in tube
- Rotation rate determines flow rate
- Software removes nonlinearities and integrates flow



4D CT Acquisition

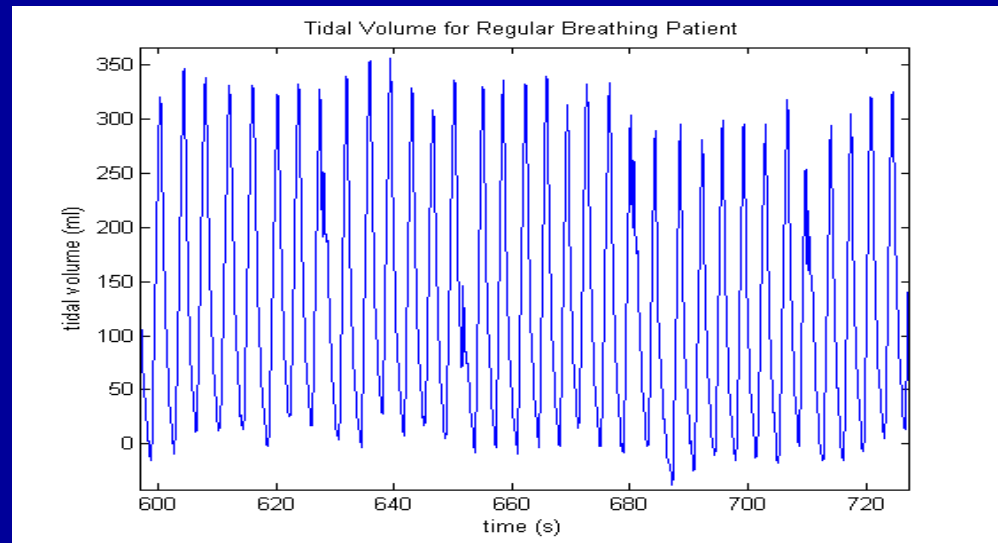
- Image acquisition
 - Ciné or helical modes
 - Simultaneous monitoring of patient breathing
 - Ciné acquires CT images without moving the couch
 - Images are typically selected from a sequence of acquired images according to breathing phase
 - Helical mode
 - Easiest for commercial applications: uses cardiac gating software

Gating

- Sort CT images (or reconstruct sinogram at specific times) using the metric data
- However
 - What criteria are used to determine the patient's breathing phase associated with each image?

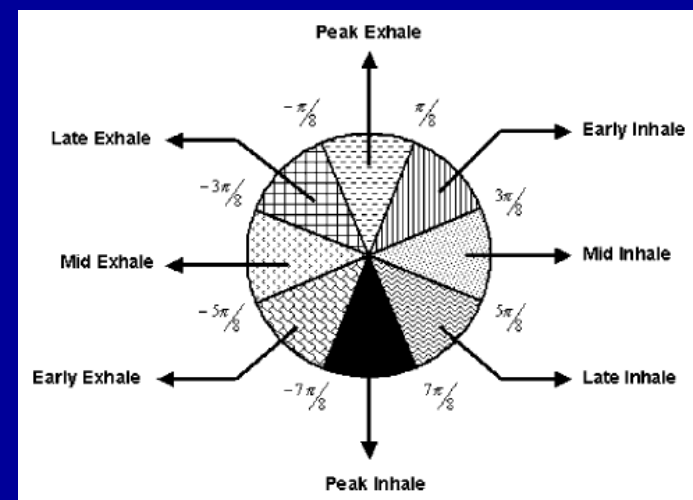
Inhalation

Exhalation



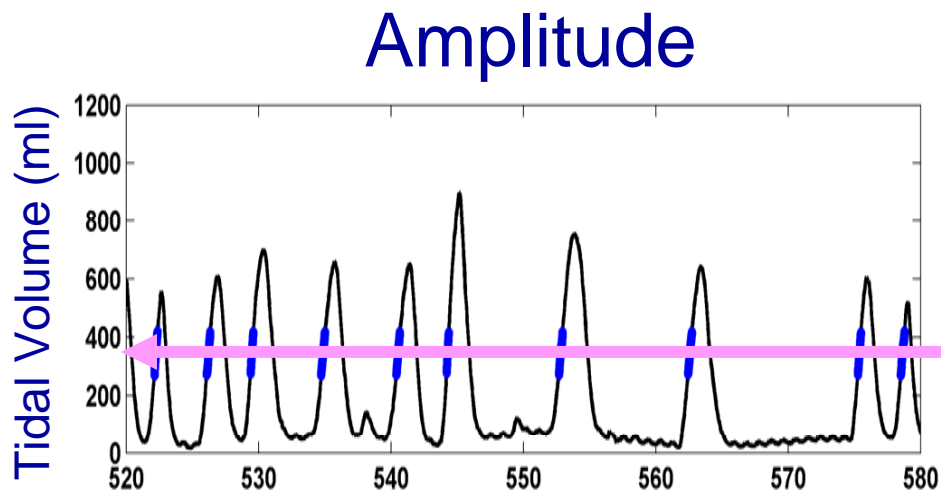
Breathing Cycle Definition

- Amplitude
 - Breathing “phase” defined by depth of breathing
- Phase Angle
 - Breathing cycle described as purely periodic process
 - Inhalation – exhalation defined by “angles” from 0-360 degrees



