Measurement of Breathing Motion

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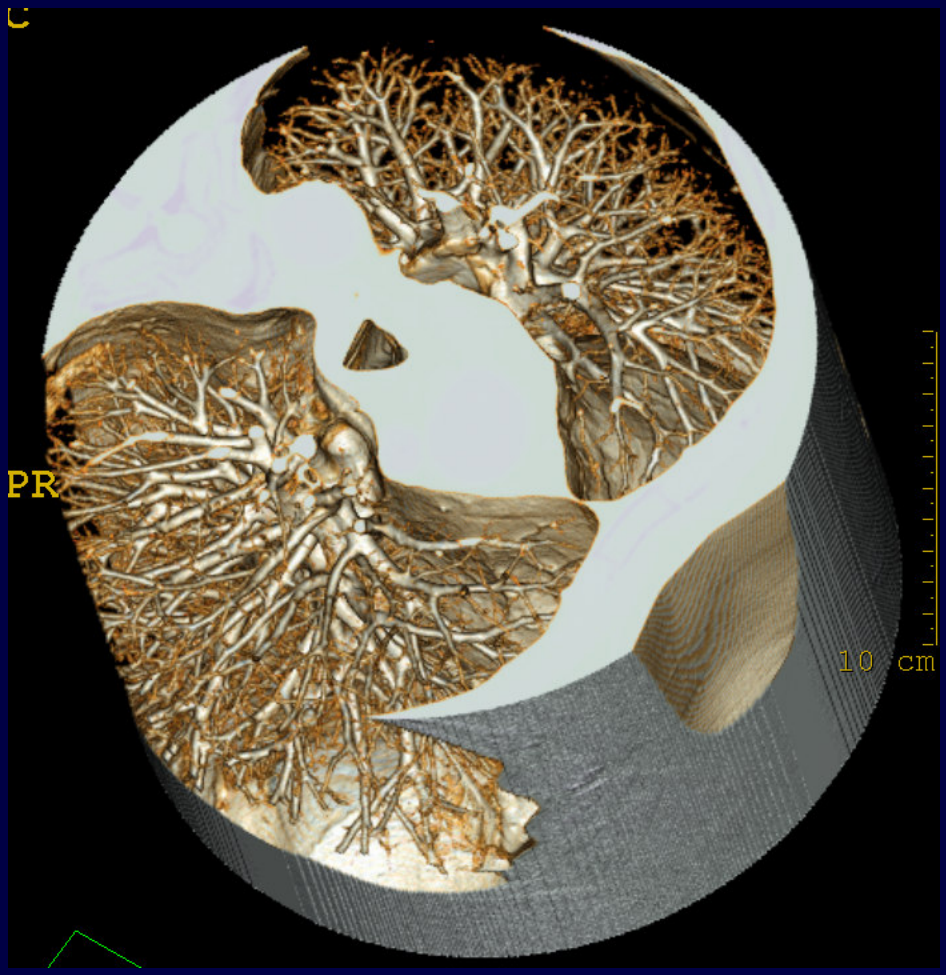
Hardware for 4-dimensional imaging

- CT
  - Excellent spatial accuracy
  - Limited acquisition flexibility
  - Fast response (<<breathing cycle)
  - Multislice CT scanners allow efficient collection of 4-D data
- MRI
  - Excellent soft tissue contrast
  - Accessibility limited
  - Limited lung image quality

Hardware for 4-D Imaging

- On-board imaging
  - kV
  - MV
  - Tomotherapy

Why CT?



4D CT (Breathing)

Applications

Technology

Quantitative Acquisition

Automated Tracking

Radiology

PET Breathing Artifact Reduction

R.O. Simulation

CT Artifact Reduction

IMRT Dose Analysis

Radiation Oncology Treatment

3D Portal Definition

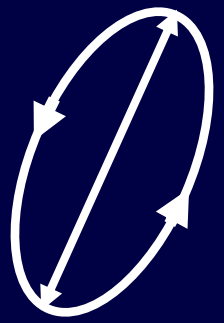
Gating (IMRT)

Tracking

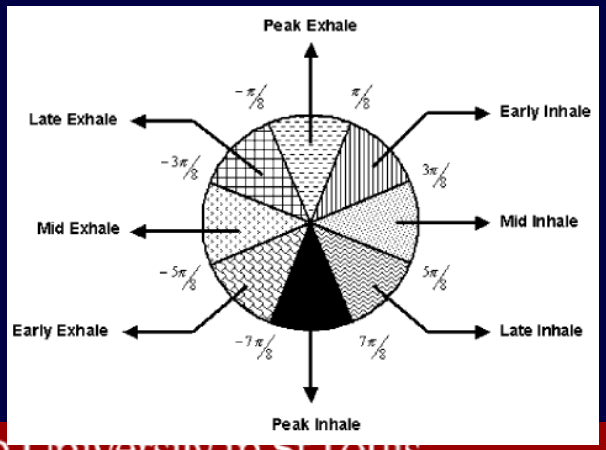
4D CT: Desired Information

- Motion (trajectories) during free breathing
- 3-D with time
  - Dose delivery operates/can be modeled as a function of time
- Breathing not sufficiently regular to use:
  - time as a basis for motion model
  - triggering (like cardiac) for image acquisition
  - time for gating treatment
- What should we use if not time? (metric)
  - Chest height (e.g. Varian RPM)
  - Spirometry

