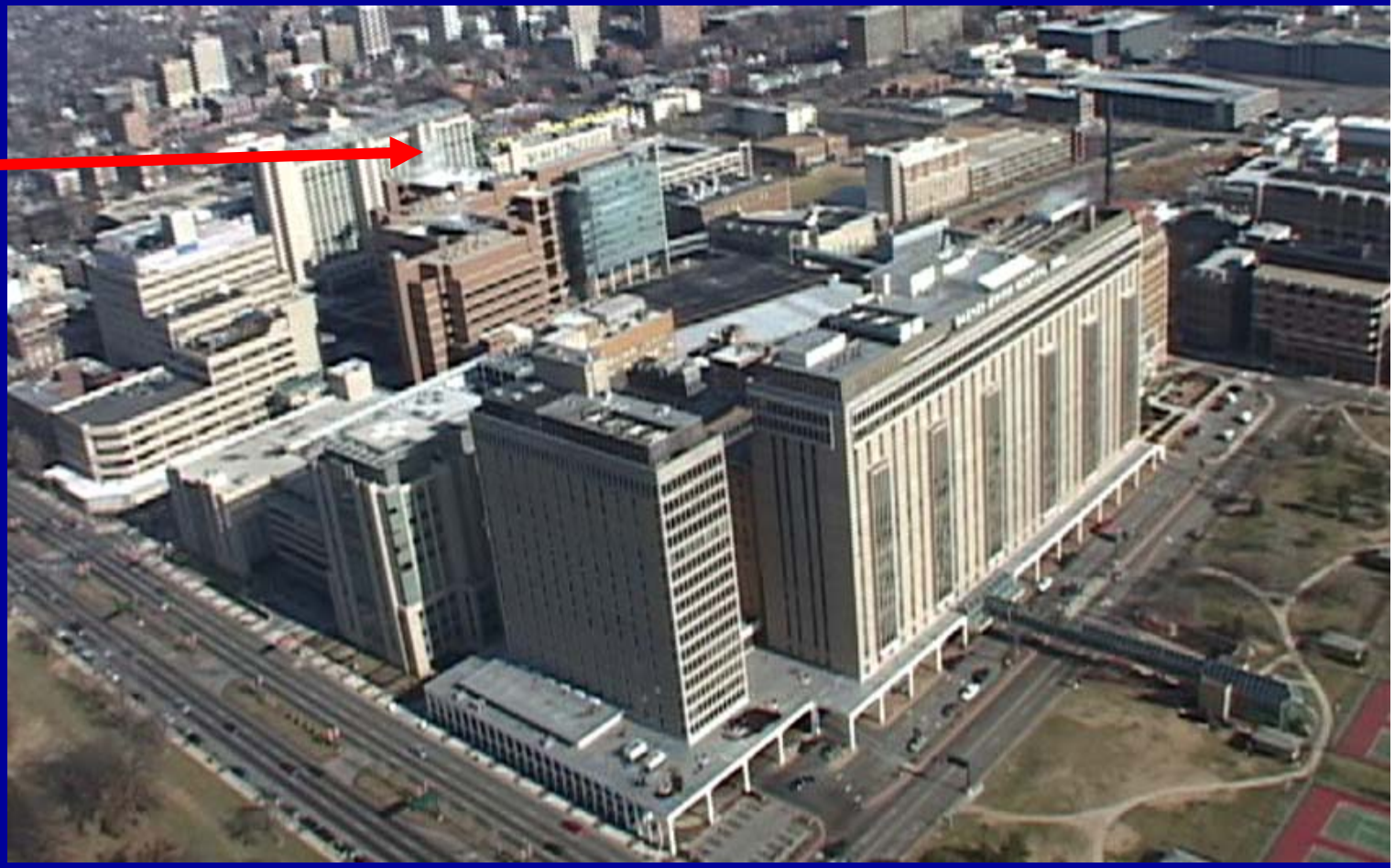
Clinical Use of 4DCT

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

Colleagues

- Wei Lu
- Parag Parikh
- James Hubenschmidt
- Jeffrey Bradley
- Sasa Mutic
- Joe Repp
- Sasa Wahab
- Issam El Naqa
- Gary Christensen

Washington University School of Medicine
Department of Radiation Oncology



Outline

- Why is 4D CT necessary?
- What is 4D CT?
- How do we characterize breathing?
- What do we do with 4D CT information?

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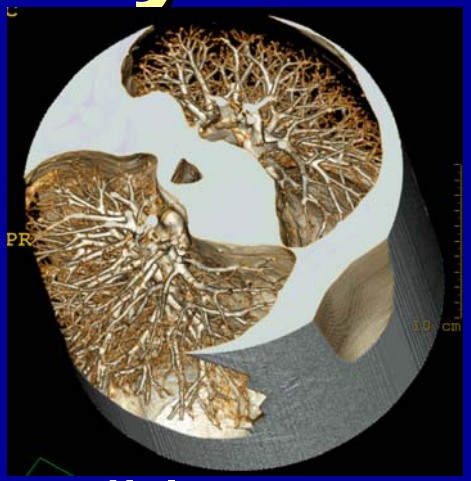
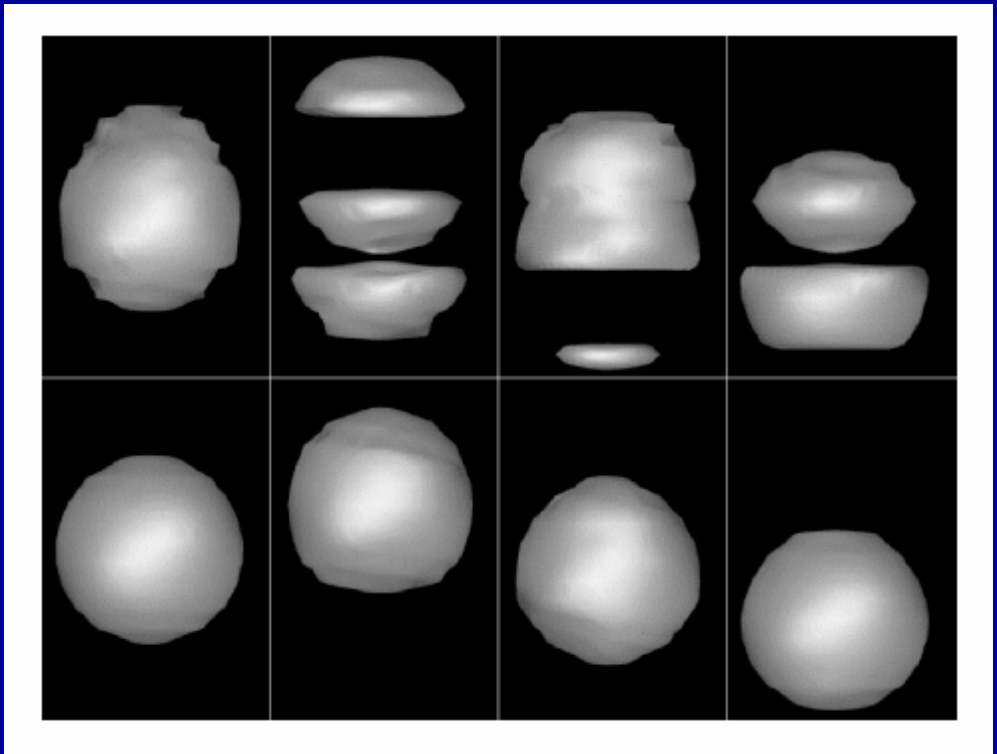
Why is 4D CT Necessary?



- Breathing
  - Quasi-voluntary function
  - Breath hold possible
  - Modification of breathing pattern possible
- Motion
  - Image artifacts
  - Dose-delivery artifacts
  - Increases irradiated volume/treatment complexity

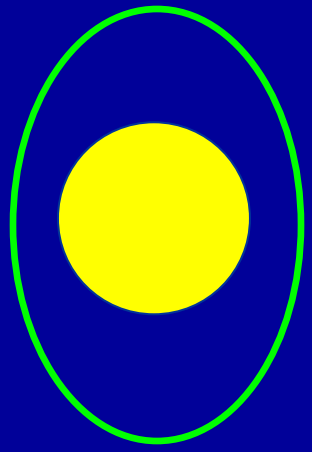
Image Artifact Reduction



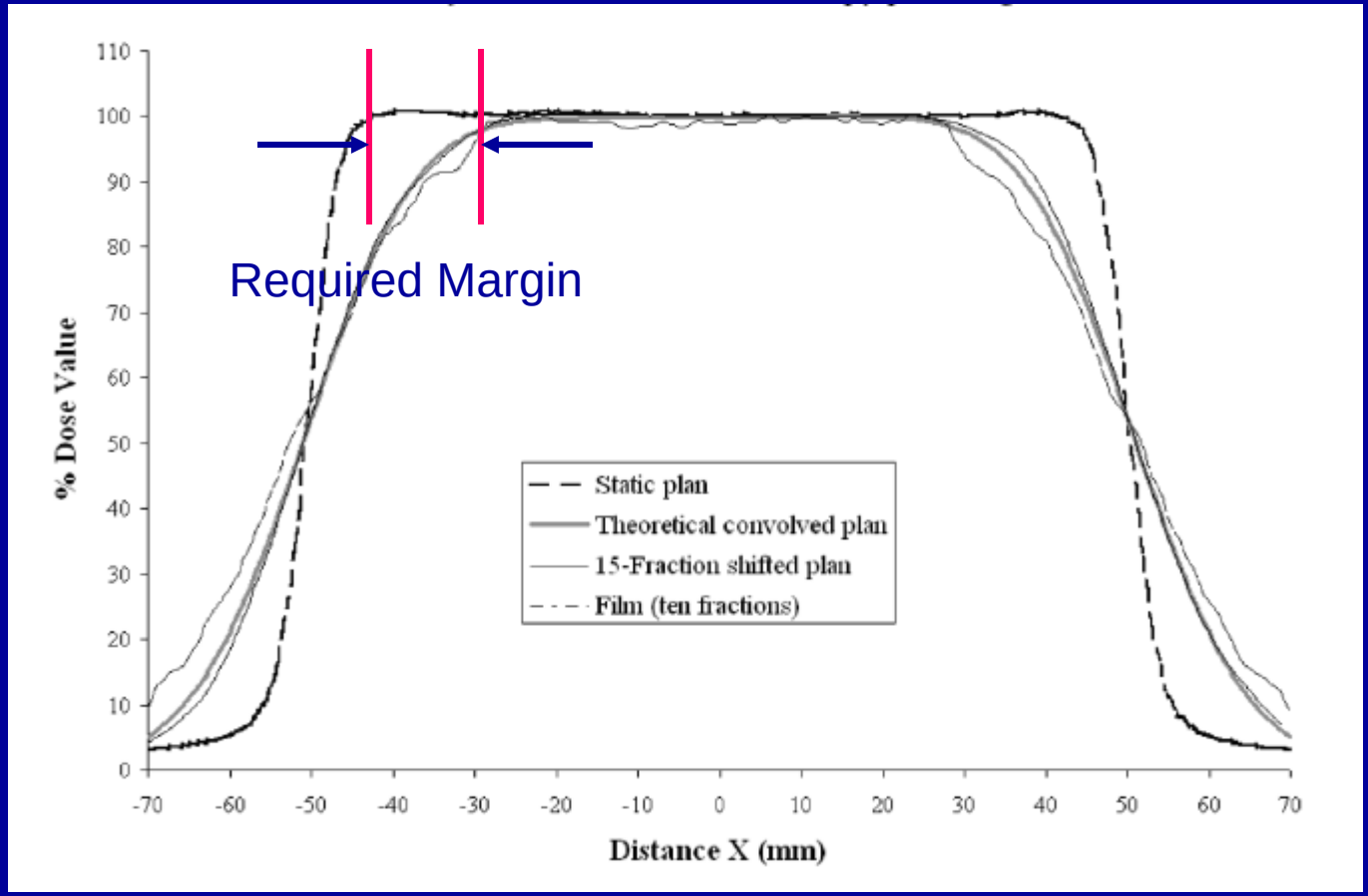
Rietzel med phys 32 874

Treatment Effects

- Breathing motion increases the apparent size of the tumor
  - Increases portal sizes
  - Increases normal organ irradiation



Motion Blurring



σ = 10 mm

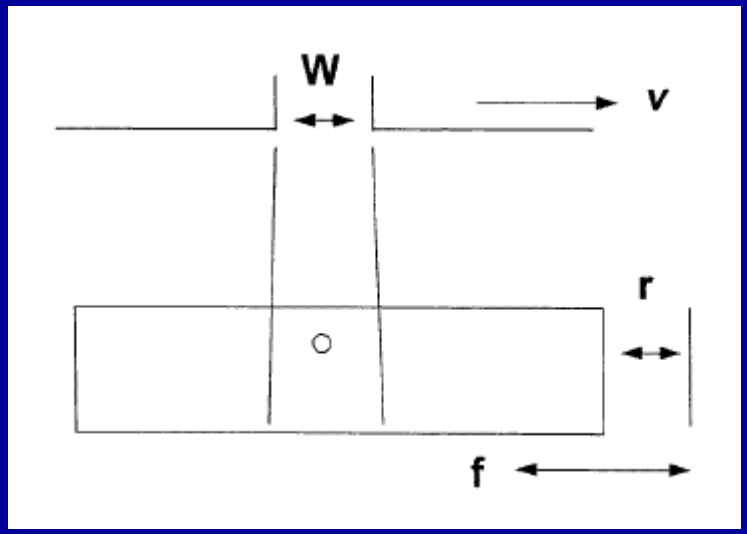
McCarter and Beckham, PMB 2001

Effects of Motion on IMRT

- Blurring of IMRT dose distributions
- Interplay effects
- Dose deformation (interface effects)

- How big are these effects?