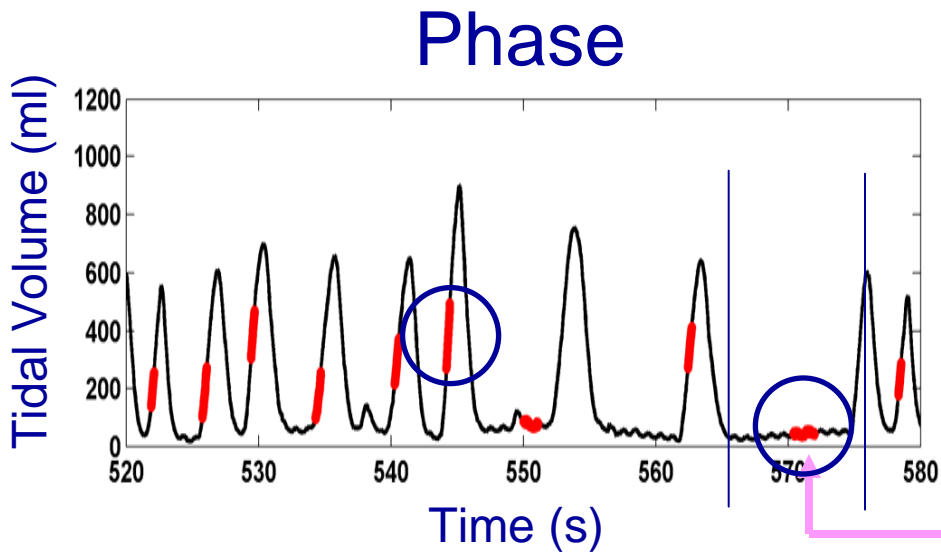
Vedam et al, PMB 2003

Phase vs. Amplitude

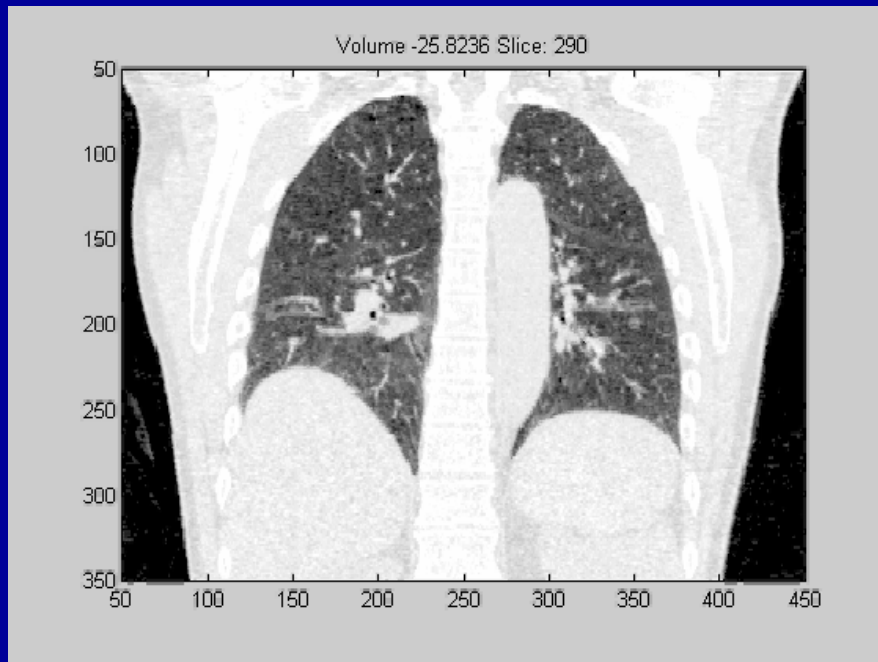


Select mid-inspiration

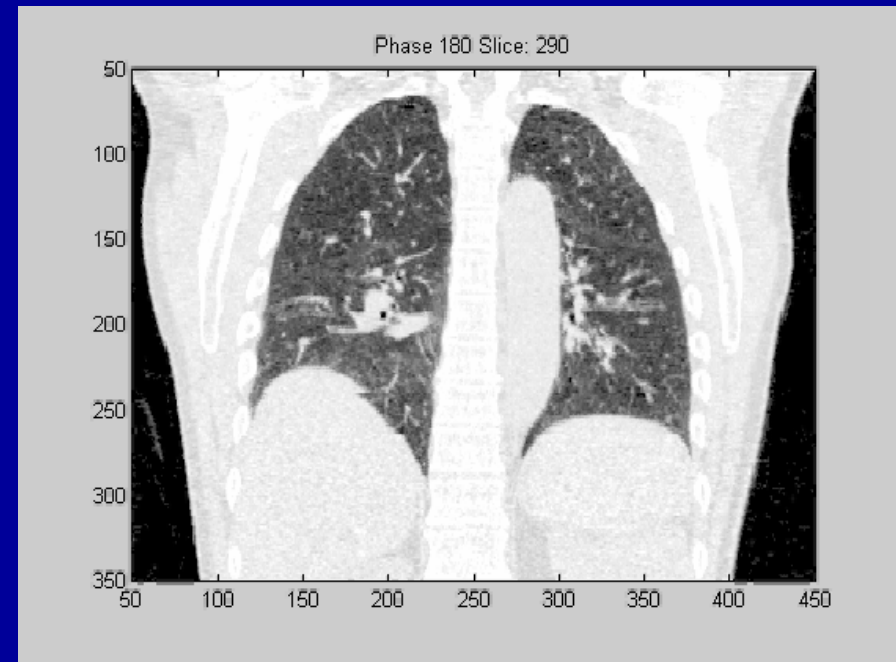
Mid-inspiration defined by percentile tidal volumes