Breathing Cycle

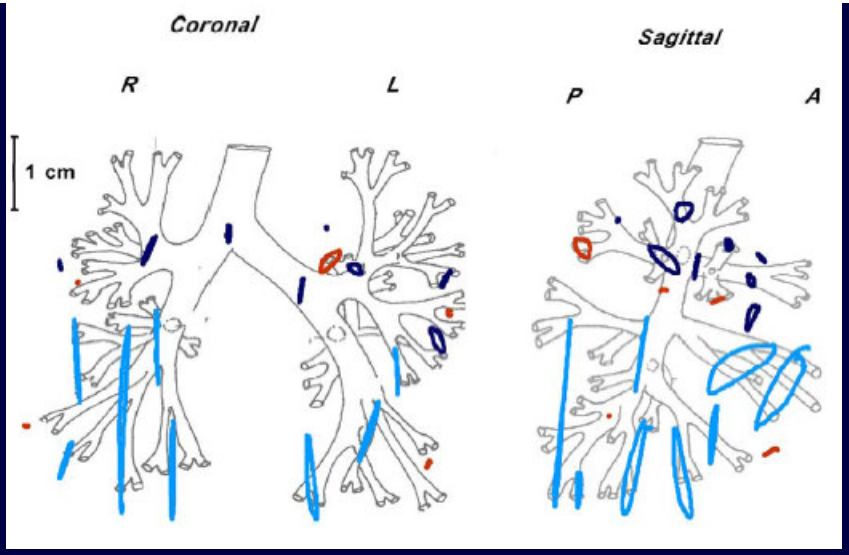


- How do we treat breathing?
  - Two competing models being used to model breathing; amplitude and cyclic
  - Cyclic:
    - Motion is function of breathing phase
    - Hysteresis concept straightforward to consider
  - Amplitude
    - Cyclic nature from time-dependence of amplitude
    - Hysteresis breaks down strict amplitude model

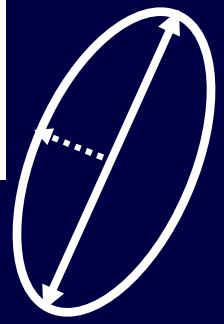


Vedam et al, PMB 2003

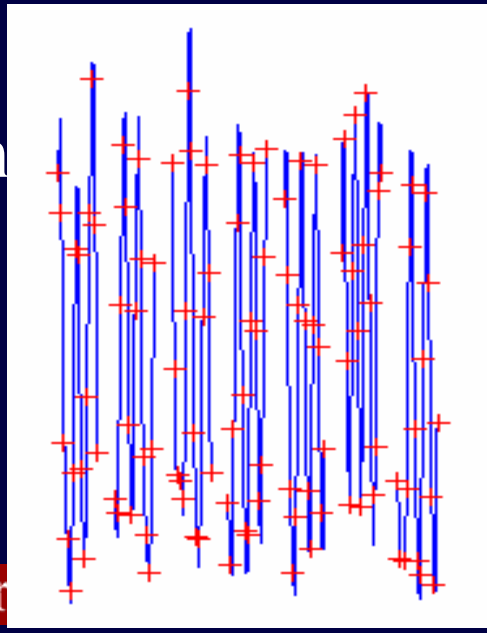
Breathing Cycle



Shirato et al Semin Rad Onc 14 10 (2004)