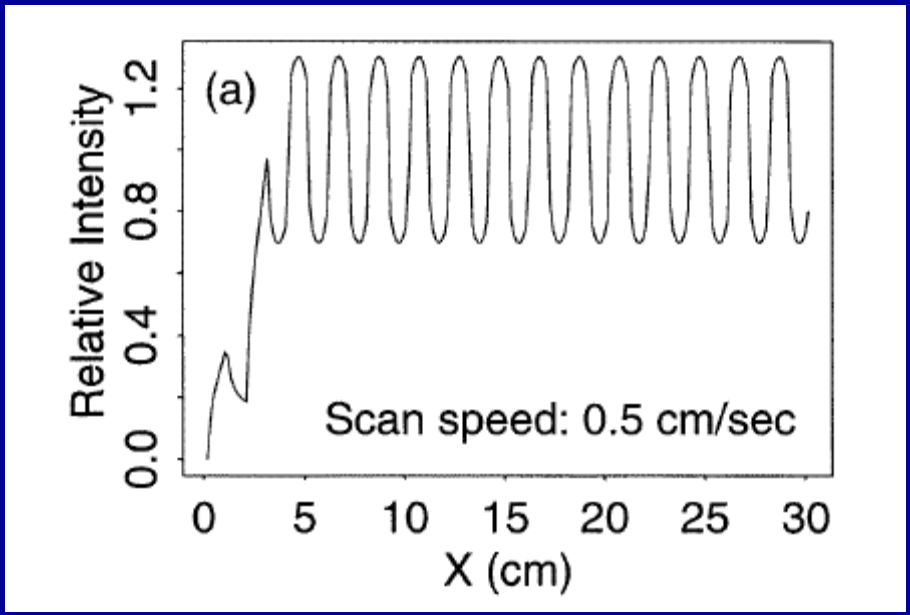
Interplay Effects

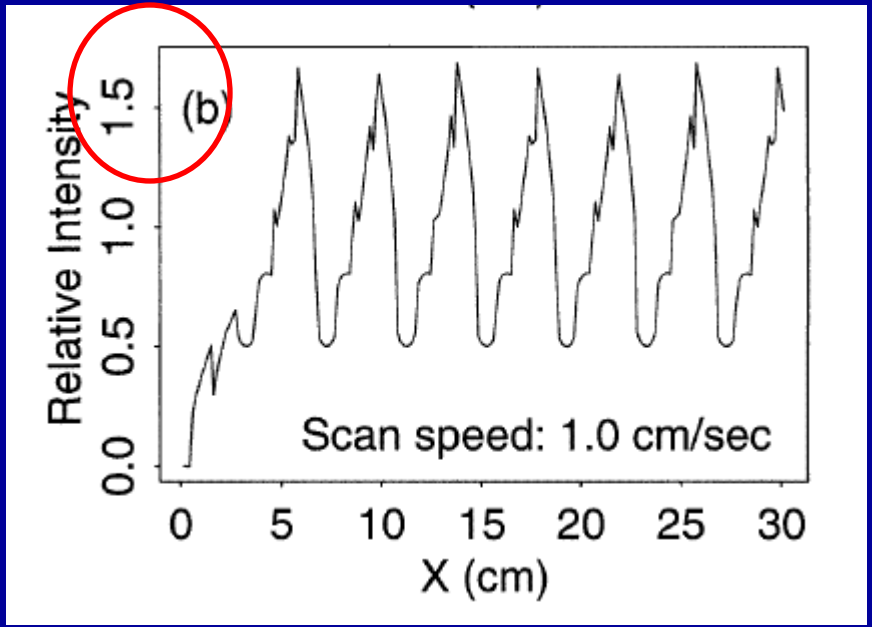


Simulate dynamic IMRT field and moving tumor

Yu et al, PMB 1998

Examples of Dose Error

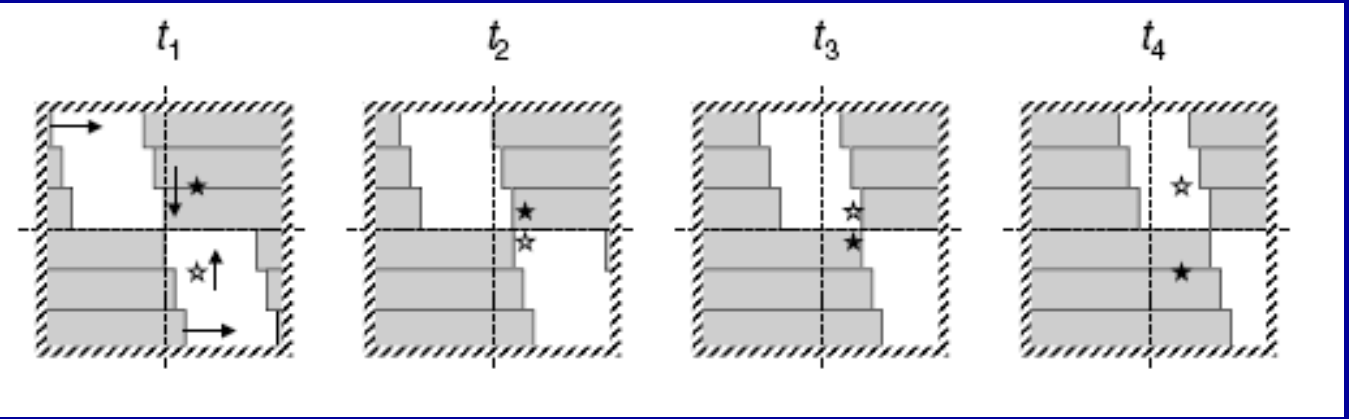




1 cm wide slit beam, 3 cm amplitude, 4 s breathing period

Interplay: Fractionated

- Fractionated therapy tends to blur dose errors
- Beam motion tends to be orthogonal to patient motion

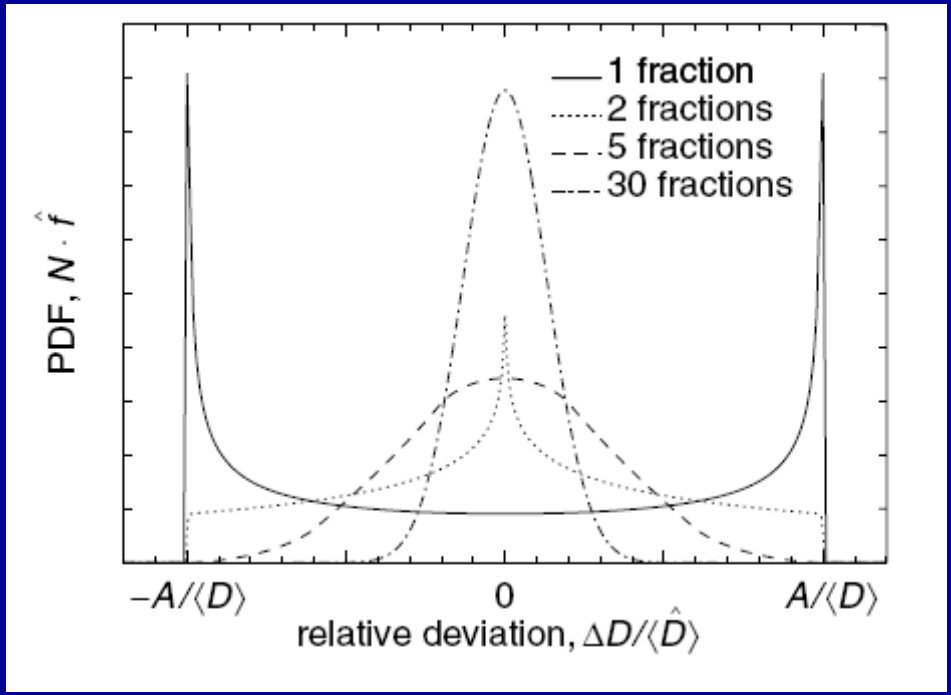


Multiple simulations with realistic IMRT dose distributions

Analyzed multiple points to determine dose error due to motion

Results: Dose error depended on whether point was in/near steep dose gradient region, but dose was local average

Bortfeld et al, PMB 2002



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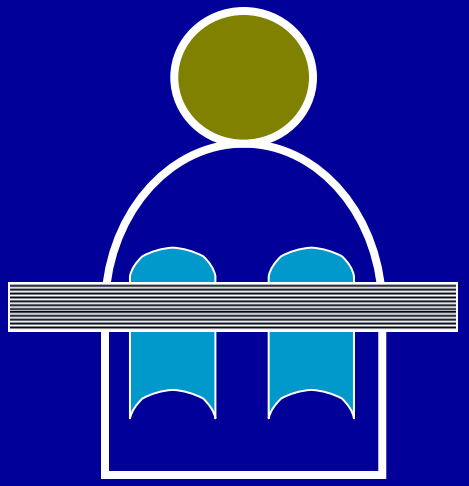
What is 4D CT?

- 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”

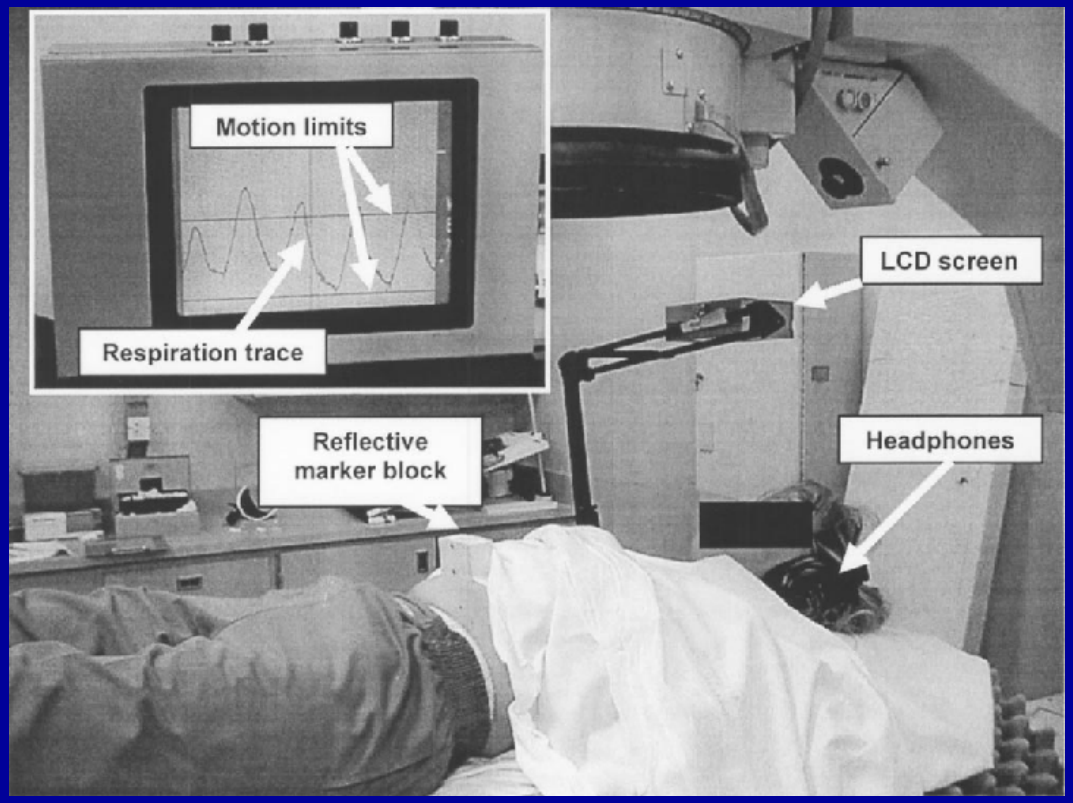
Some Issues to Address

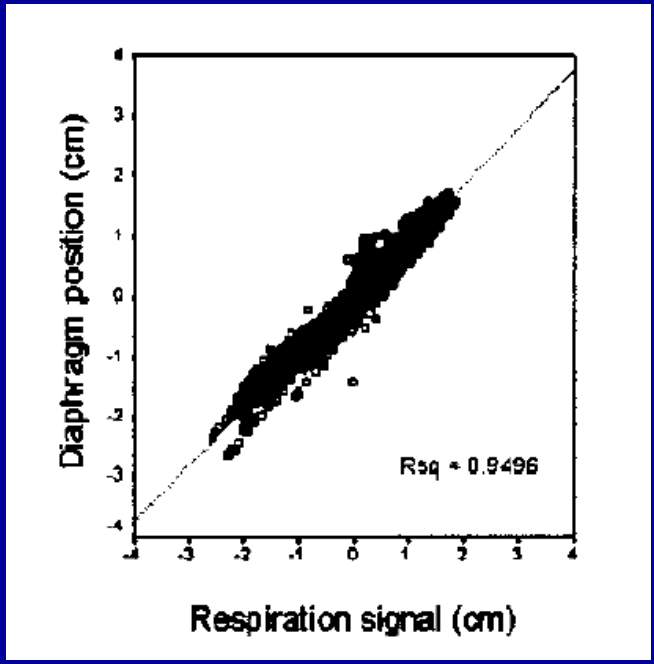
- Breathing is not perfectly periodic
- No electronic monitorable surrogate (metric) such as with cardiac gating
- CT images are acquired throughout breathing cycle
  - Not in the same physical location
- How do we register images acquired at different times?



Metric – Chest Height

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

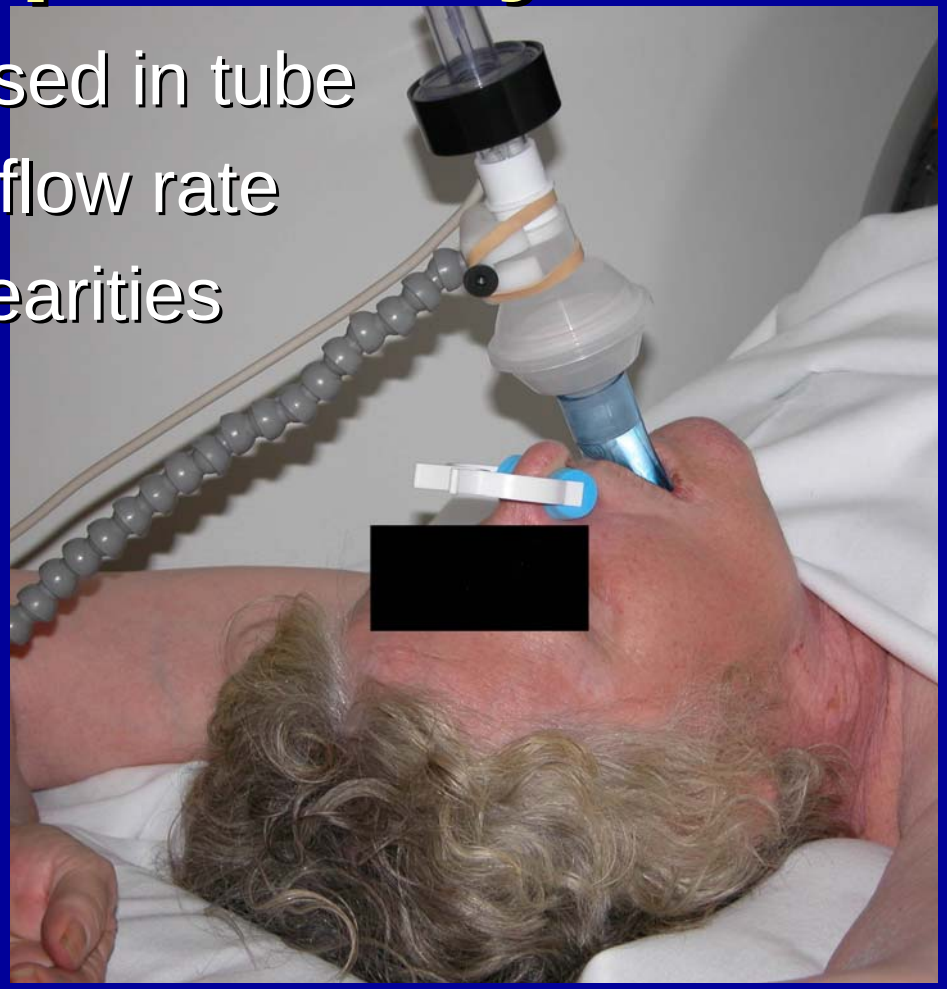


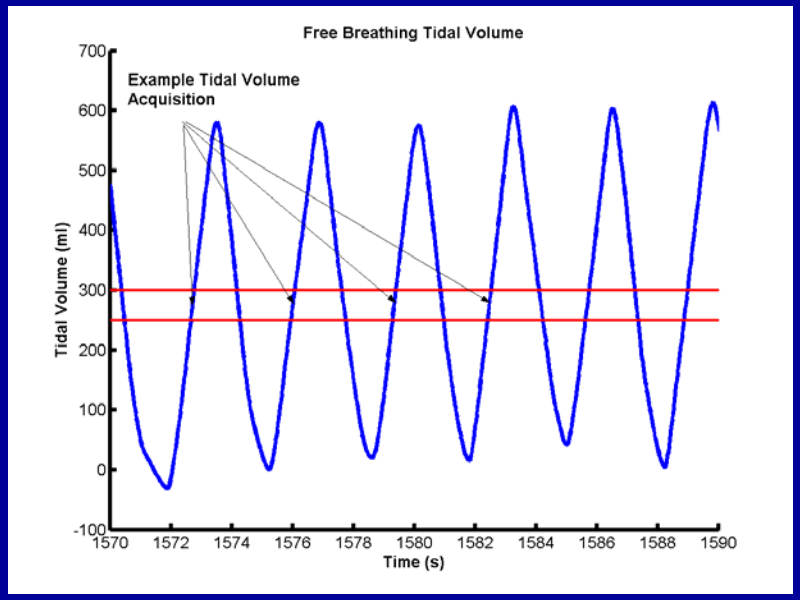


Vedam et al Med Phys 30, 505 (2003)