Mid-inspiration defined by time between exhalation and inhalation peaks

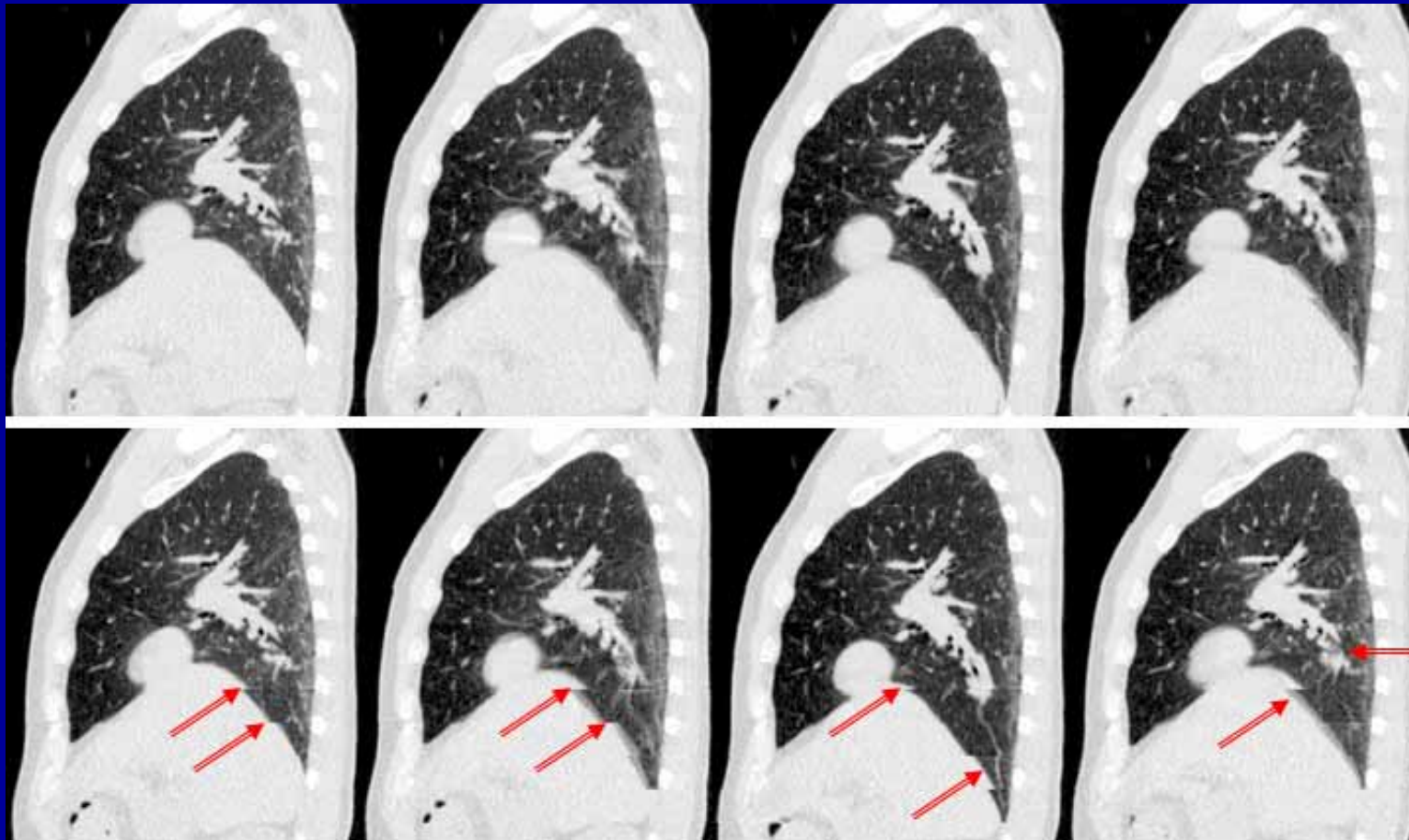


Amplitude sorting



Phase sorting

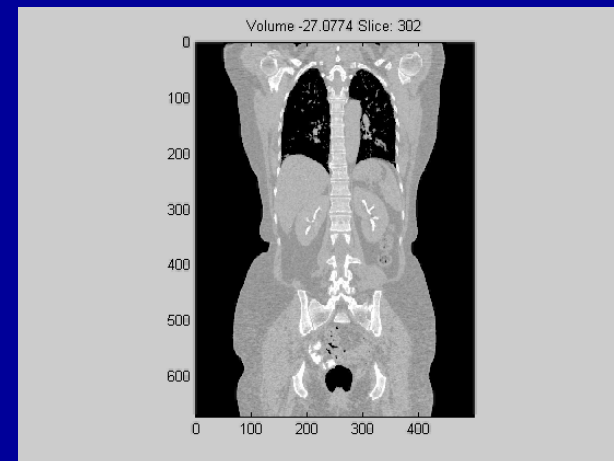
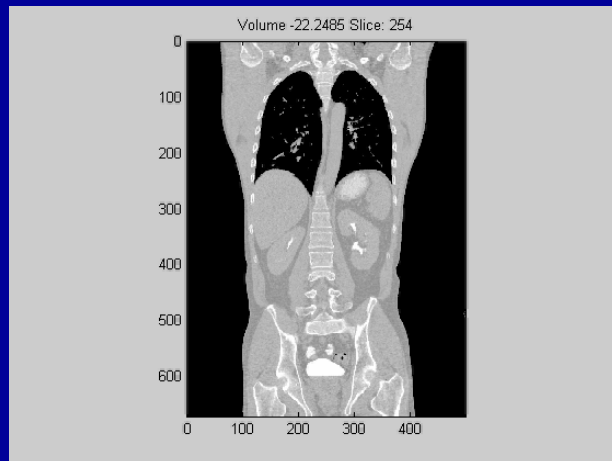
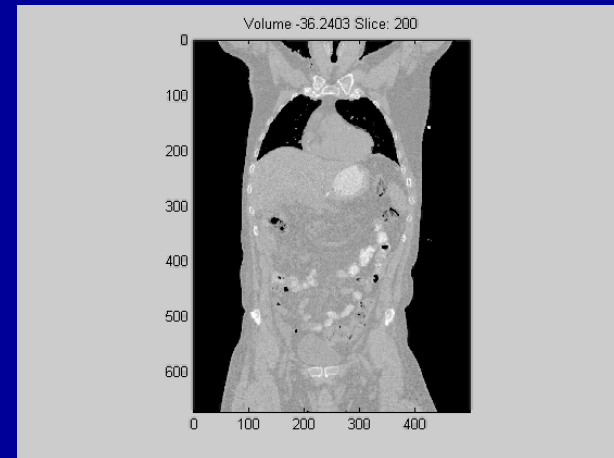
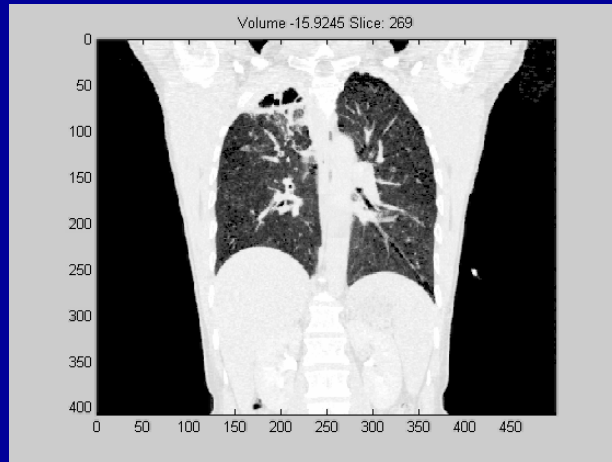
Amplitude vs Phase