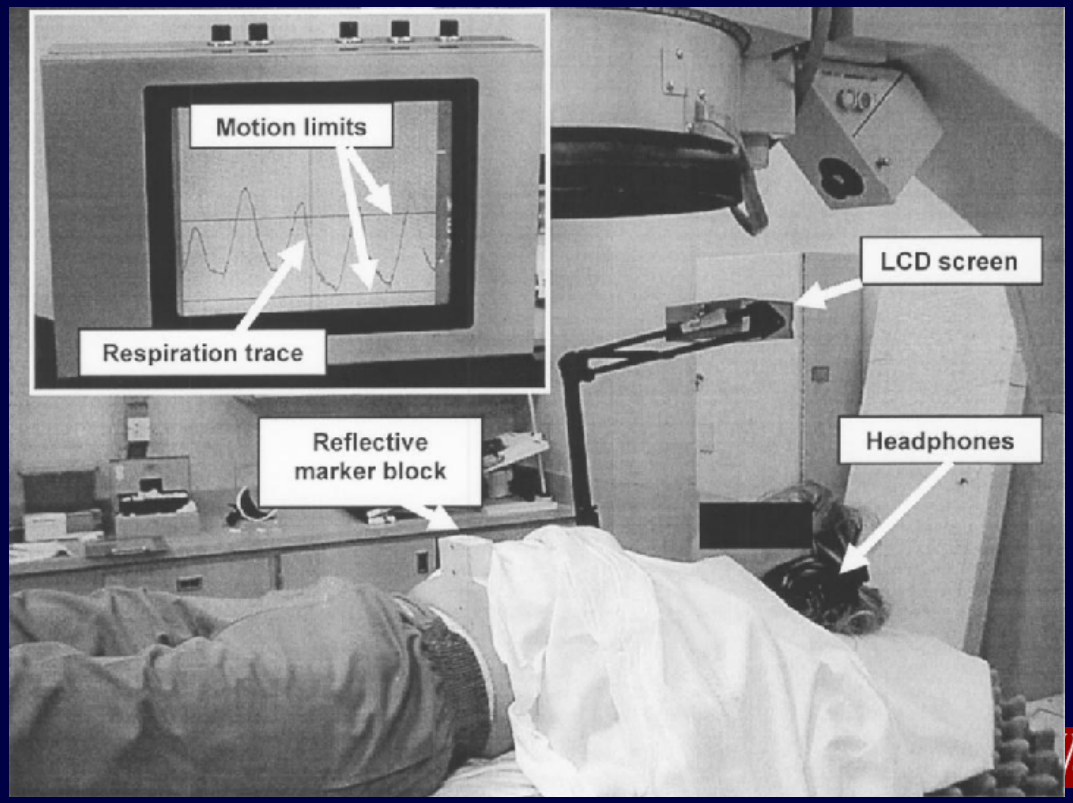


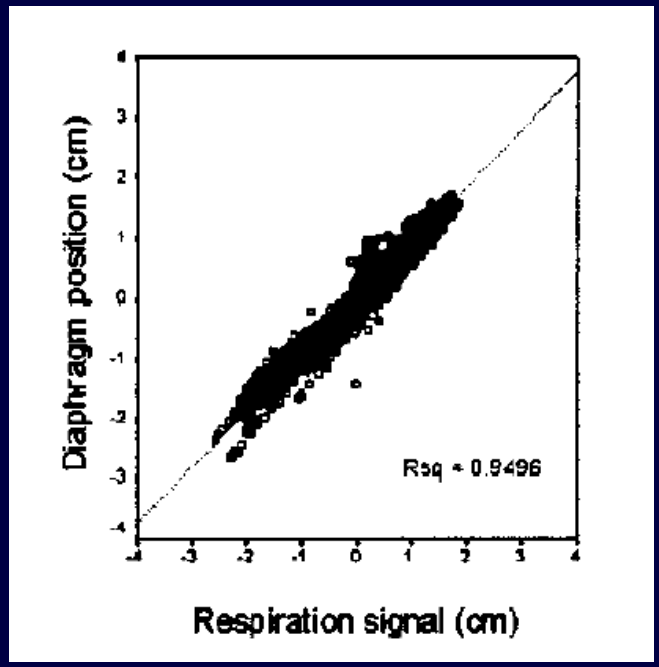
- Cyclic
  - Amplitude variations
    - More difficult to consider
- Amplitude
  - Hysteresis is second-order variation from primary motion
  - Amplitude variation (breathing pattern changes) straightforward to implement



Metric – Chest Height

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

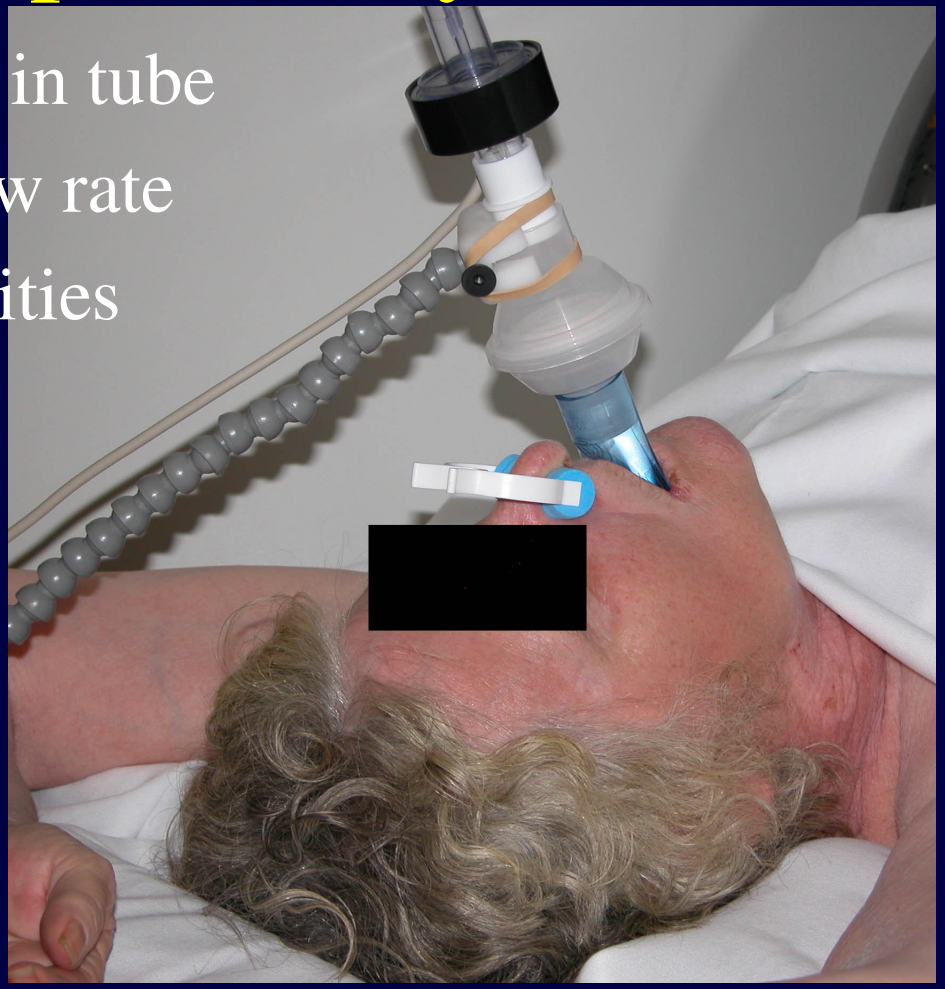


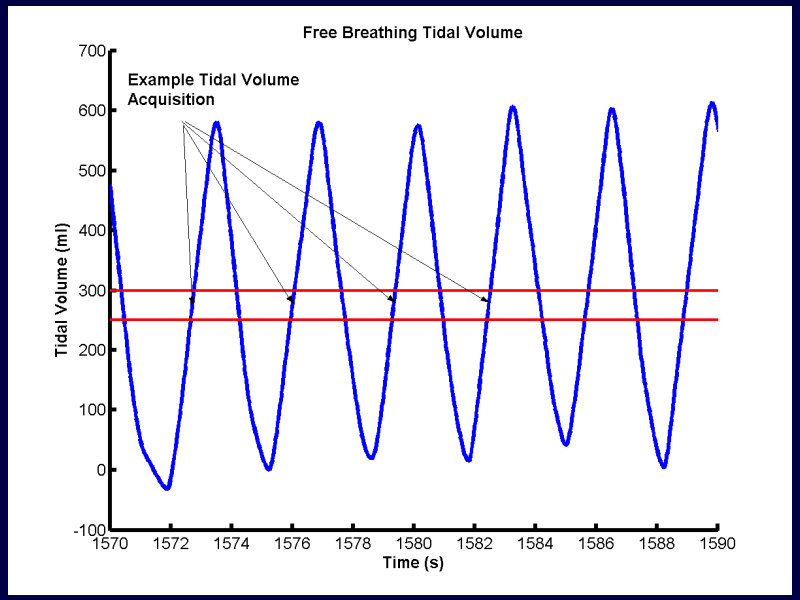


Vedam et al Med Phys 30, 505 (2003)