Metric - Spirometry

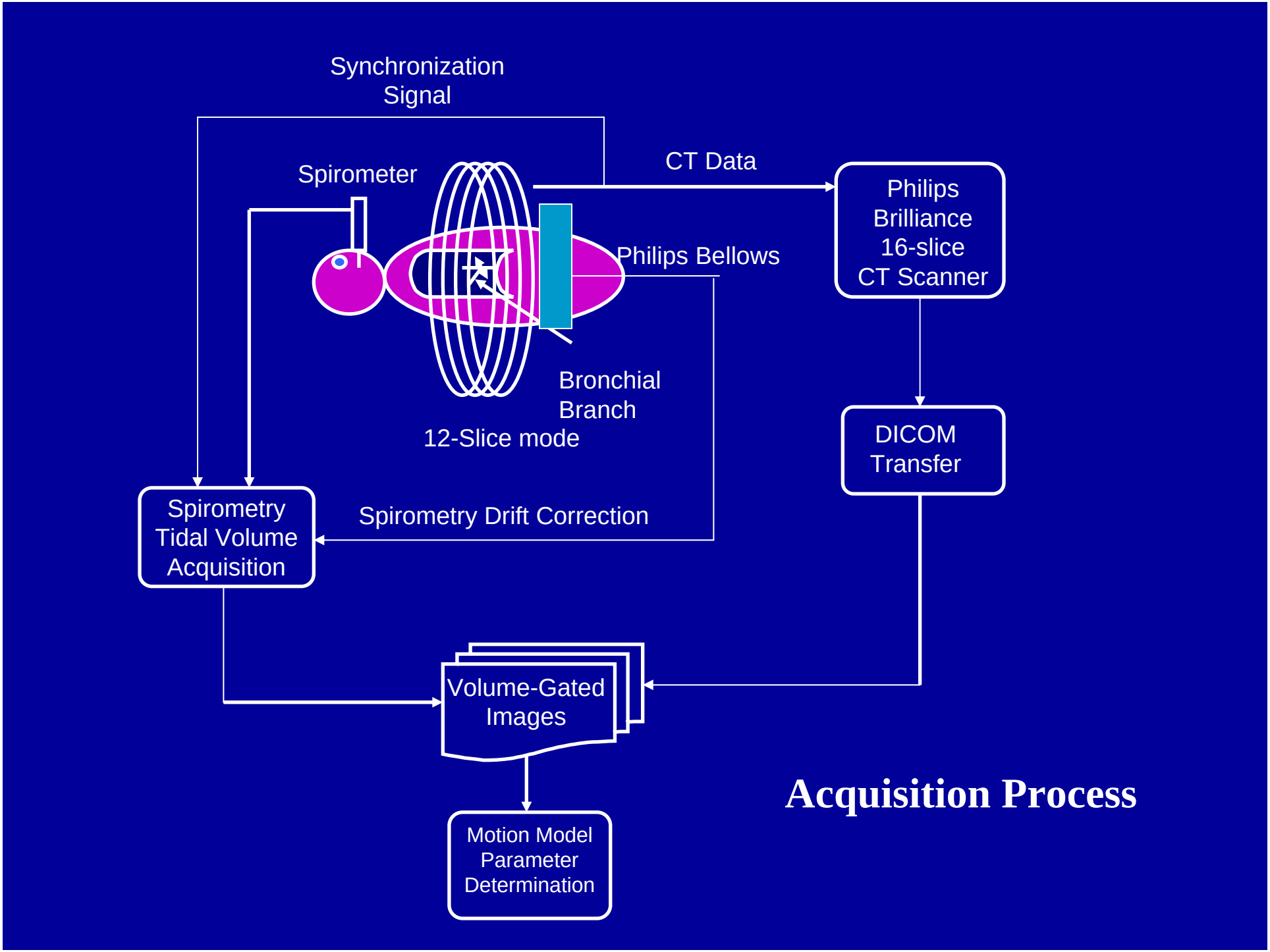
- Turbine-shaped fan encased in tube
- Rotation rate determines flow rate
- Software removes nonlinearities and integrates flow

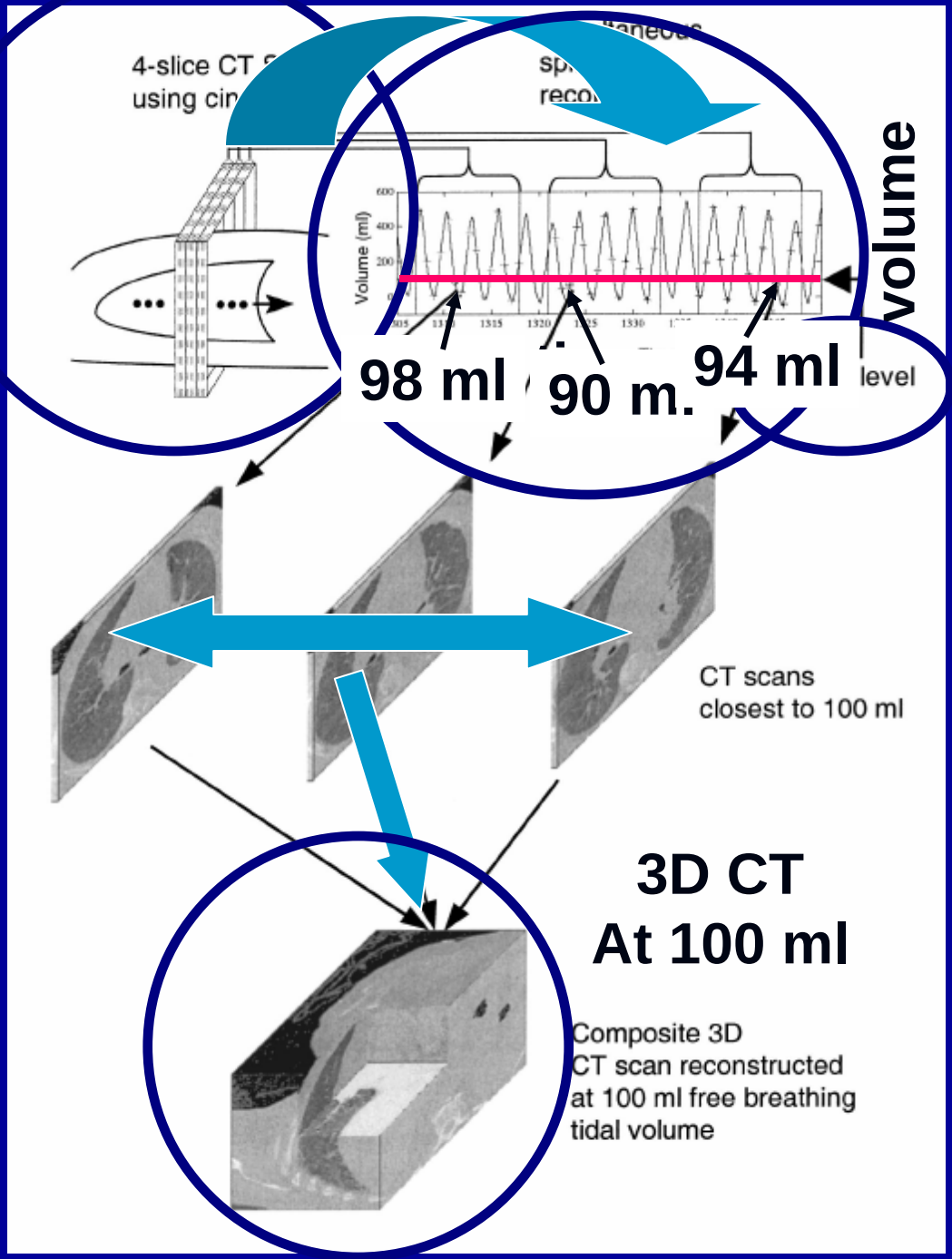




4D CT Process

- 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


Synchronization Signal
Spirometer
CT Data
Philips Brilliance 16-slice CT Scanner
Philips Bellows
Bronchial Branch
12-Slice mode
DICOM Transfer
Spirometry Tidal Volume Acquisition
Spirometry Drift Correction
Volume-Gated Images
Motion Model Parameter Determination
Acquisition Process

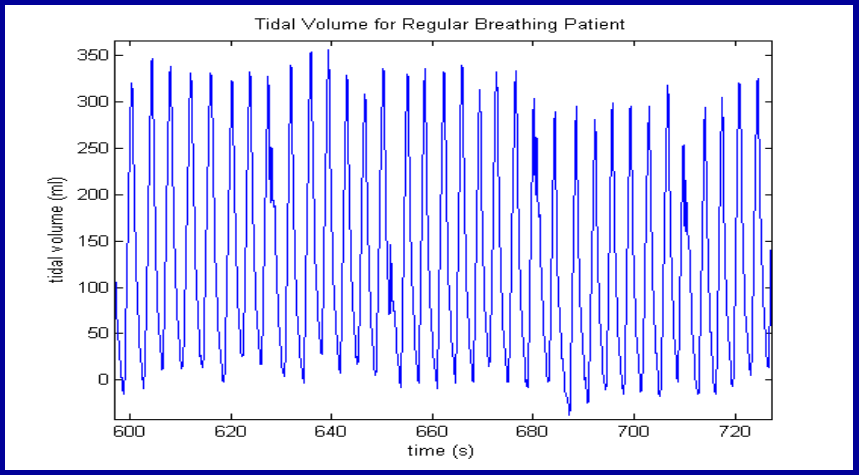

4-slice CT
using cir
Volume (ml)
volume
98 ml
90 m.
94 ml
level
CT scans
closest to 100 ml
3D CT
At 100 ml
Composite 3D
CT scan reconstructed
at 100 ml free breathing
tidal volume

Gating

- Have process that
  - Acquires CT images
  - Sorts CT images using metric data
- However
  - What criteria are used to determine the patient's breathing phase associated with each image?