A

P

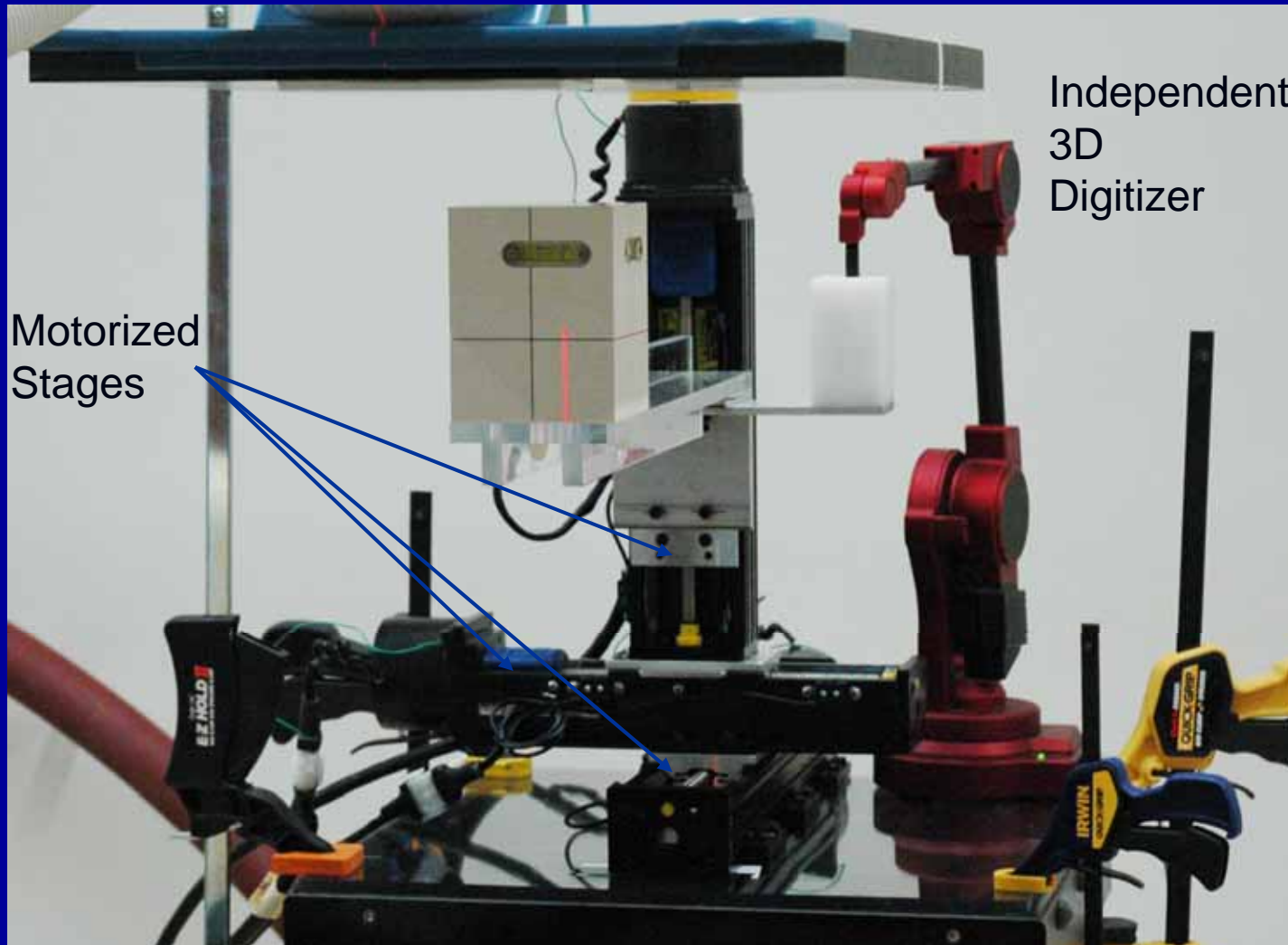
What 4D CT Can Do



Quality Assurance

- Accuracy of 4D process
- Phantoms developed to QA process
- Some operate in 1D, periodic
 - Breathing is non-periodic
 - Breathing motion is 3D