Metric - Spirometry

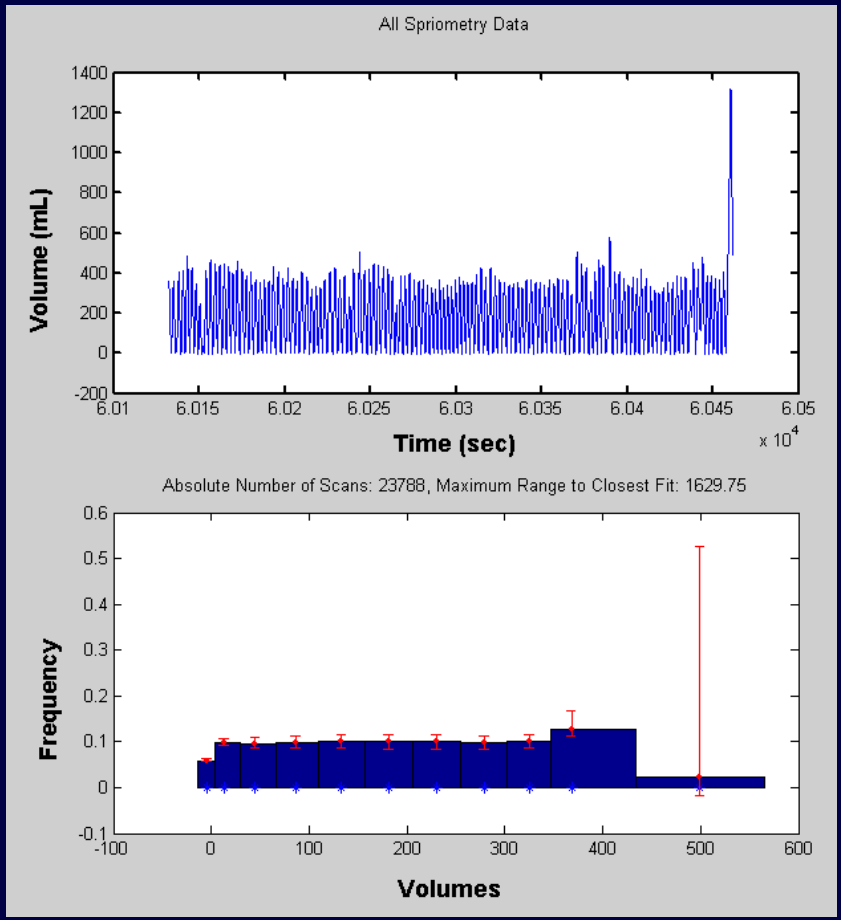
- Turbine-shaped fan encased in tube
- Rotation rate determines flow rate
- Software removes nonlinearities and integrates flow

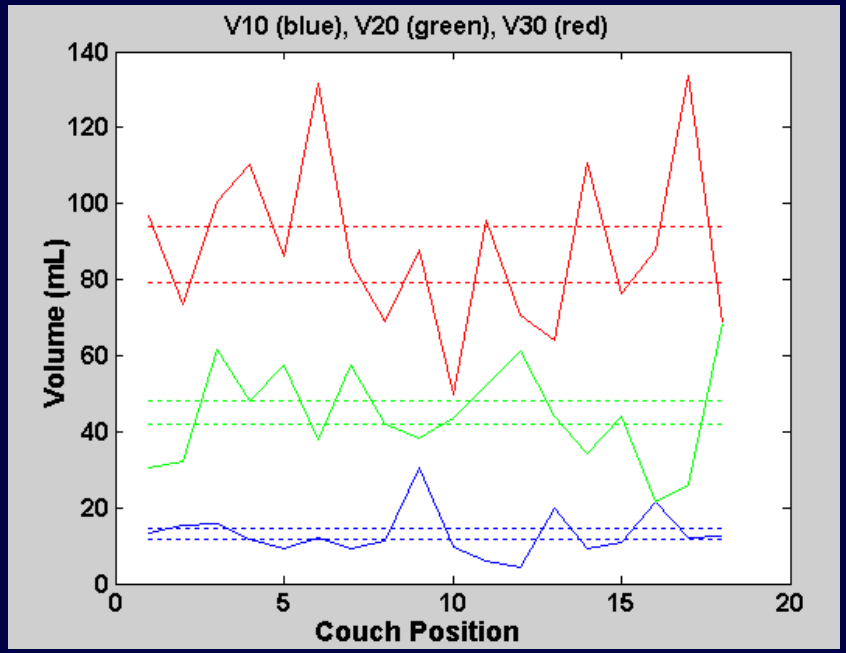




Statistical Review

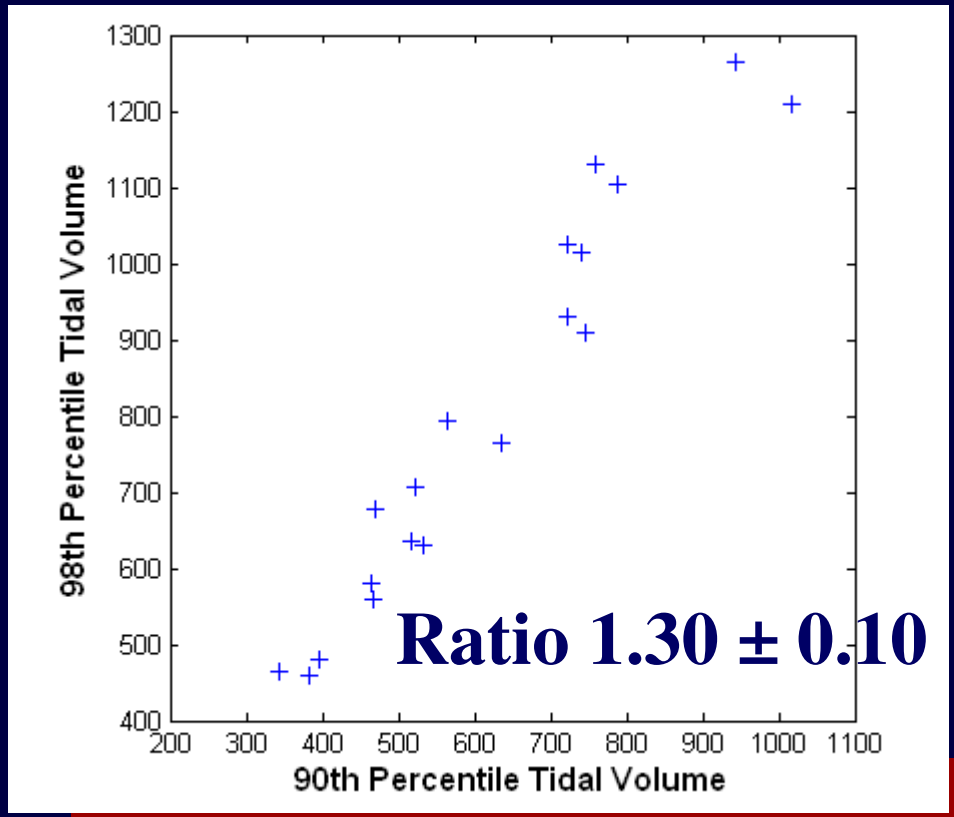
Examine tidal volumes during acquisition to identify which volumes to use for reconstruction