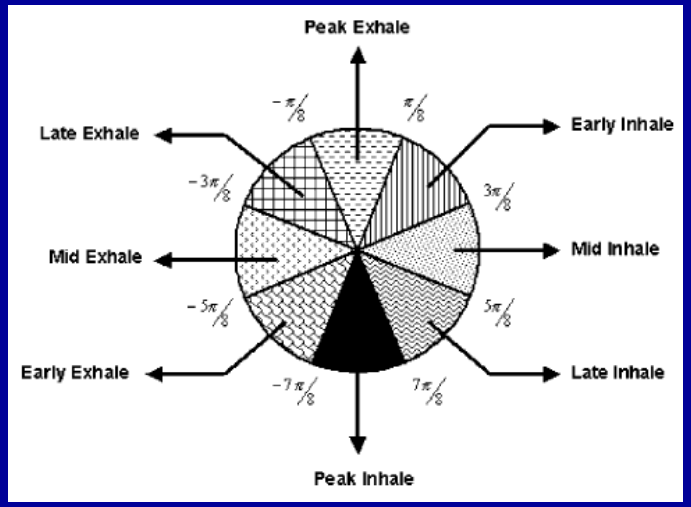
Inhalation

Exhalation



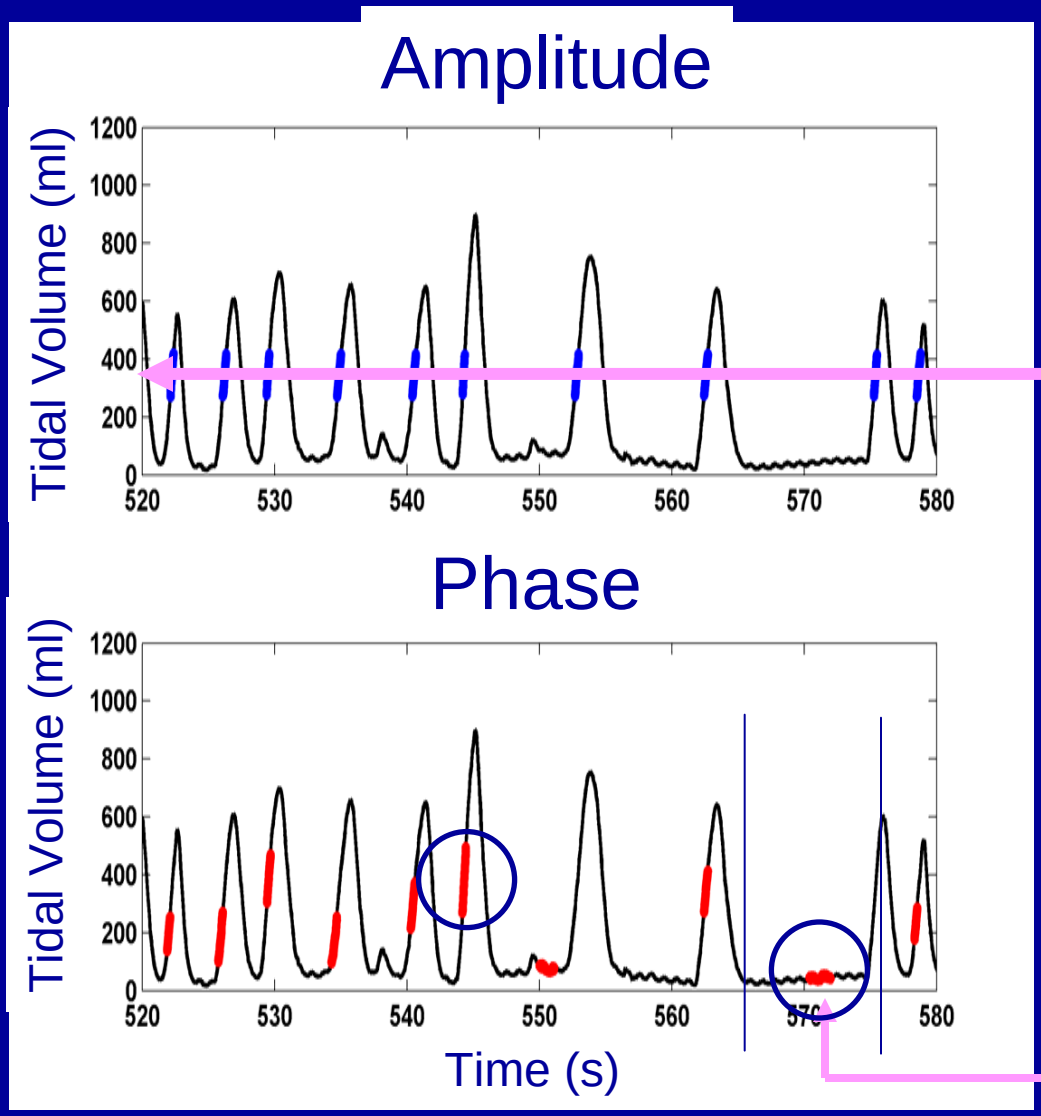
Breathing Cycle Definition

- 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

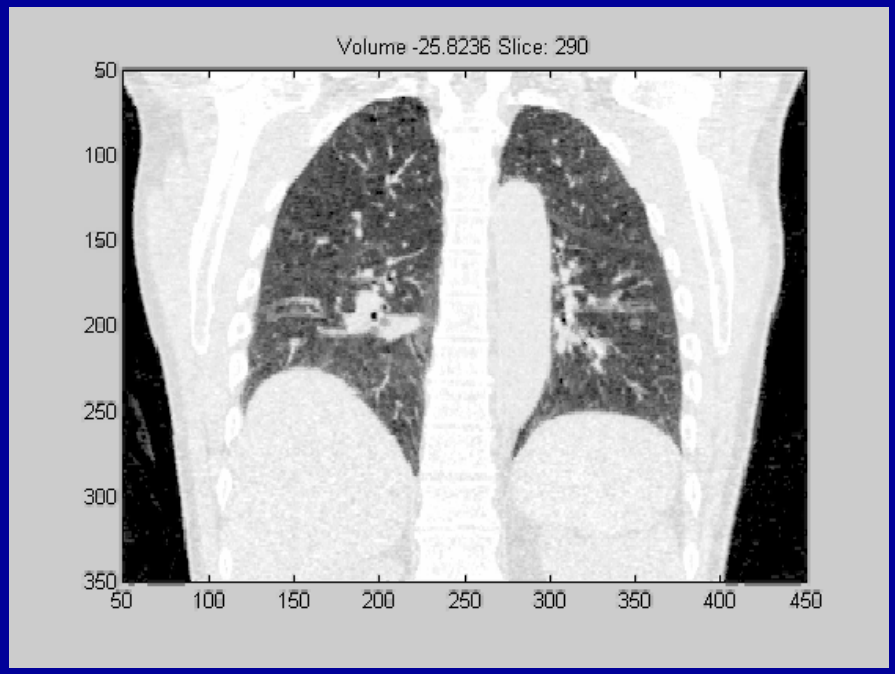
Phase vs. Amplitude

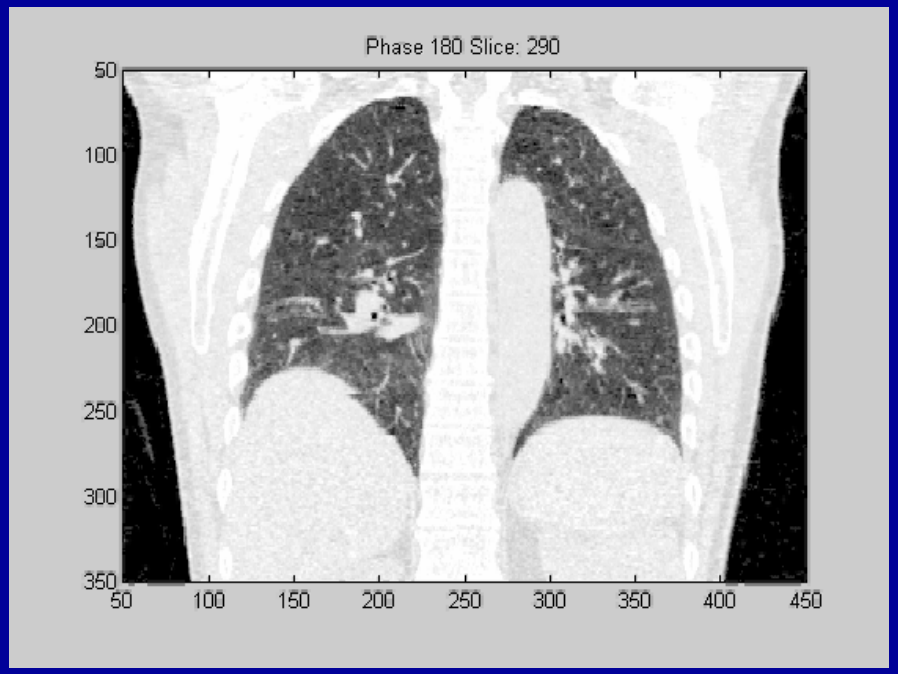


Select mid-inspiration

Mid-inspiration defined by percentile tidal volumes

Mid-inspiration defined by time between exhalation and inhalation peaks

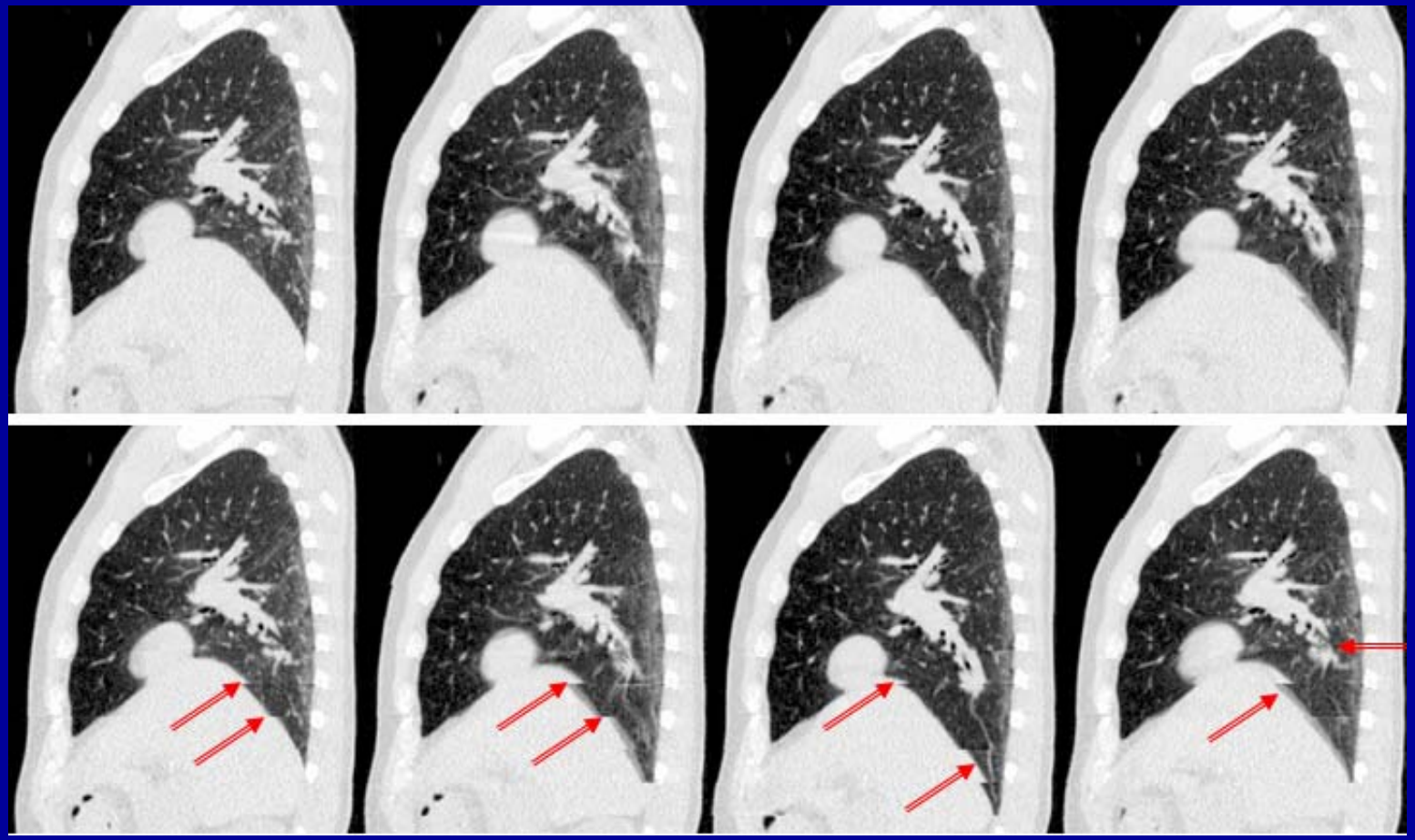




Amplitude sorting

Phase sorting

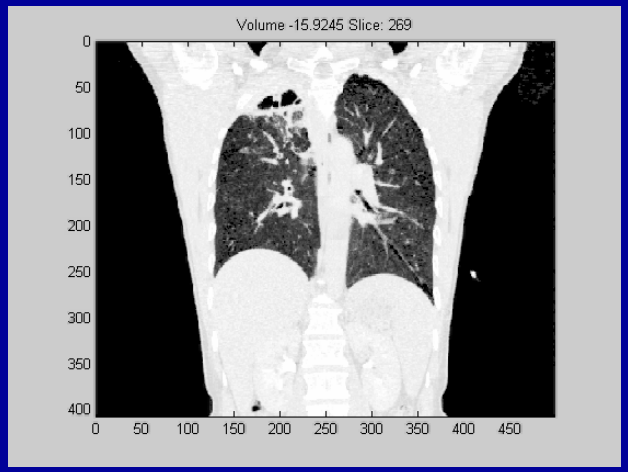
Amplitude vs Phase

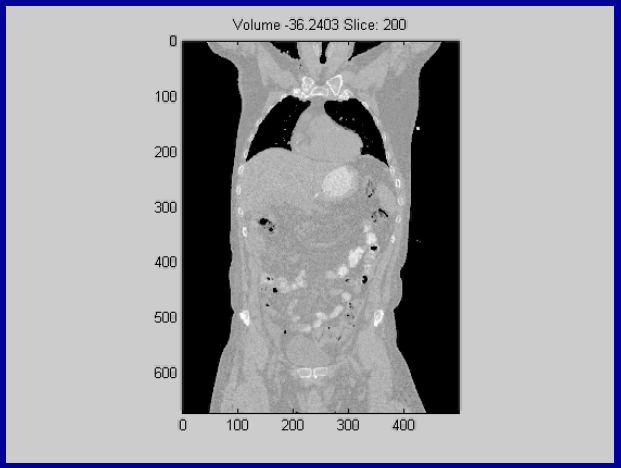


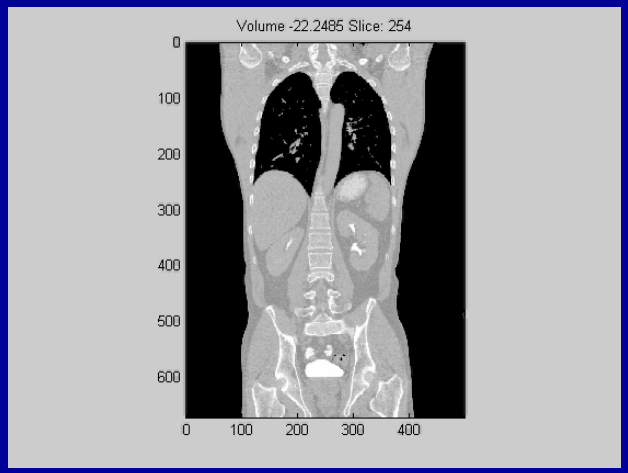
A

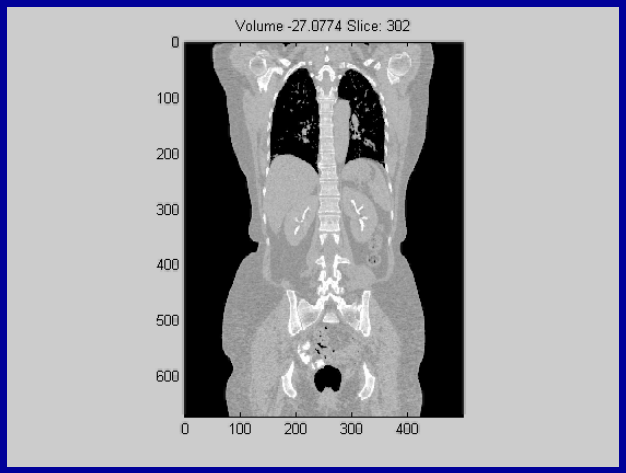
P

What 4D CT Can Do





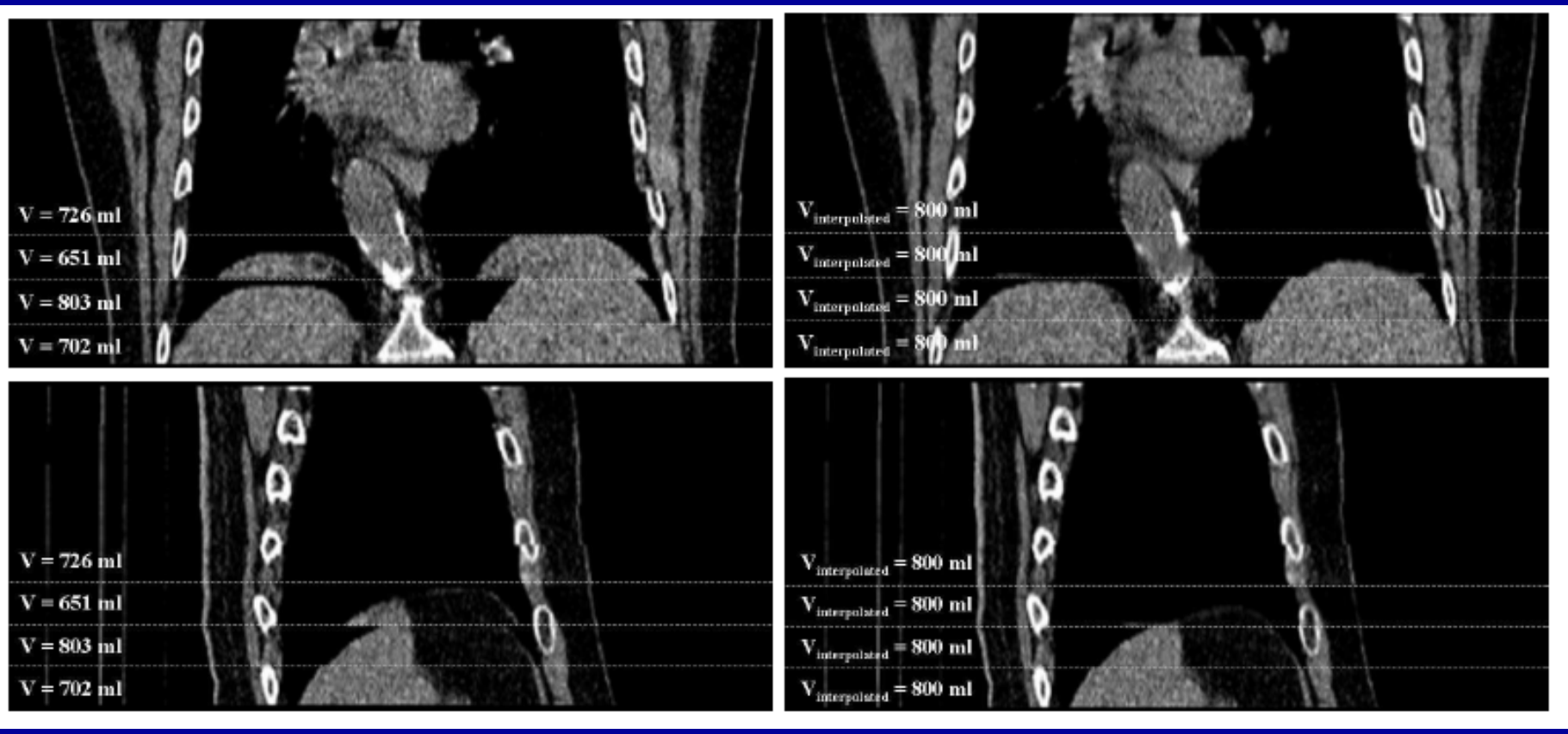




Clinical Images

- Difficulties with amplitude-based retrospective gating is that images are not necessarily acquired at the same breathing phase for each couch position
- Interpolation may be a method for interpolating to a common breathing phase
- Requires a deformable map of motion