QA of 4D

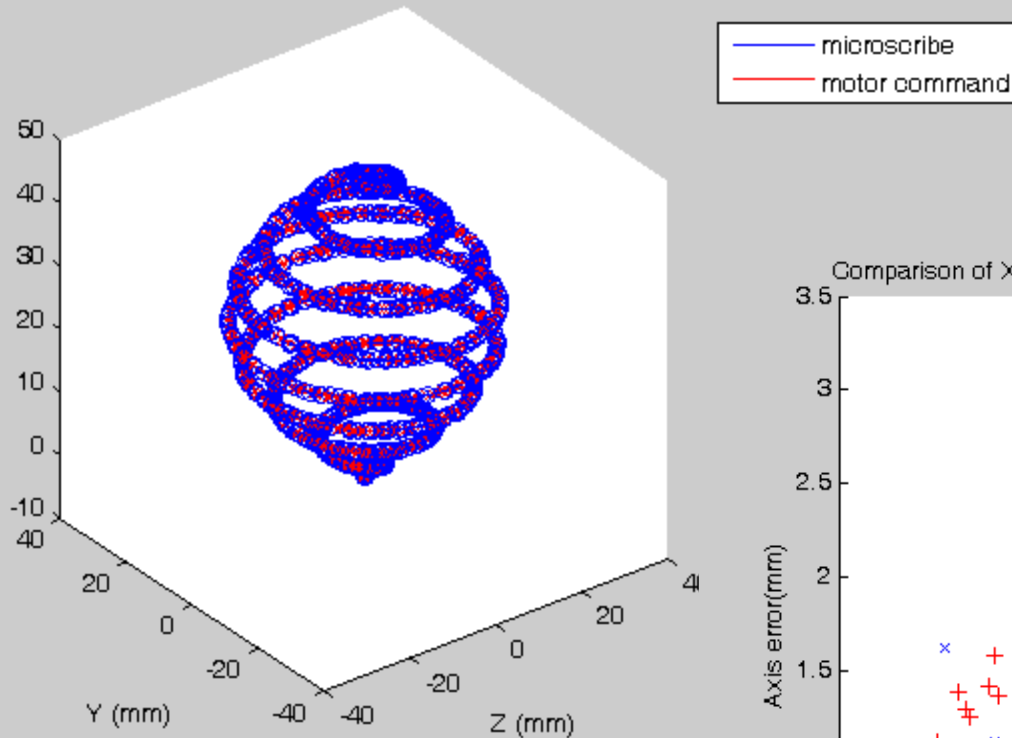


Example: Calypso

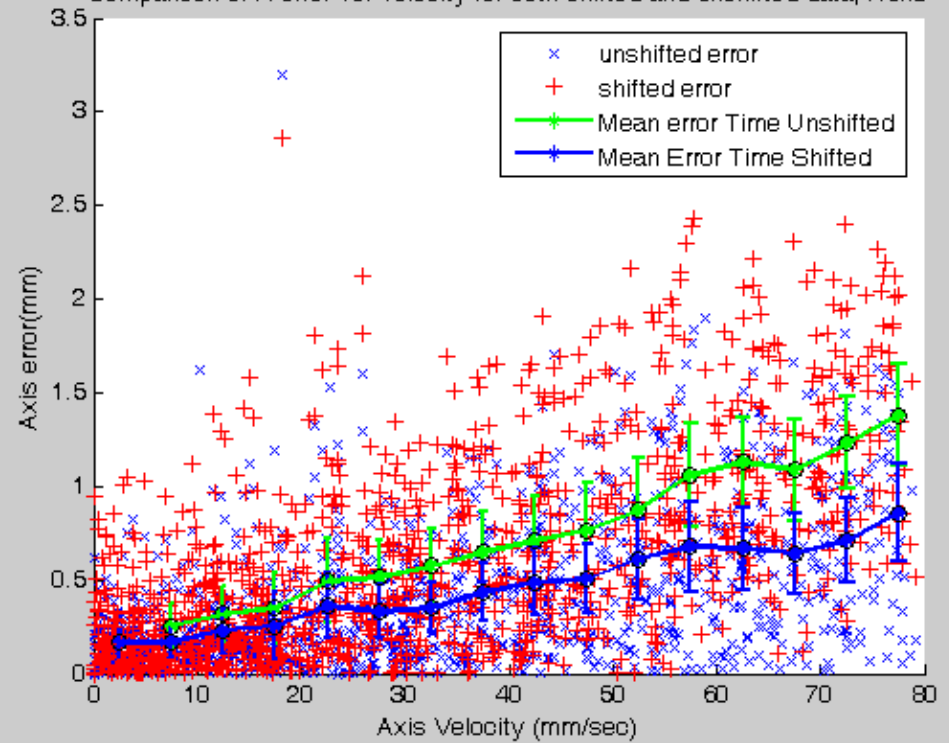


QA of 4D

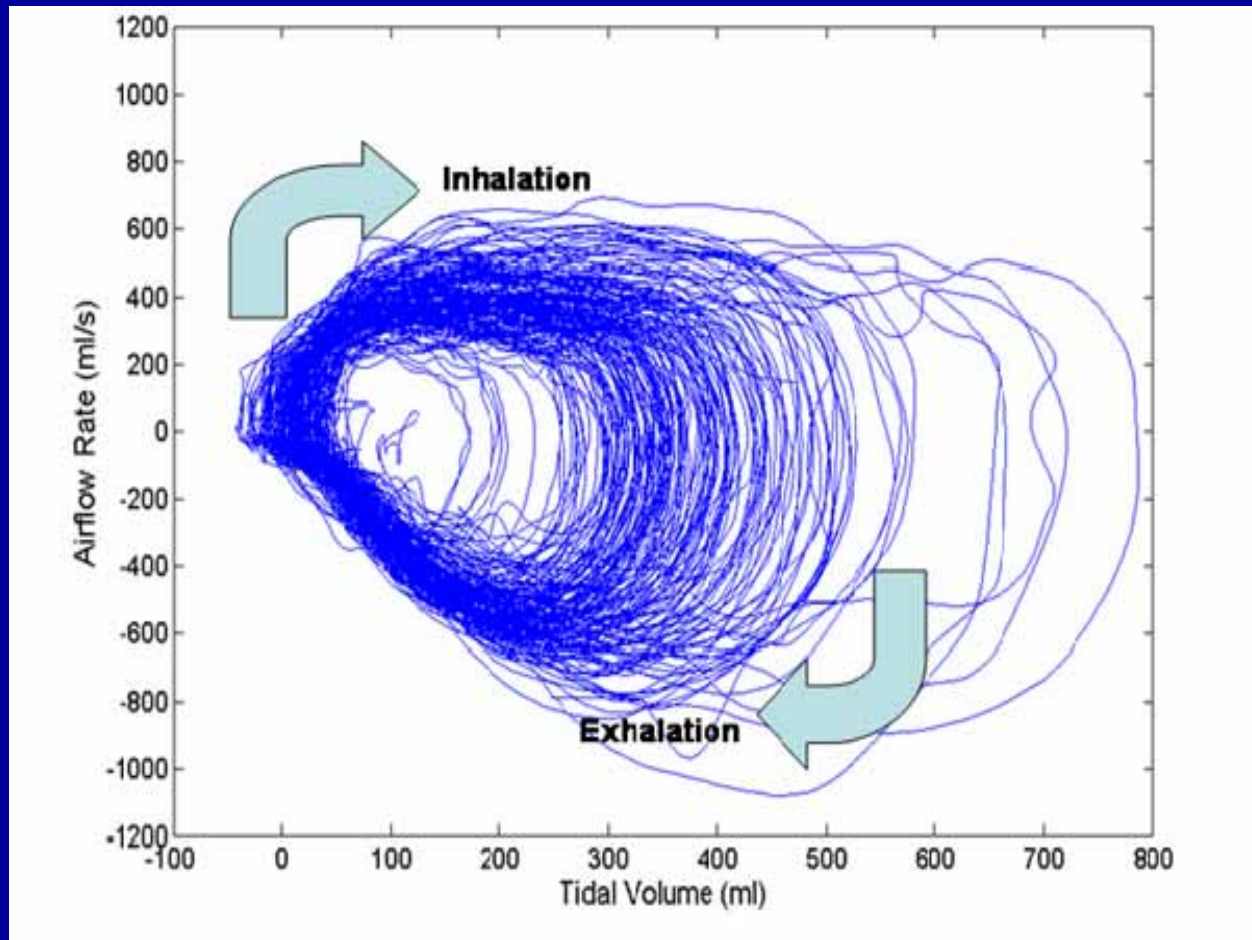
Plot of both Motor Commands and Microscribe position, Run1