Extrapolation

- Cannot reconstruct 3D images at breathing extents
- Use breathing record to define percentiles vs tidal volume



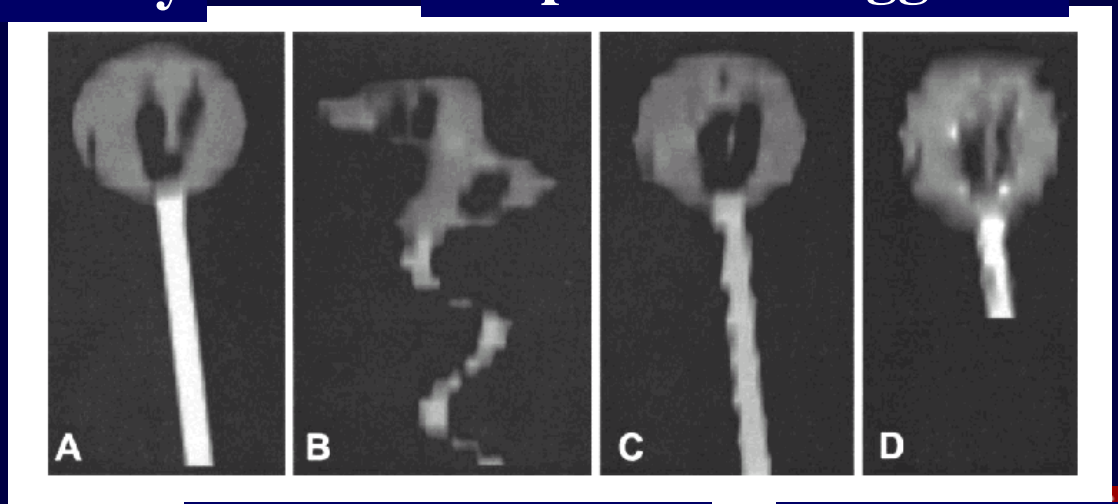
4-D CT

- Vedam, et al (PMB 48, 45-62 2003)
- External respiratory signal and monitor CT scan
- Small pitch helical (overlapping slices)
- Acquired clinical and phantom data

4-D CT

- Ford, et al. (Memorial) developed “respiration correlated spiral CT”
- Uses external marker (abdomen)
- Single helical CT, pitch 0.5, 180 degree reconstruction

Stationary **Respiration Triggered**



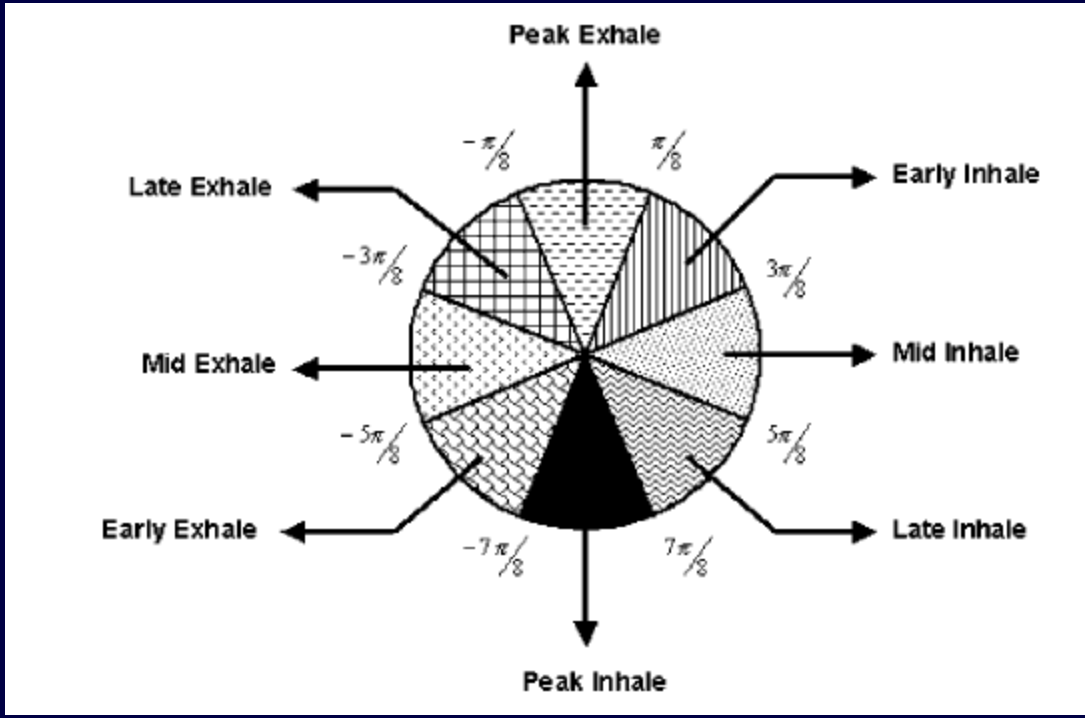
Med. Phys. 30, 88 (2003)