Interpolation using optical flow deformation: Removal of Residual Artifacts

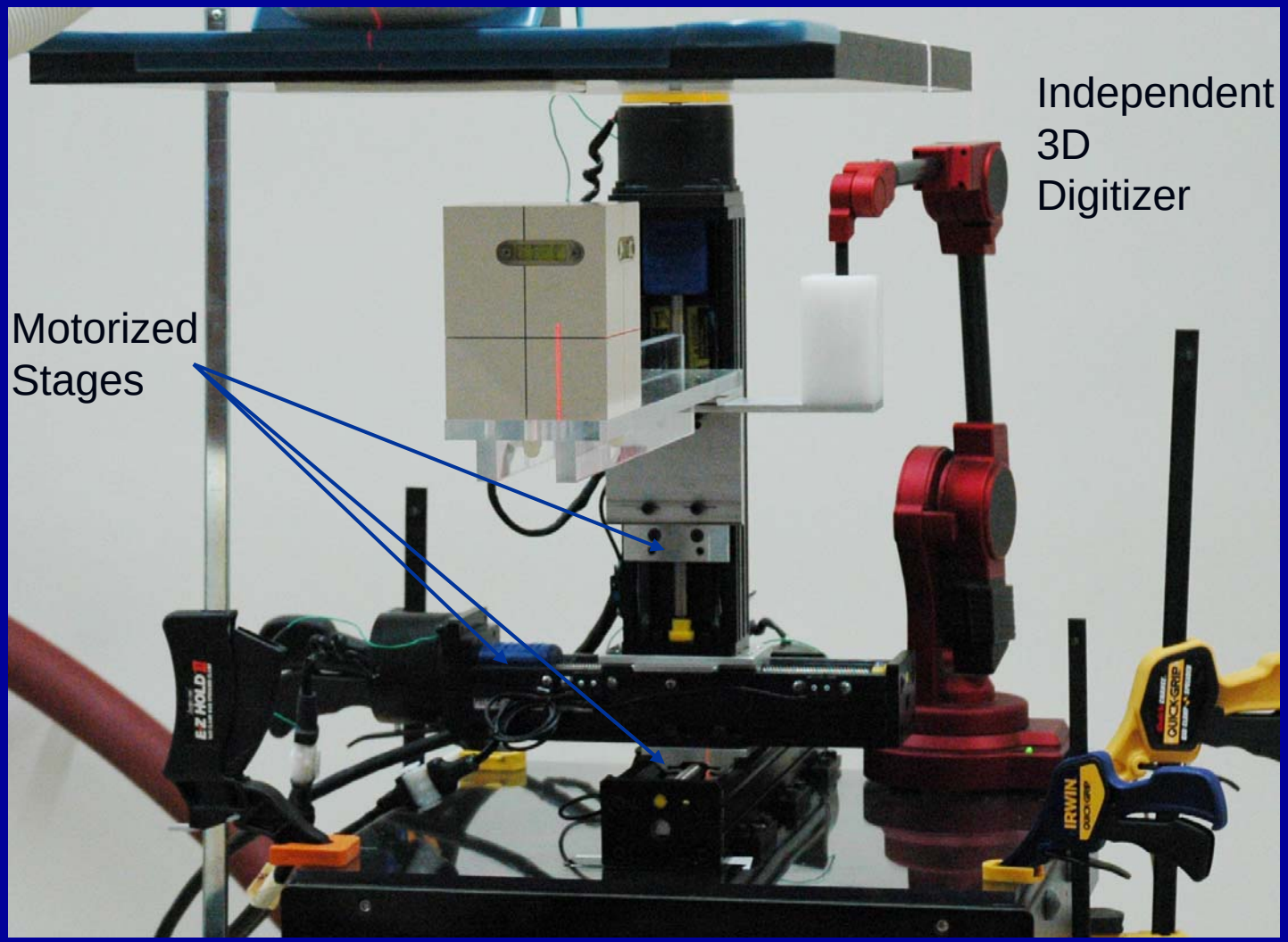


Erhardt et al, SPIE 2006

Quality Assurance

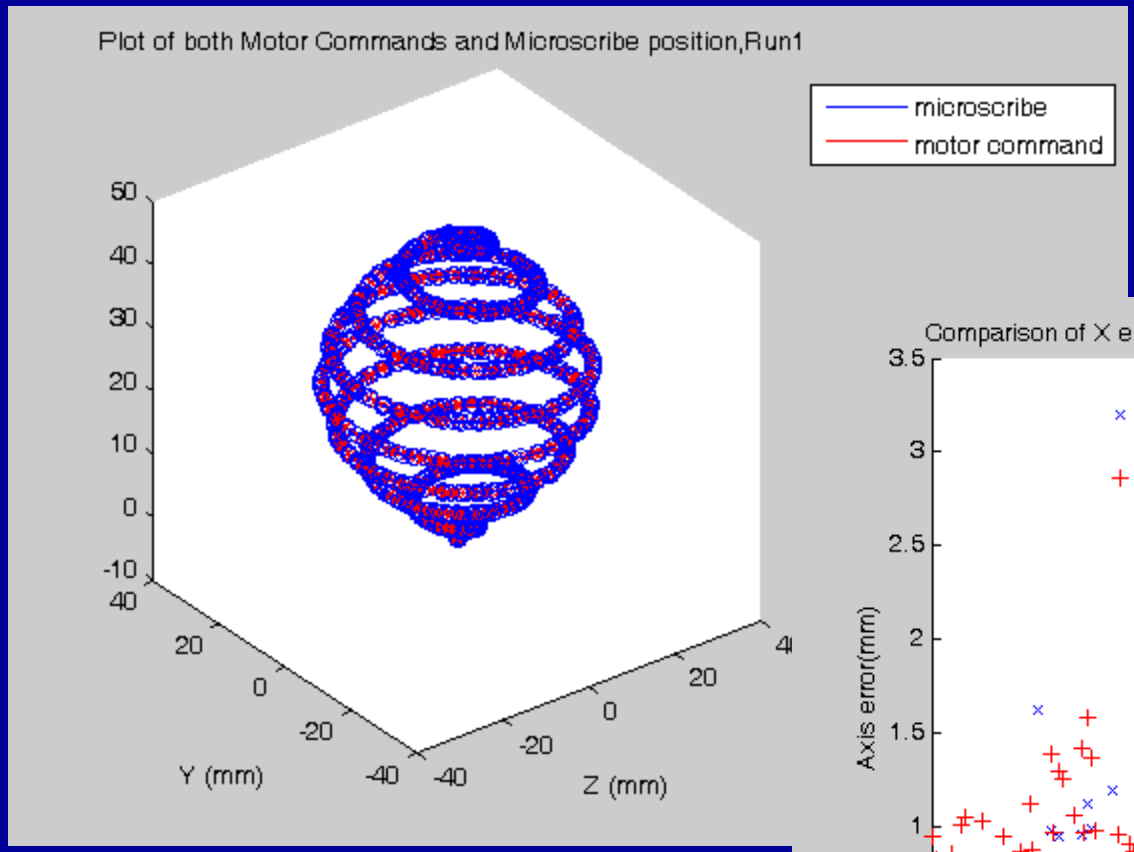
- Accuracy of 4D process
- Phantoms developed to QA process
- Some operate in 1D, periodic
  - Breathing is non-periodic
  - Breathing motion is 3D

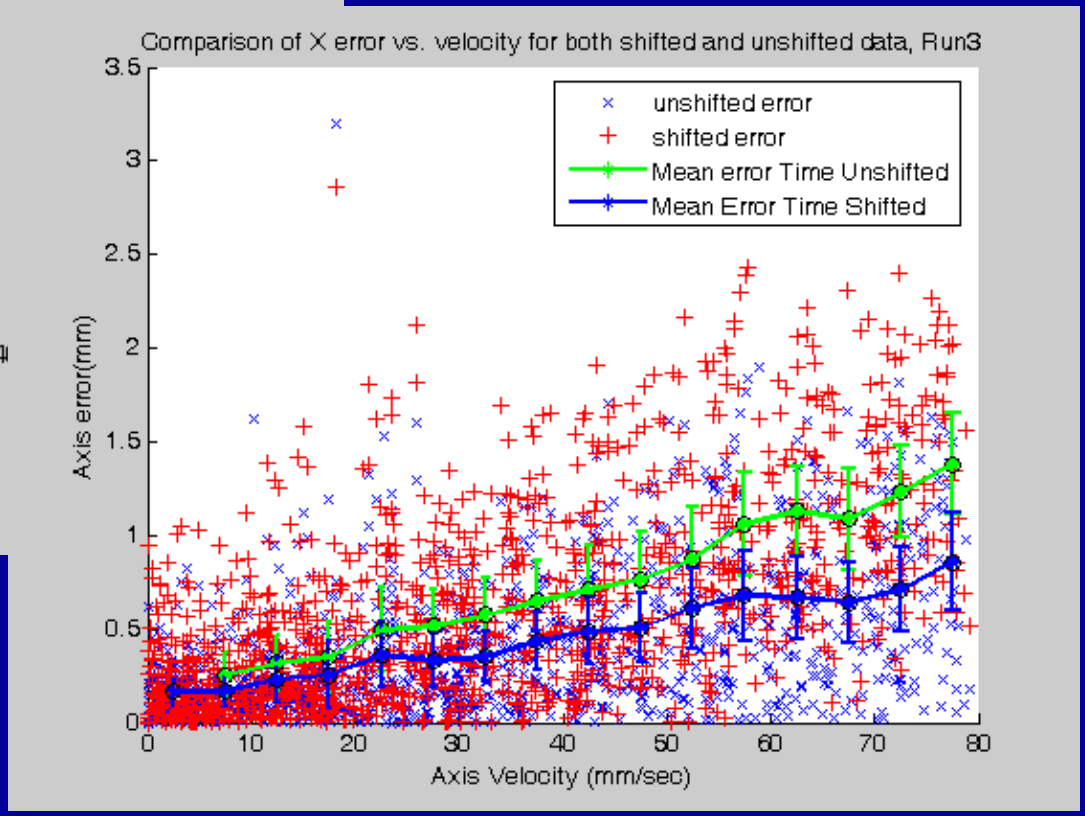
QA of 4D



Example: Calypso

QA of 4D


Plot of both Motor Commands and Microscribe position,Run1
microscribe
motor command
50
40
30
20
10
0
-10
40
20
0
-20
-40
Y (mm)
-40
-20
0
20
Z (mm)


Comparison of X error vs. velocity for both shifted and unshifted data, Run3
unshifted error
shifted error
Mean error Time Unshifted
Mean Error Time Shifted
Axis error(mm)
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
Axis Velocity (mm/sec)

What Next?

- We have a method for describing breathing cycle
- We can create 3D image datasets at specific breathing phases
- What do we do with this info?
- A) Create 3D CT at specific phases
  - Contour these phases and use the data
- B) Use CT data to fit a motion model
  - Model will be used to drive treatment planning

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Tumor Trajectories: What our Model Has To Be Able To Do

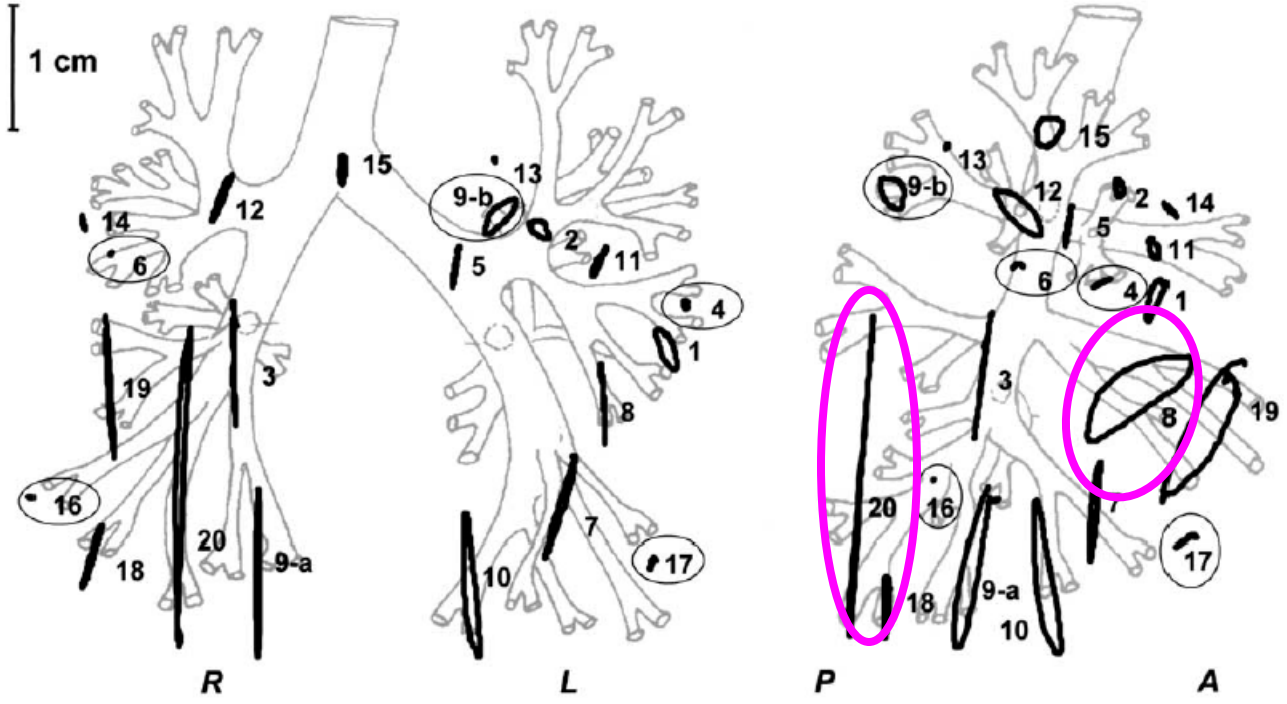


Fig. 4. Orthogonal projections of the trajectories of the 21 tumors on (left) the coronal (LR-CC) and (right) the sagittal (AP-CC) plane. The tumors are displayed at the approximate position, based on the localization mentioned in the treatment chart. Tumors that were attached to bony structures are circled.

Seppenwoolde *et al.* Int. J. Radiation Oncology Biol. Phys., Vol. 53, No. 4, pp. 822–834, 2002

Breathing Motion Modeling

Seppenwoolde, Red J 53, 822-834 2002

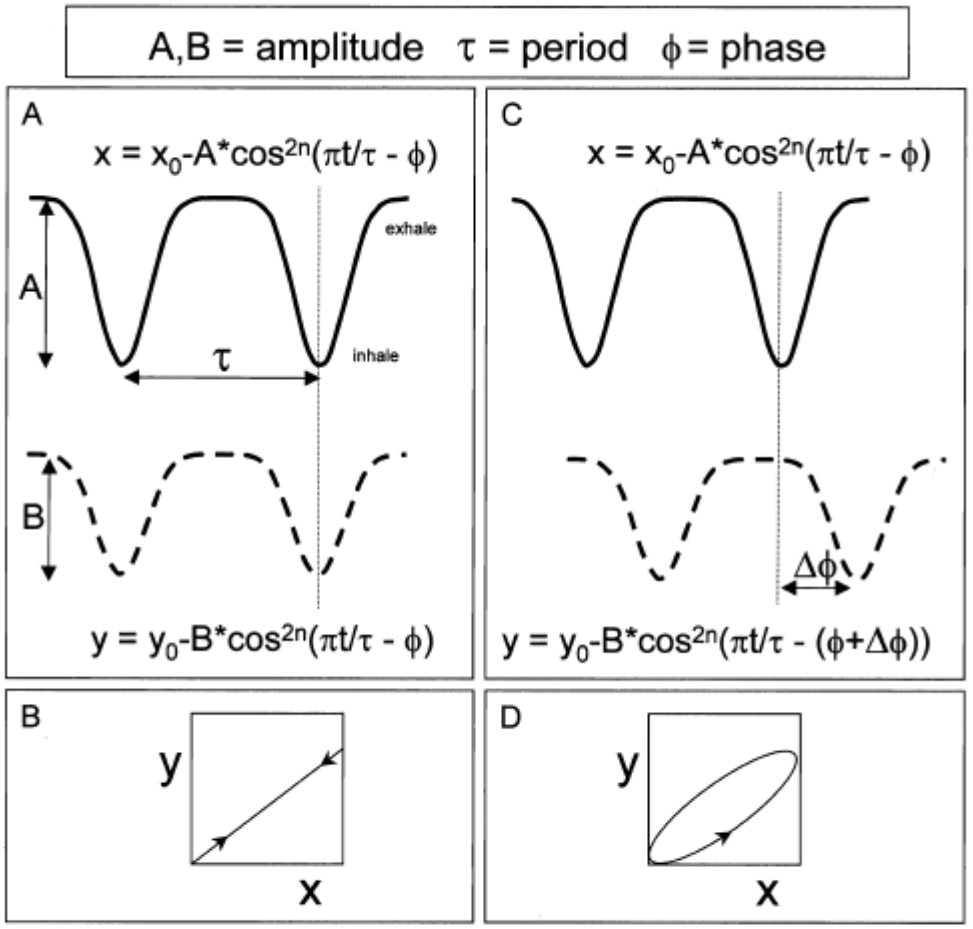


Fig. 1. The principle of hysteresis. When there is (A) no phase difference between two sinusoid signals with equal frequency, there is (B) no hysteresis; the position of the *y* direction is directly related to that of the *x* direction. When there is (C) a phase difference (ϕ), there are two possible positions where the tumor is at the same *x* position, depending on (D) the position in the breathing cycle. (D) The width and the shape of the hysteresis ellipsoid depend on the phase difference and the amplitude of both signals.