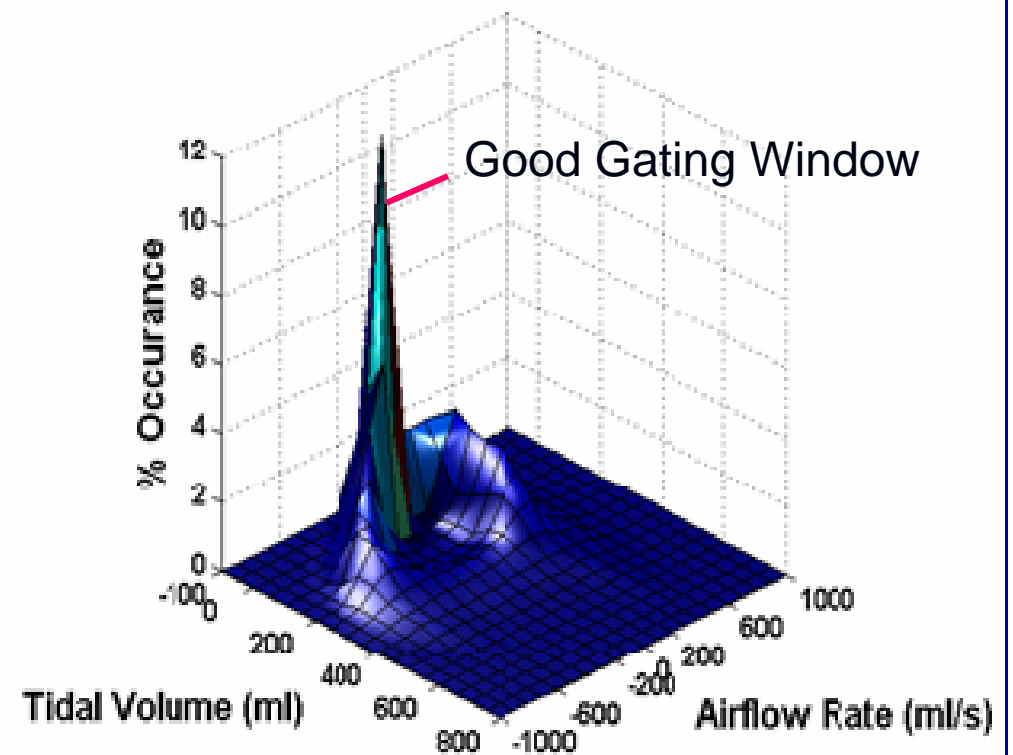
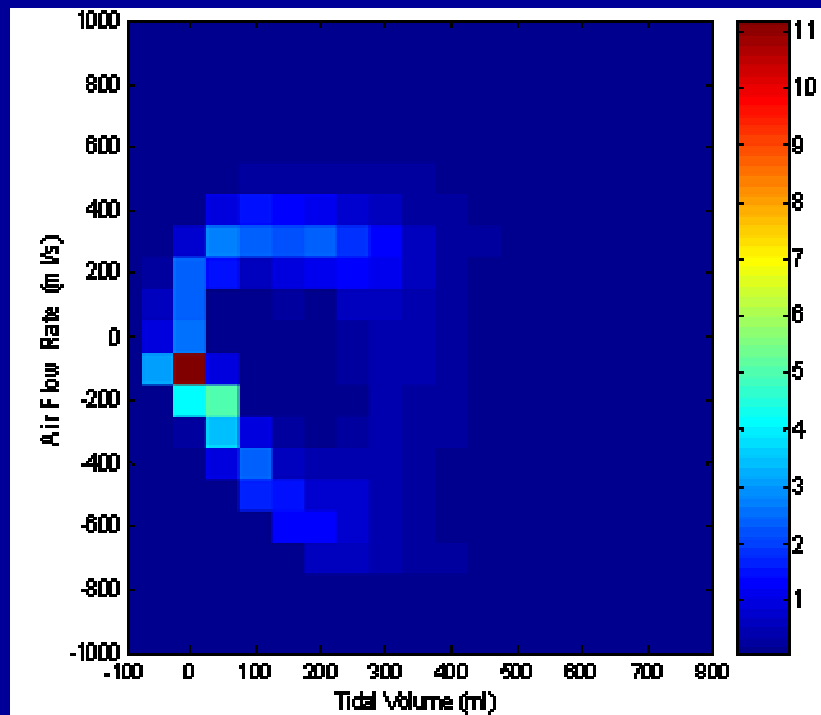
Comparison of X error vs. velocity for both shifted and unshifted data, Run3