No Compensation **Respiration Correlated**

Vedam 4D CT

Breathing cycle

Virginia Commonwealth



Vedam et al, PMB 2003

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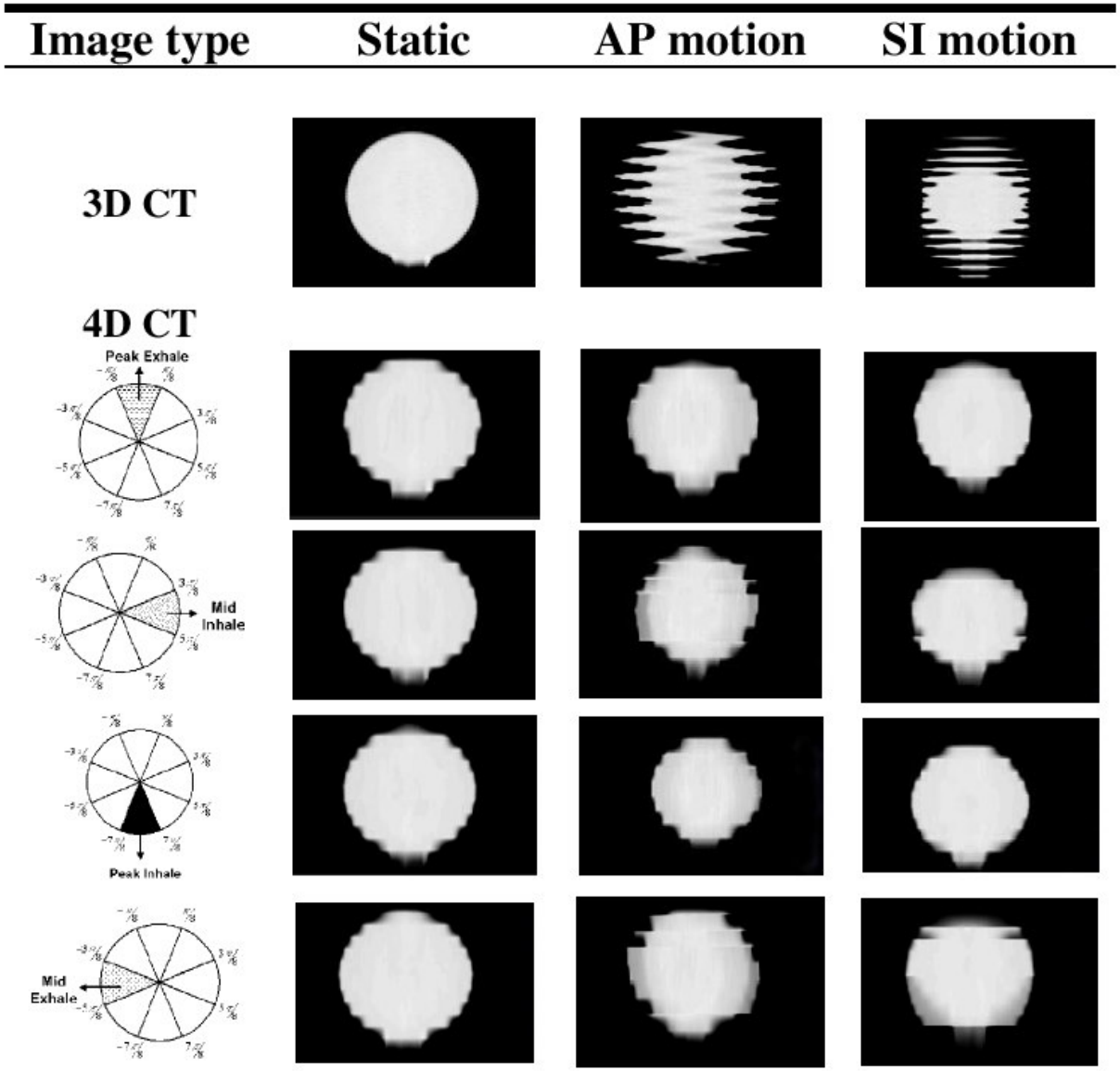
Vedam 4D-CT