Breathing Motion Modeling

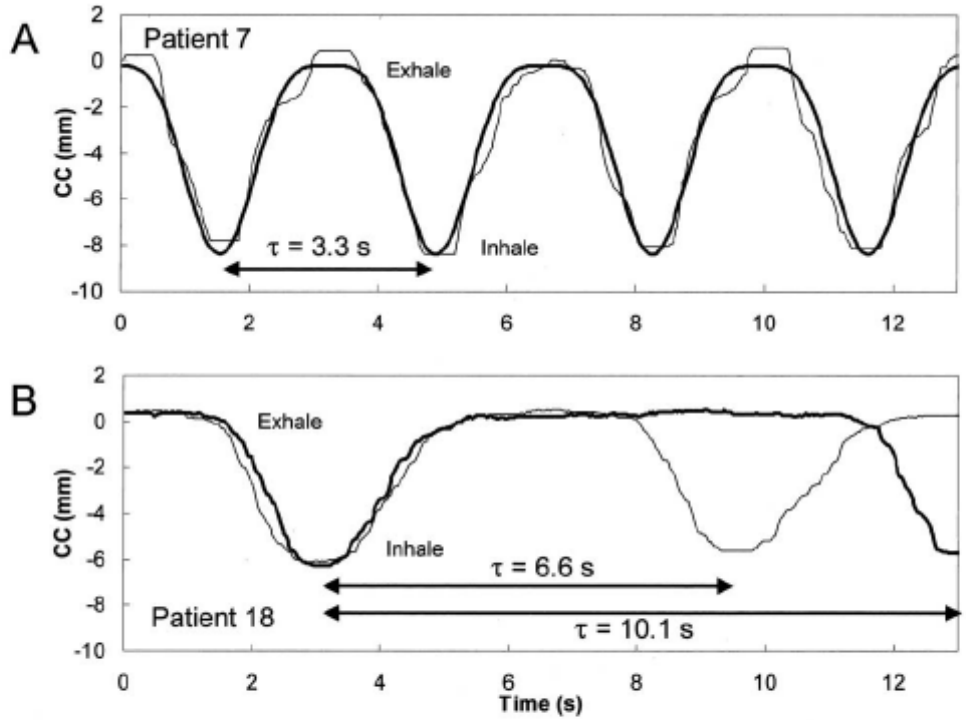


Fig. 6. (A) The time signal of the tumor motion of Patient 7 (CC direction). A curve was fitted through the data with (τ = 3.3 s and n = 2. (B) The time signal of the tumor motion of Patient 18, who had a very irregular breathing pattern (CC direction). The thin line represents tumor motion with a period of 6.6 s, whereas later on the period was 10.1 s. The first cycle could be fitted well with n = 3; the second cycle was fitted with n = 9. Note that the shape of the tumor motion of the longer period is similar to that of the shorter cycle, only the time spent in the exhale position is prolonged in the longer cycle.

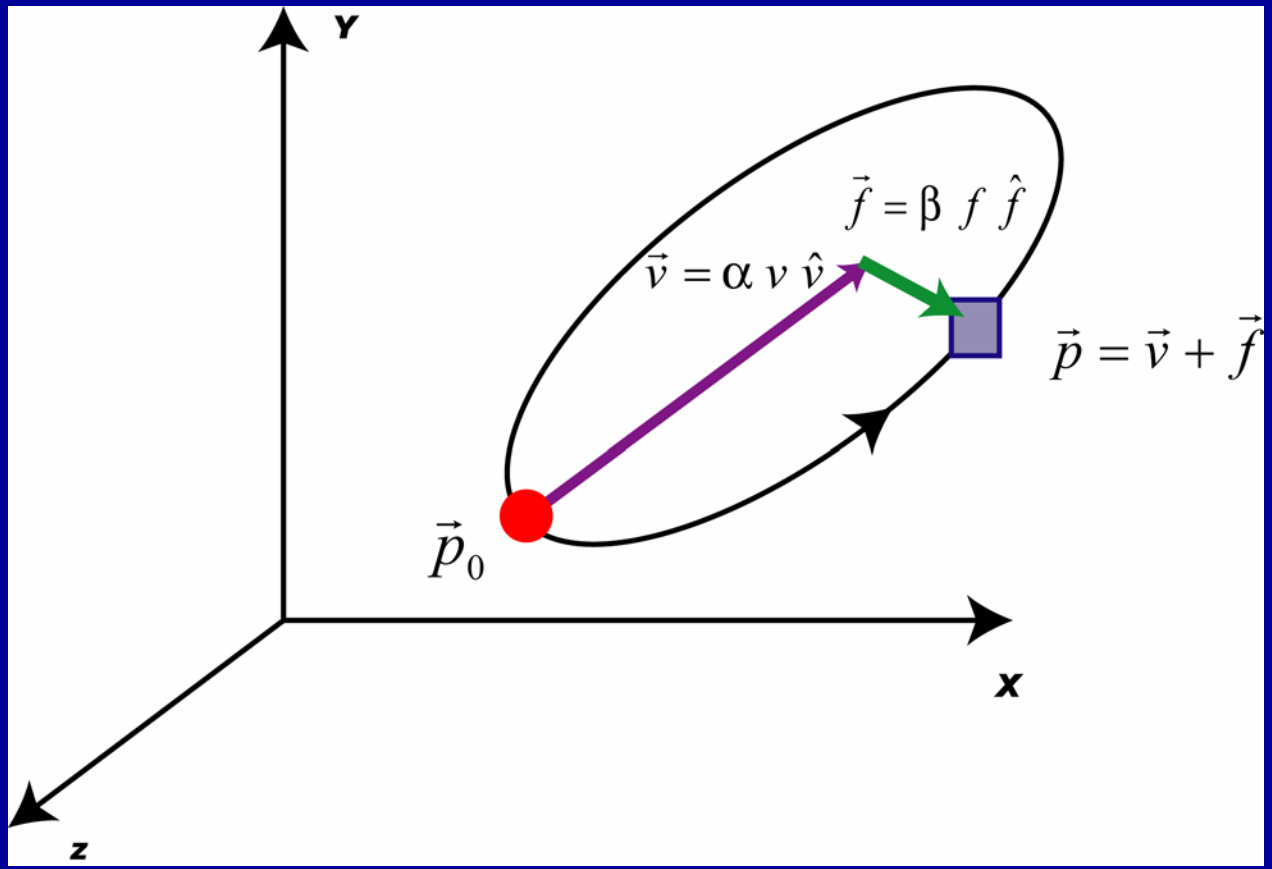
Seppenwoolde, Red J 53, 822-834 2002

Mathematical Model

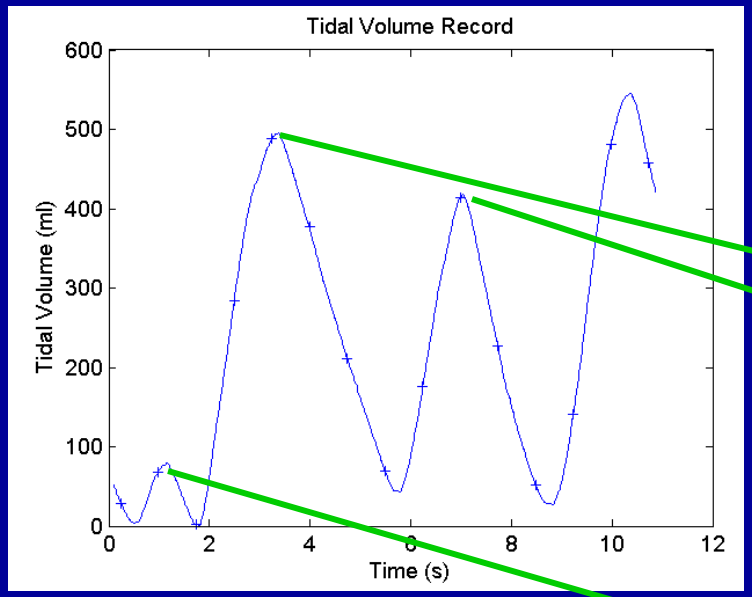
Linear Approximation

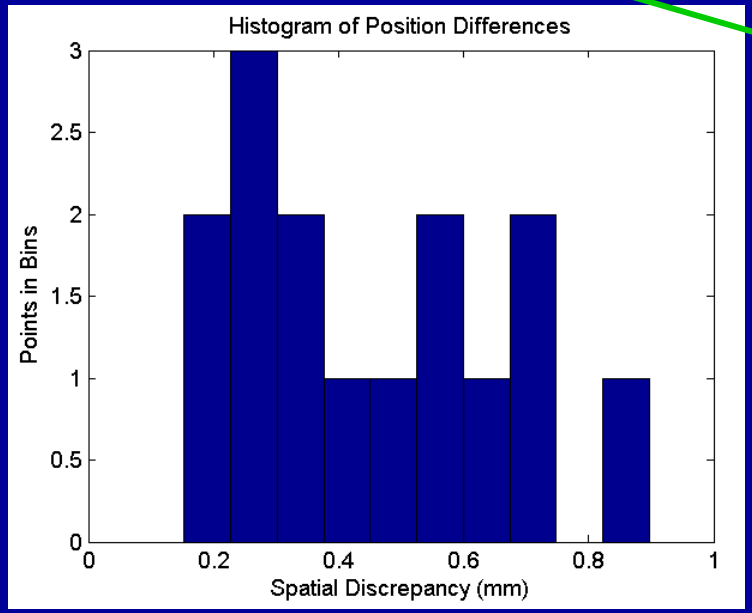
Breathing cycle is defined by Tidal Volume and Airflow

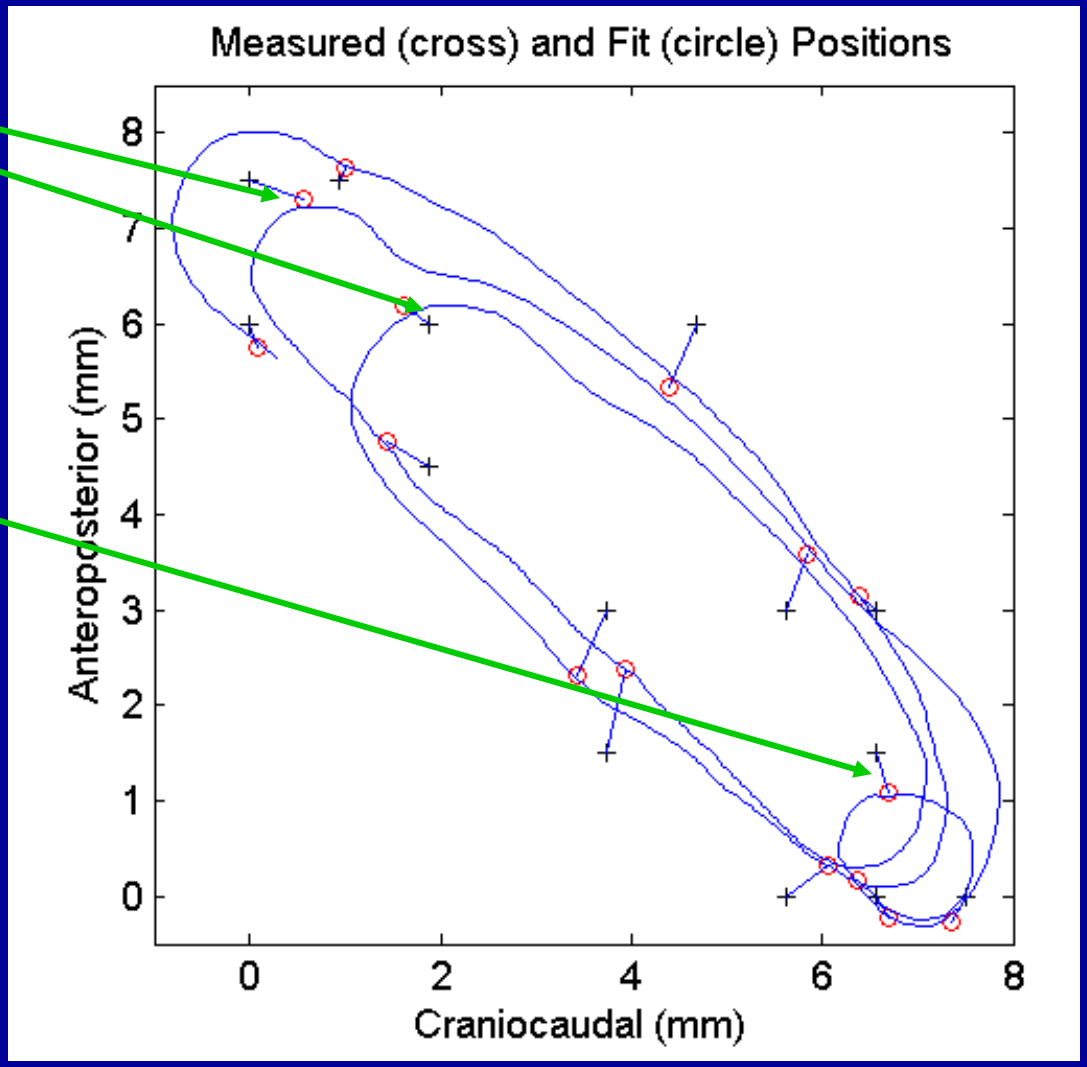
Nonlinear motion comes from airflow f = dv/dt and shape of airflow curve