Breathing Patterns

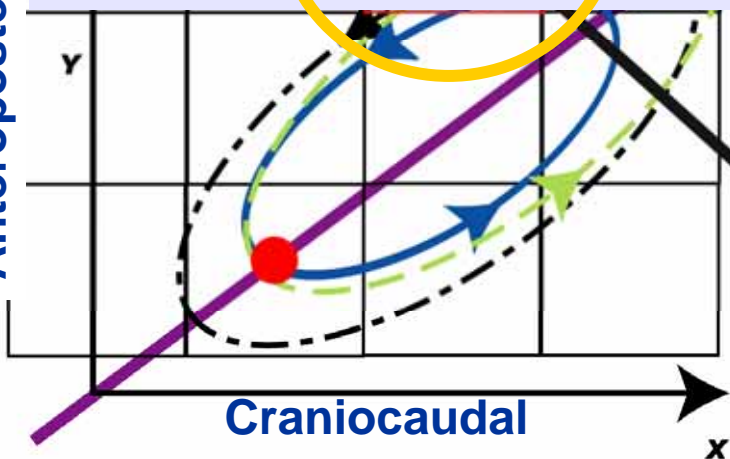


Breathing Patterns

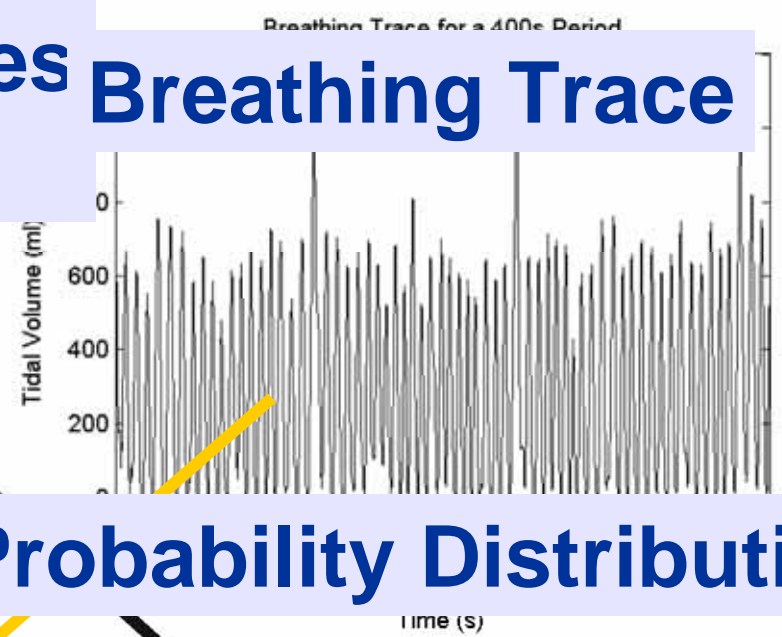


Anteroposterior

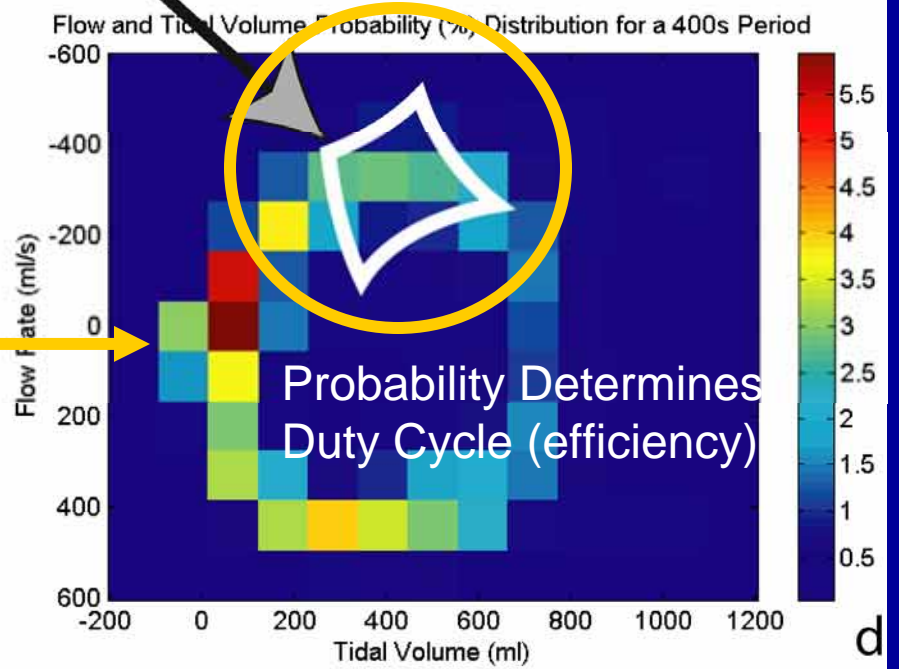
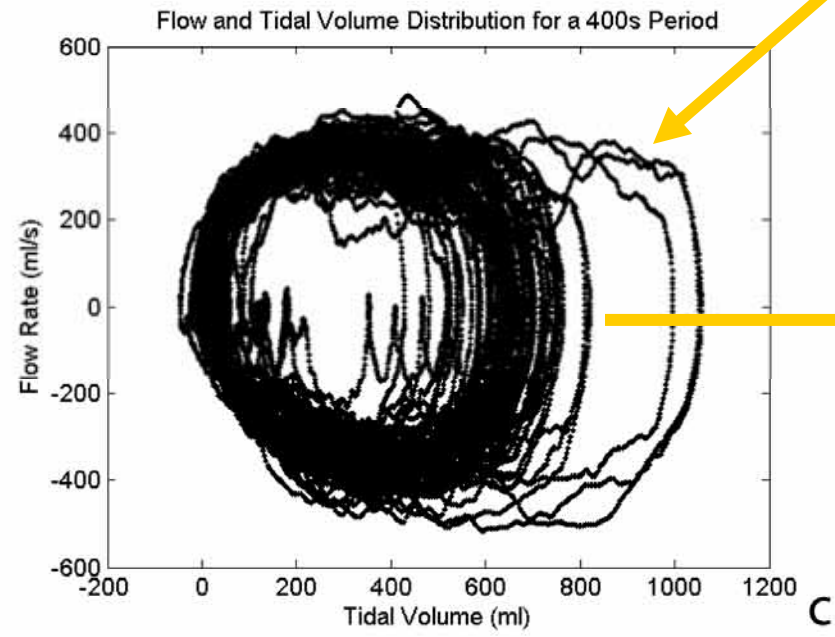
Breathing Trajectories During 4D CT