5 cm diameter
Sagittal cuts
Sinusoidal motion

Ungated

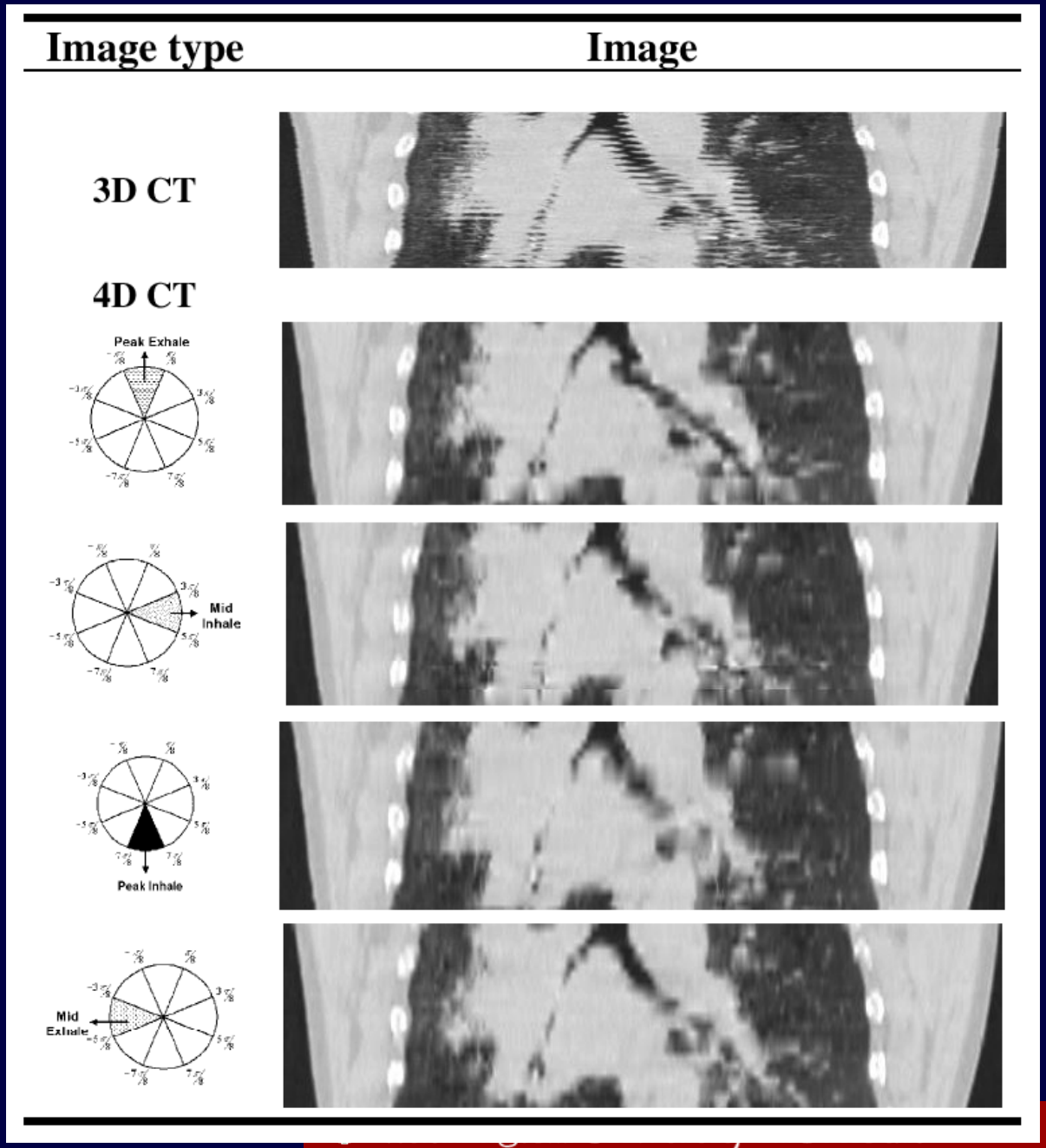
4-D CT
at different
phases

Pitch 0.5
1.5 s rotation time

Vedam 4D CT

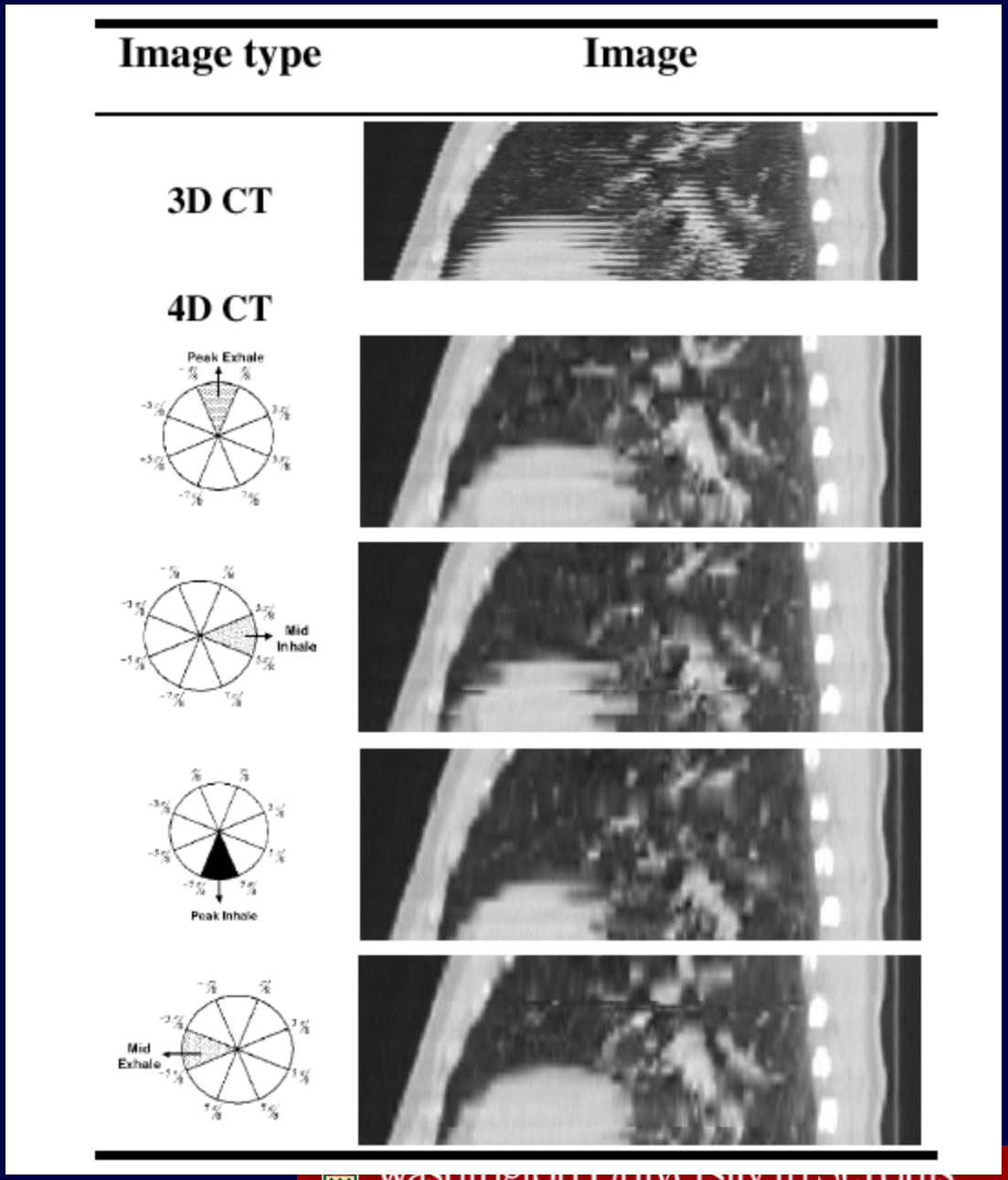
Coronal slices

External abdominal marker



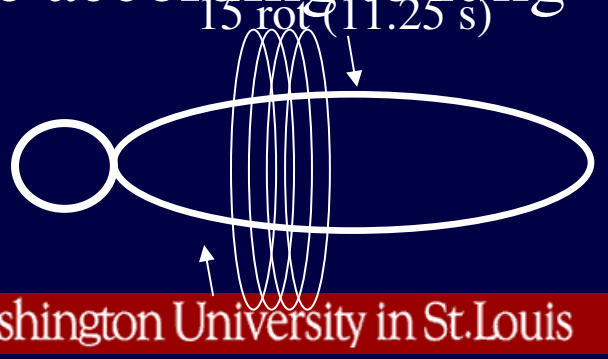
Vedam 4D CT

Sagittal



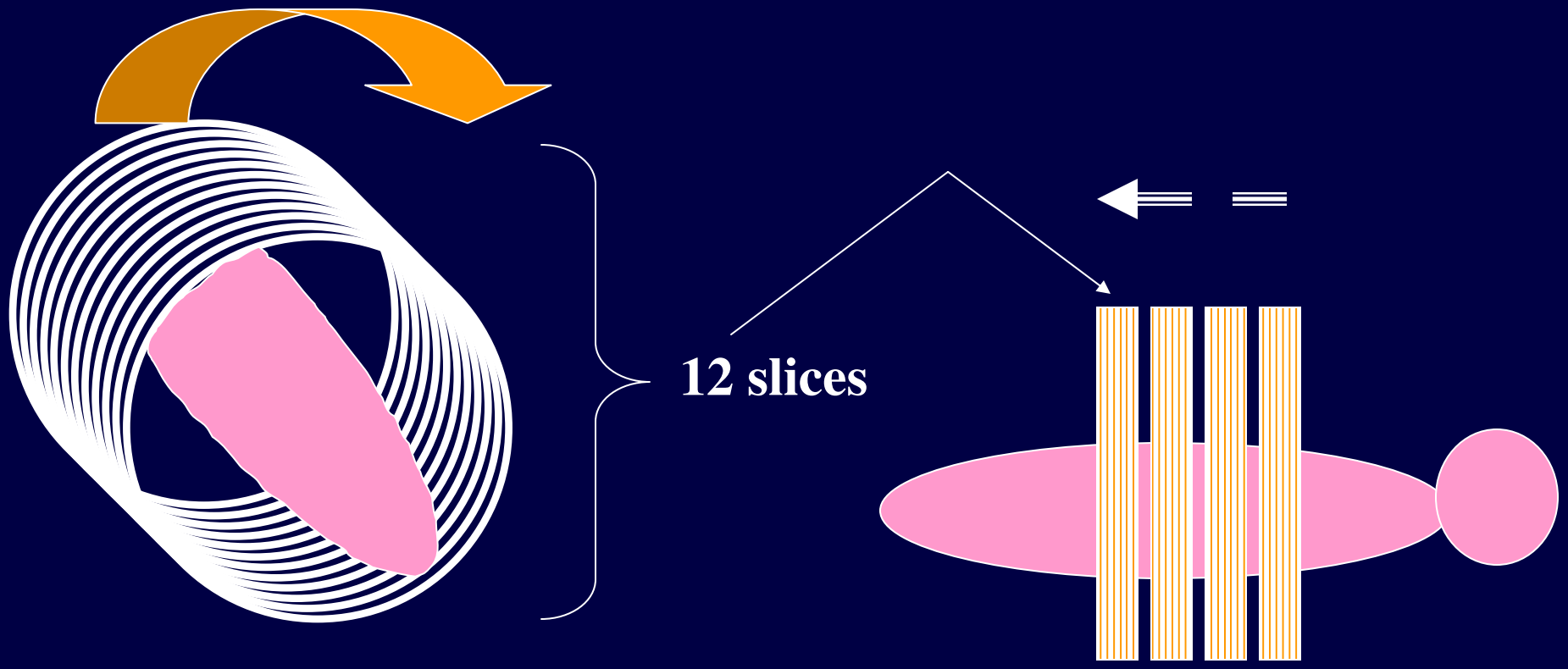
Washington University 4D CT method (free breathing)

- Use multislice CT scanner (Siemens Sensation 16 – now Philips Brilliance)
  - 12-slices, 0.5s per scan, 1.5mm per slice
- Ciné mode (15 acquisitions)
  - Couch does not move between slices