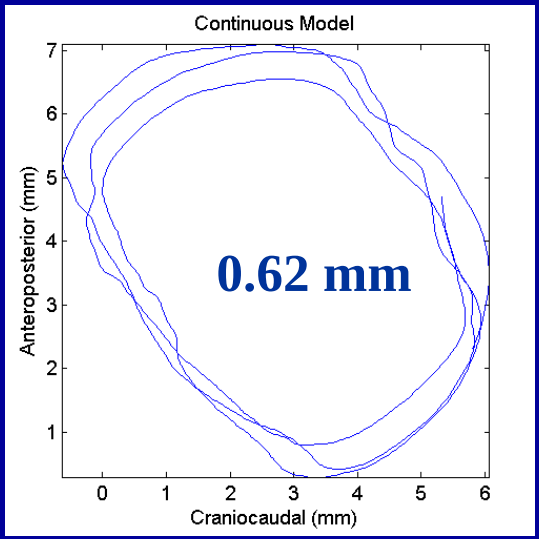
5D Breathing Motion Modeling

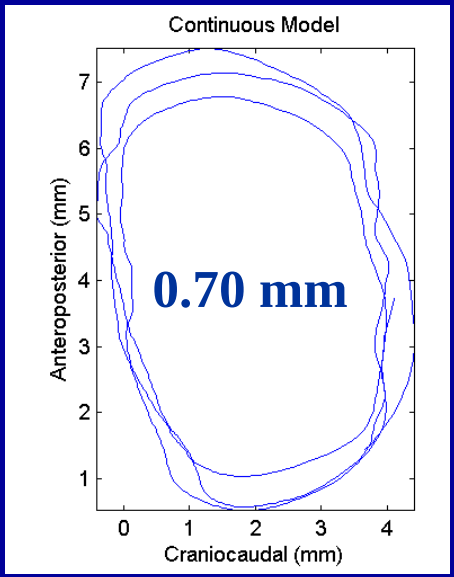


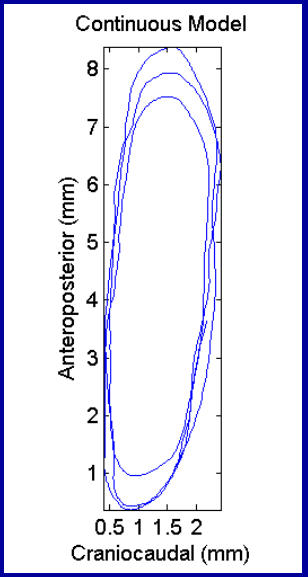




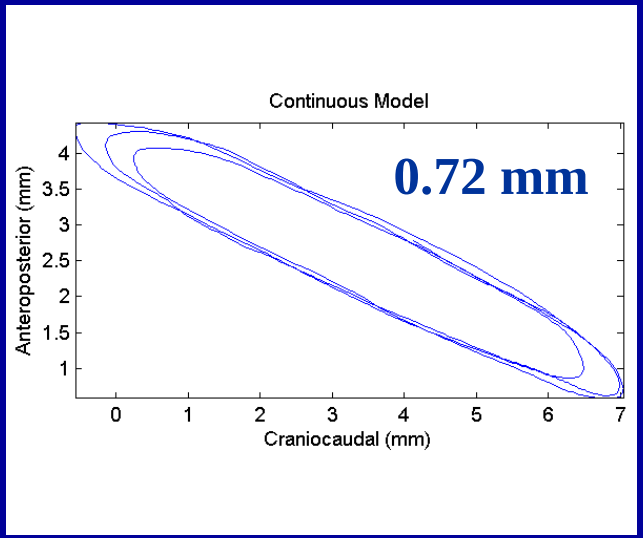
Points in Same Patient

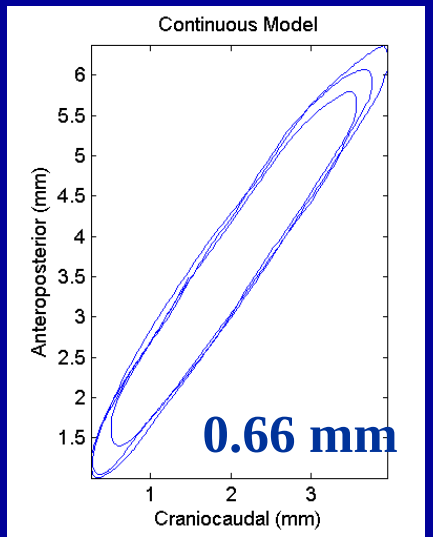


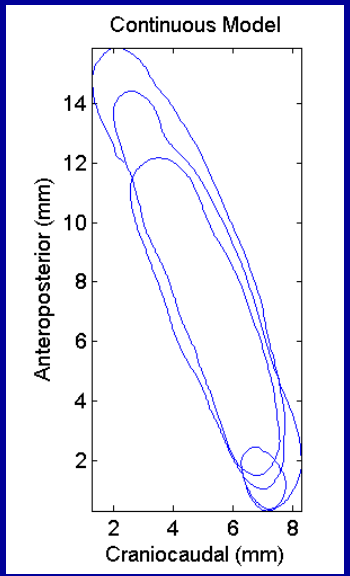




0.66 mm





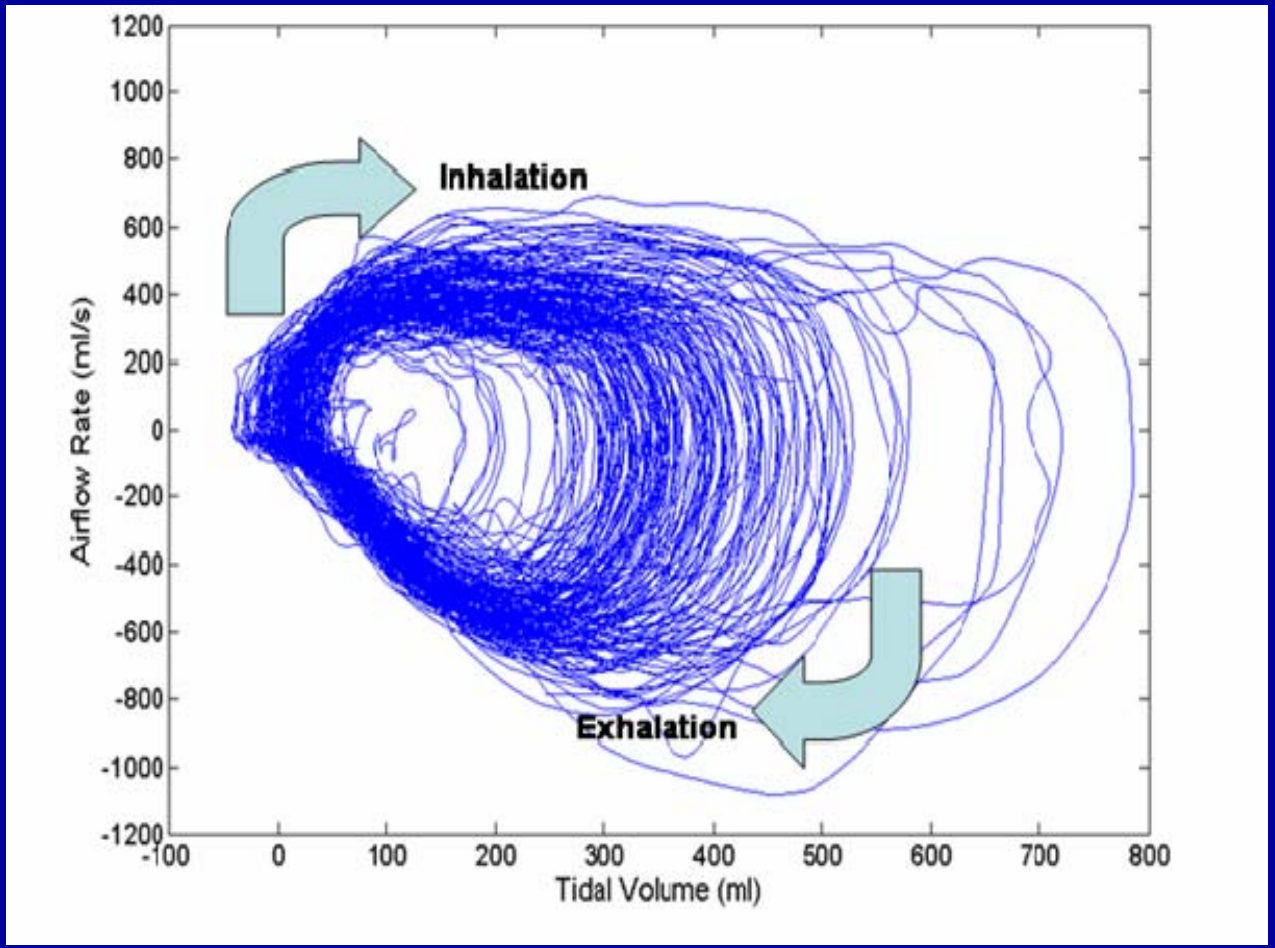


0.46 mm

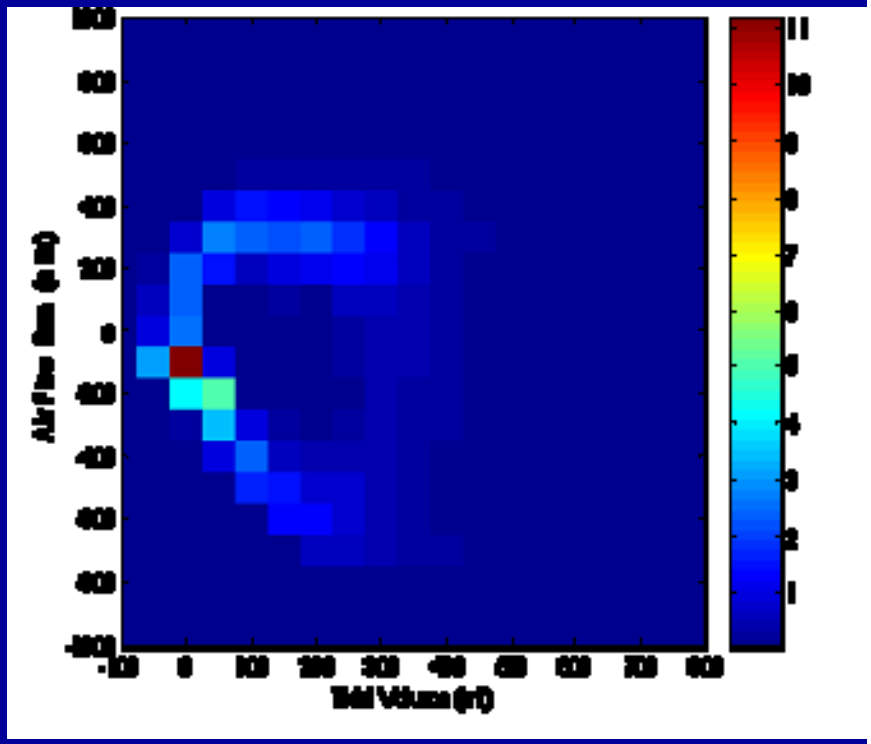
Breathing

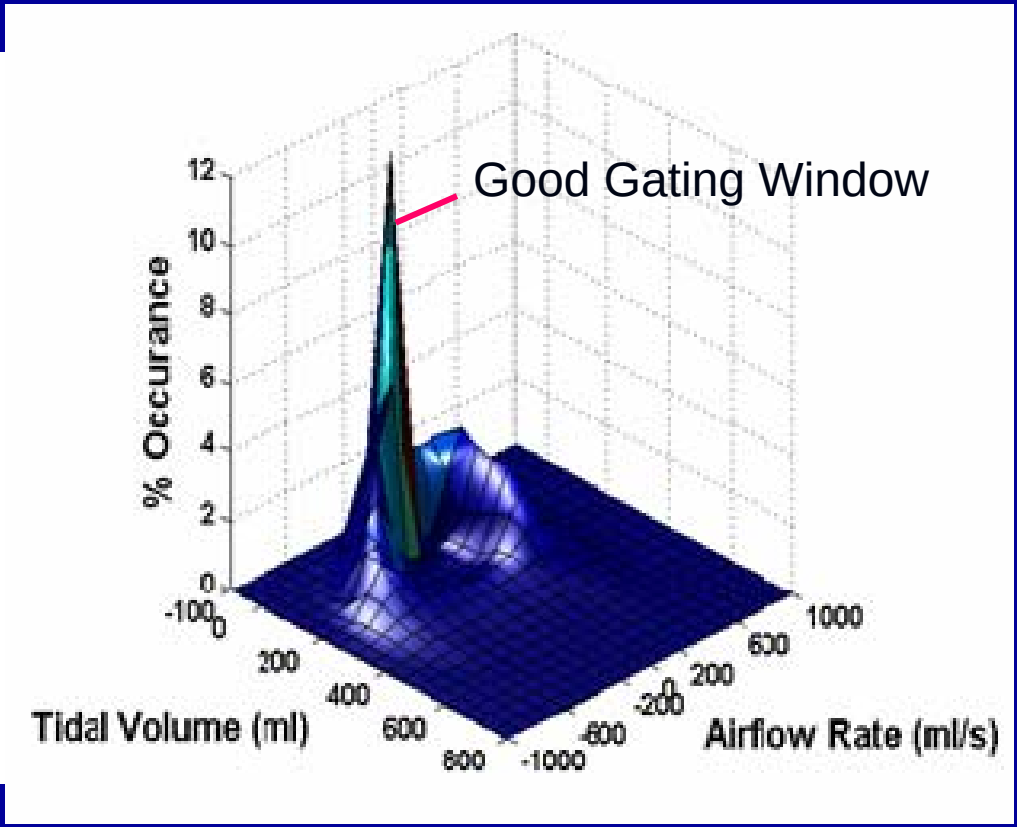
- How do we define the “breathing” cycle?
- What is an inhalation and exhalation?
- How do the acquired images correspond to the actual tumor positions during treatment?
  - ITV creation requires accurate understanding of breathing cycle
- How do we define a gating threshold?
  - Planning process
  - Efficiency versus conformality