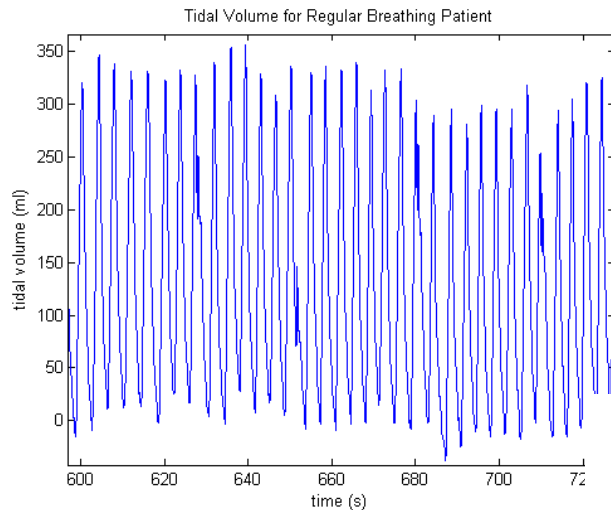
Breathing Trace



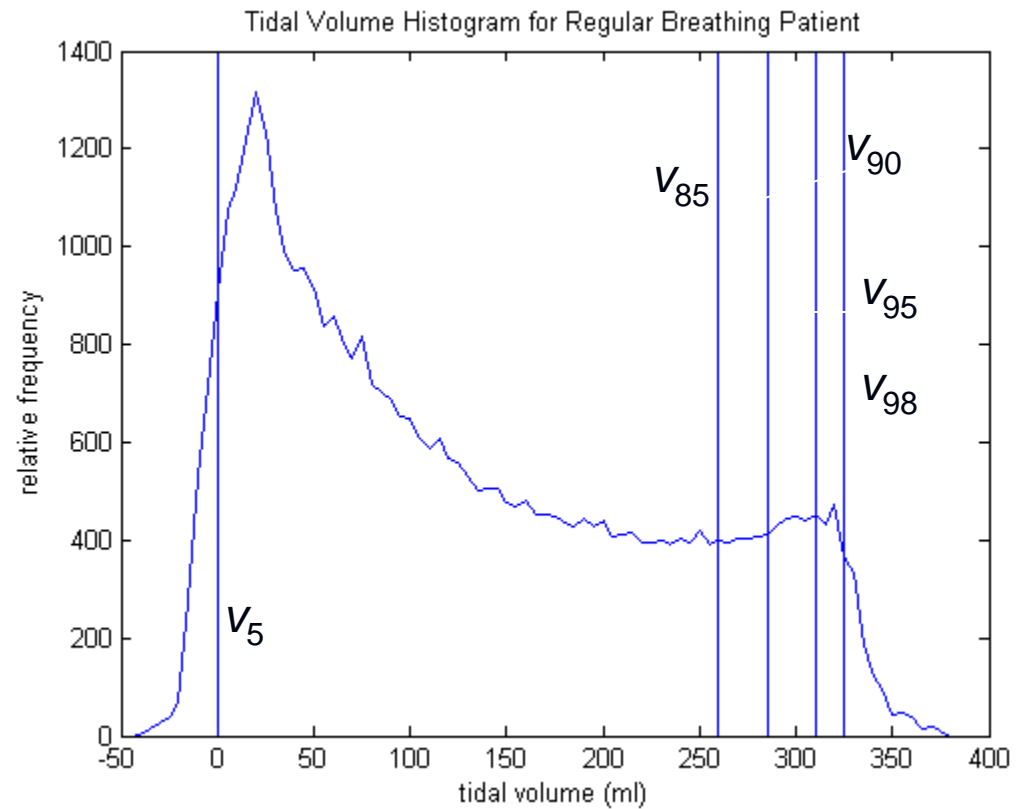
Probability Distribution



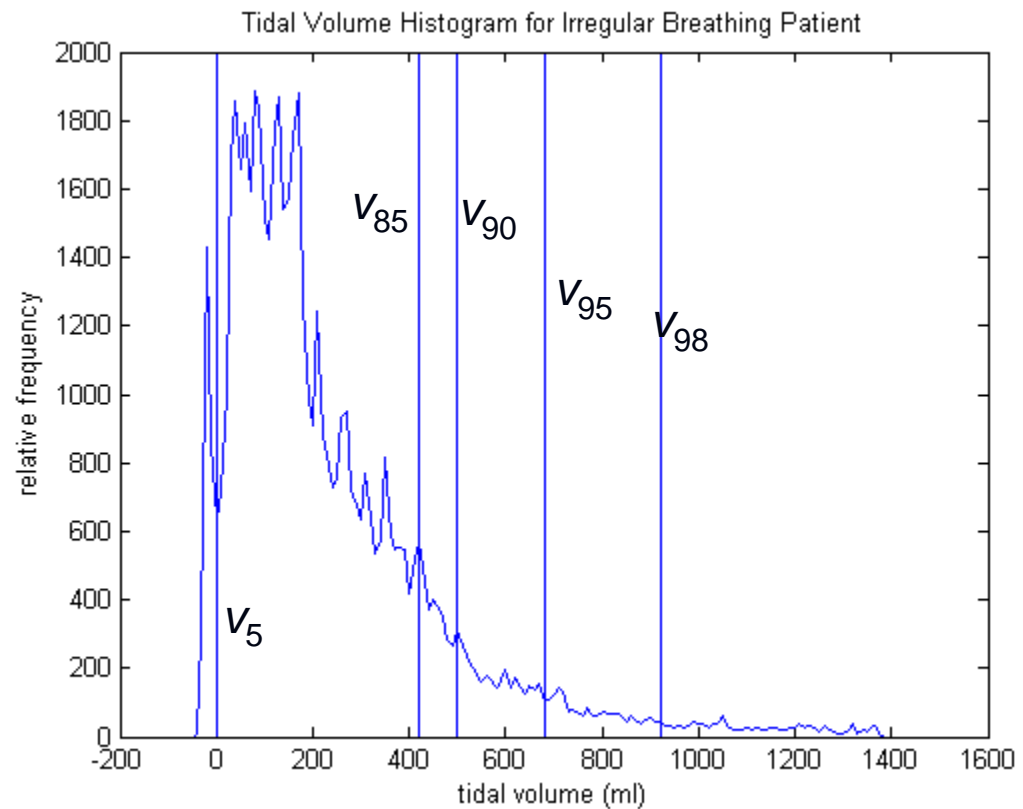
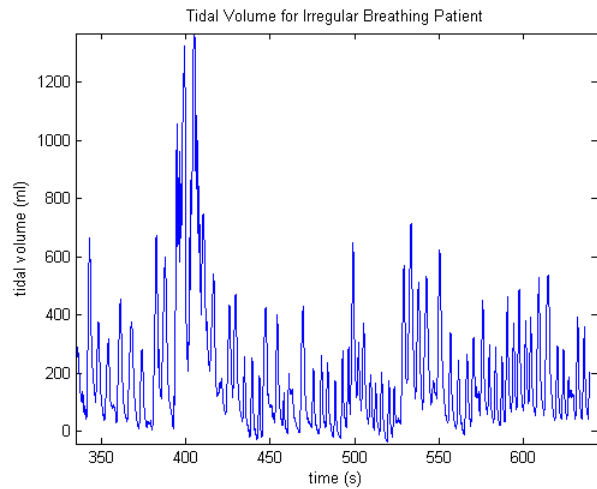
Regular Breather



v_x = Volume at which patient had v or less volume $x\%$ of the time



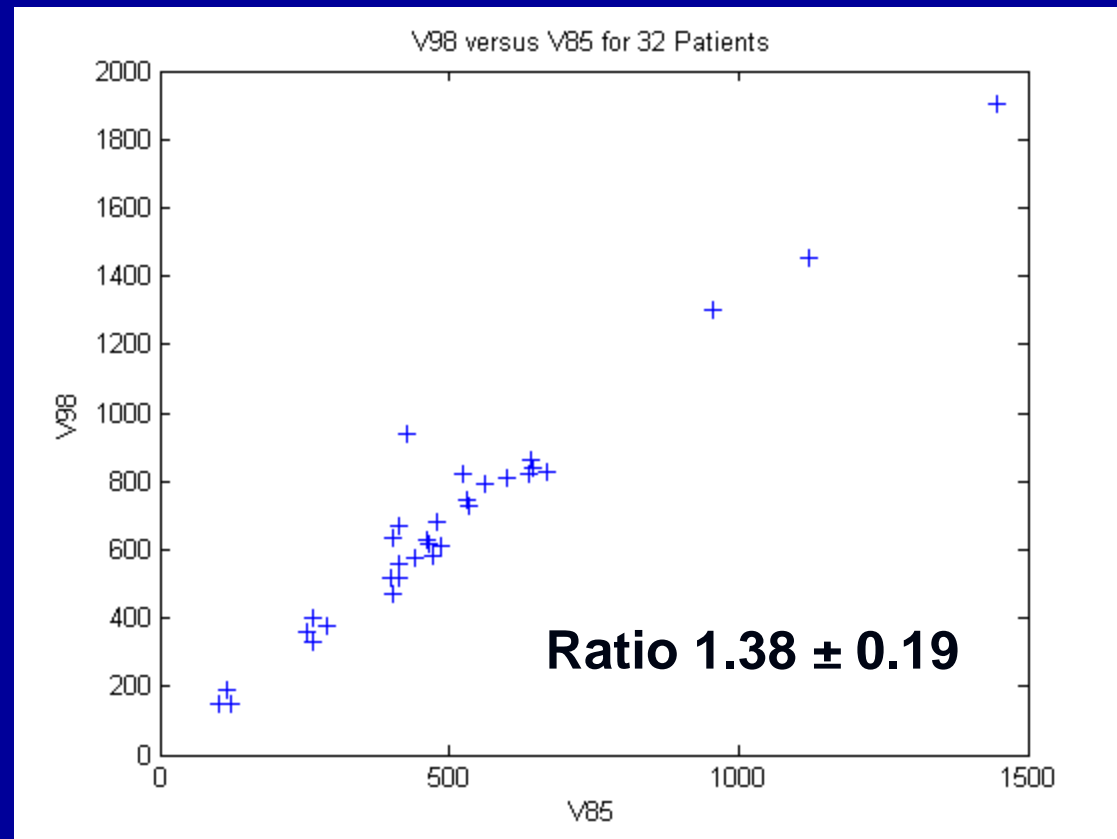
Irregular Breather



V_{98} (93% of time) vs V_{85} (80% of time)

Amount of Motion We Want to Know

Available 3D Image Datasets



Images that cover 80% of breathing cycle show only 72% of the motion at 93% of the breathing cycle!

Conclusions

- QA needs to consider the unreliability of phase-based gating
- QA needs to allow for irregular frequency and amplitude of breathing
- Amplitude-based gating = ability to extrapolate from existing image data
- 4D treatment process has not yet been finalized