Breathing Patterns

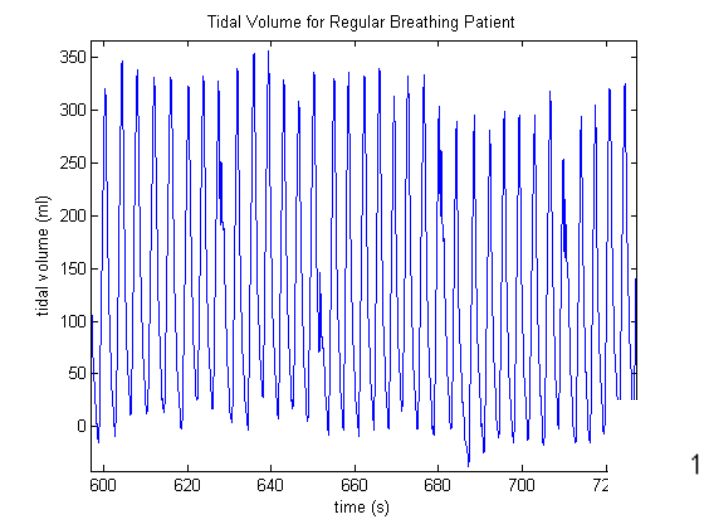


Breathing Patterns

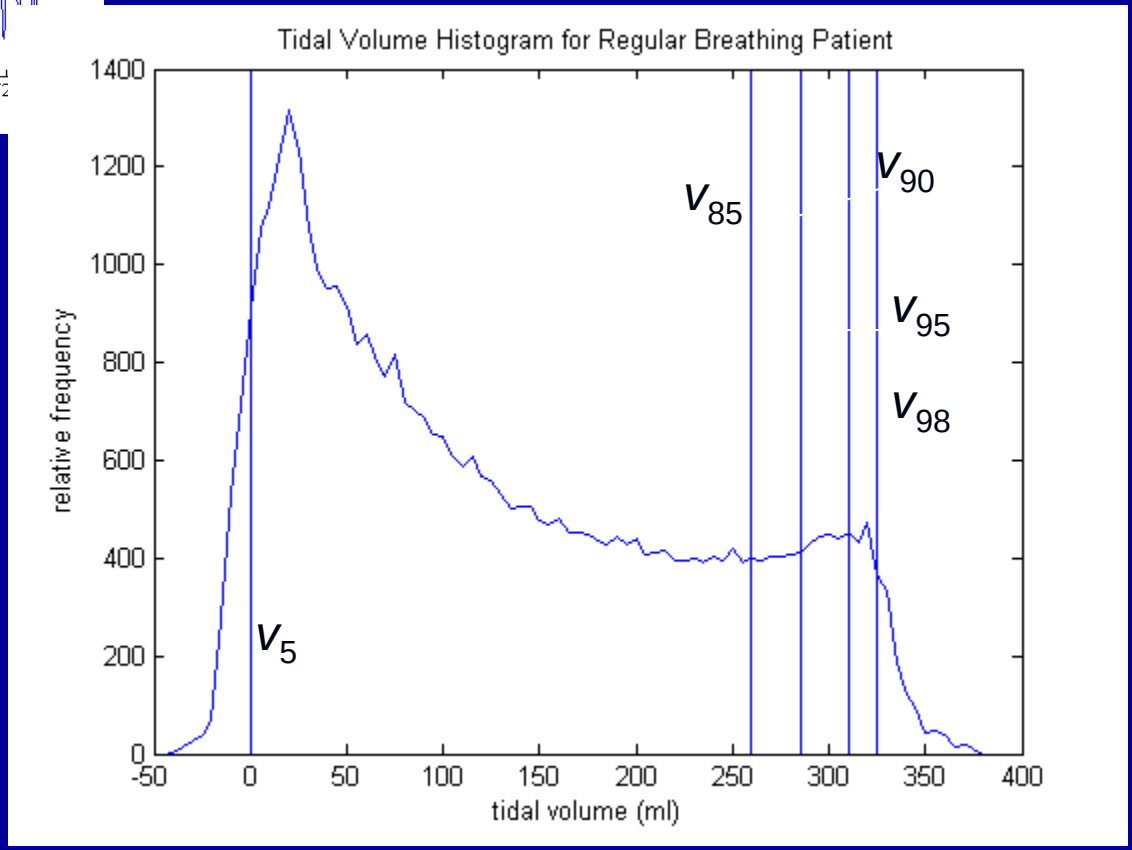




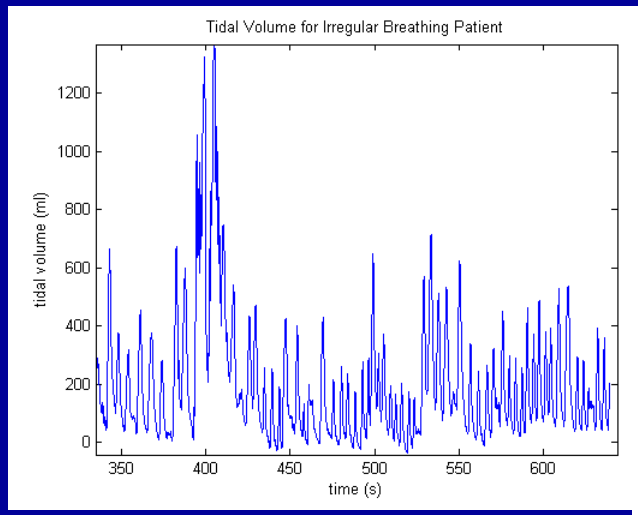
Regular Breather

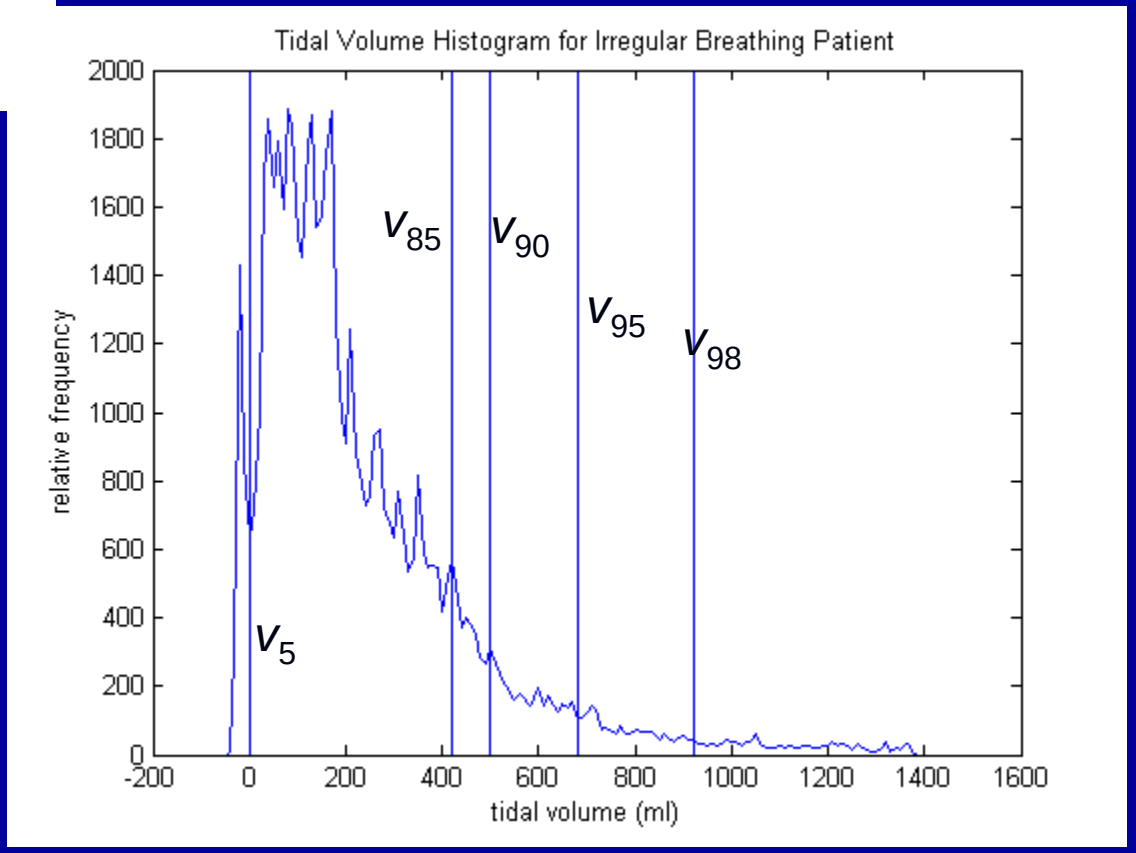


v_x = Volume at which patient had v or less volume x% of the time



Irregular Breather

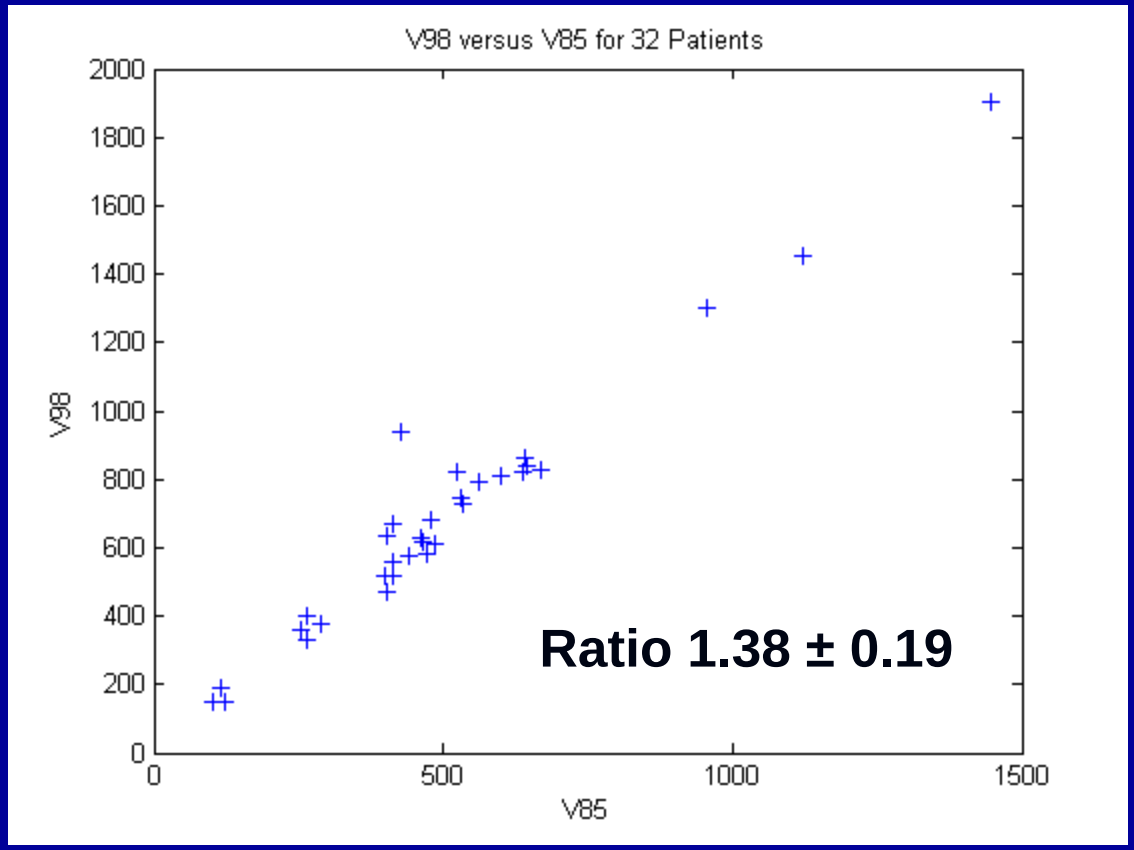




V_{98} (93% of time) vs V_{85} (80% of time)

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!

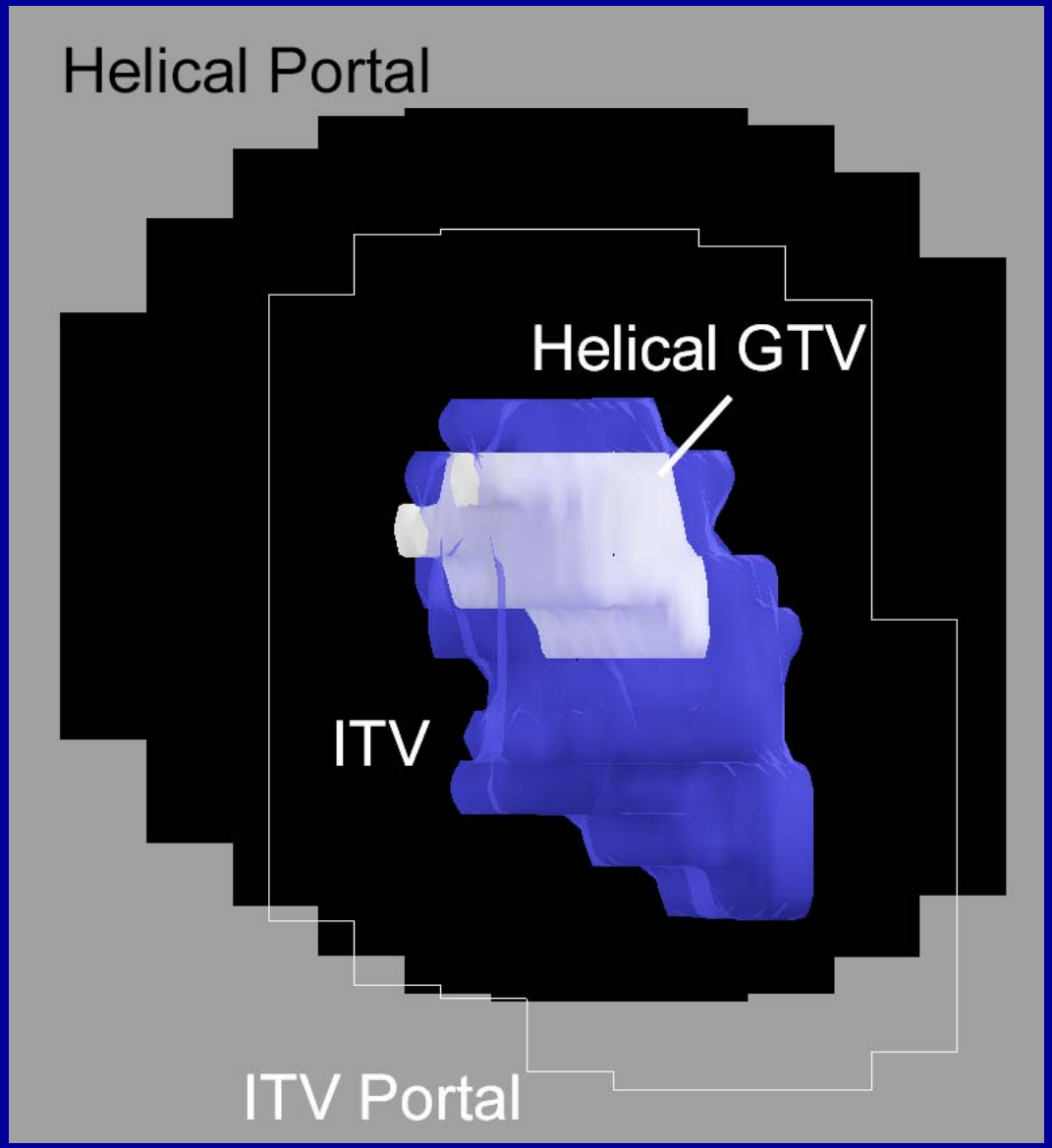
Outline

- Why is 4D CT necessary?
- What is 4D CT?
- How do we characterize breathing?
- What do we do with 4D CT information?

Treatment Planning

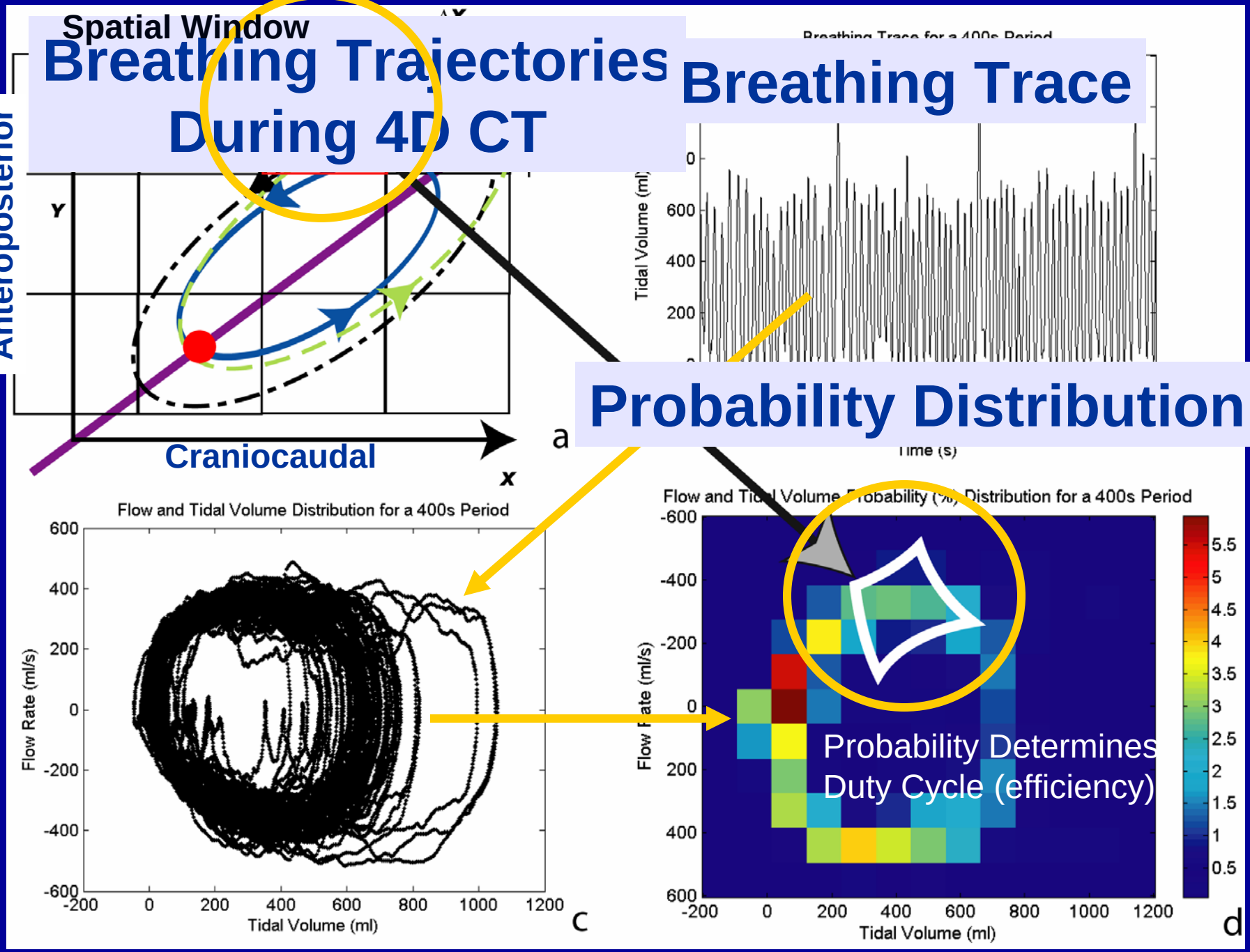
- Images provide Geometry (functional) data for treatment planning
- Treatment planning provides prediction of treatment course
  - Spatial uncertainties = margins
  - Extrapolation
- Breathing motion
  - ITV
  - Gating
  - Tracking

ITV



Gating

- Spatial “window”
  - Determined by planning process via dosimetric considerations
- 4D CT and breathing motion model
  - Couples spatial window to fraction of time spent in that window
  - Determines duty cycle
- Planning system provides cost/benefit analysis of conformality versus delivery efficiency


Spatial Window
Breathing Trajectories During 4D CT
Breathing Trace
Probability Distribution
Anteroposterior
Craniocaudal
Y
x
a
Tidal Volume (ml)
Time (s)
Flow and Tidal Volume Distribution for a 400s Period
Flow Rate (ml/s)
Tidal Volume (ml)
c
Flow and Tidal Volume Probability (%) Distribution for a 400s Period
Probability Determines
Duty Cycle (efficiency)
d

Tracking

- Tracking system require very accurate understanding of tumor position
- When you track the tumor, you *untrack* everything else
  - Critical structures define dose limits, not tumors
- Planning system will need to provide predictions of normal organ doses

Tumor Tracking Methods (1/2)

- Imaging + Surrogate
  - OBI Cone-beam CT
  - Soft-tissue contrast of cone-beam CT used to identify tumor in 3D
  - Surrogate maps motion and that map used to determine position throughout treatment (monitor surrogate)

Tumor Tracking Methods (2/2)

- Implants
  - Implants + Surrogate
    - Fluoroscopic imaging systems
  - Implants alone
    - Calypso Medical
- These systems will require significant developmental efforts

Conclusions

- More quantitation is required!
- Amplitude-based gating = ability to extrapolate from existing image data
- 4D CT should be used as data to feed a mathematical/physical model of human breathing
- The model feeds the treatment planning process