- Spirometry indexes CT scans for later analysis
- Take CT scans and redistribute according to lung volume
- Produced 4-D CT scan



CT Protocol

15 times **0.5 s + 0.25 s = 11s**



Synchronization Signal

Spirometer

CT Data

Siemens Sensation 16 Console

Abdomen Height Digital Video

Bronchial Branch

12-Slice mode

DICOM Transfer

Spirometry Tidal Volume Acquisition

Spirometry Drift Correction?

Volume-Gated Images

Motion Model Parameter Determination

Acquisition Process

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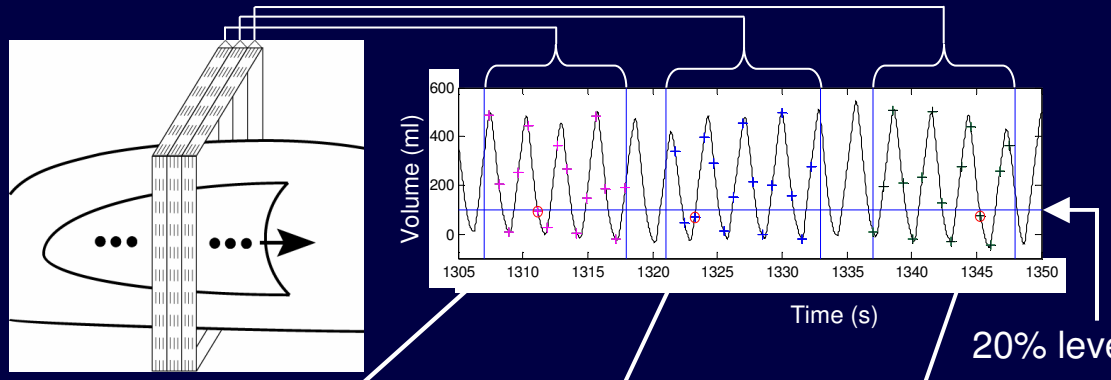
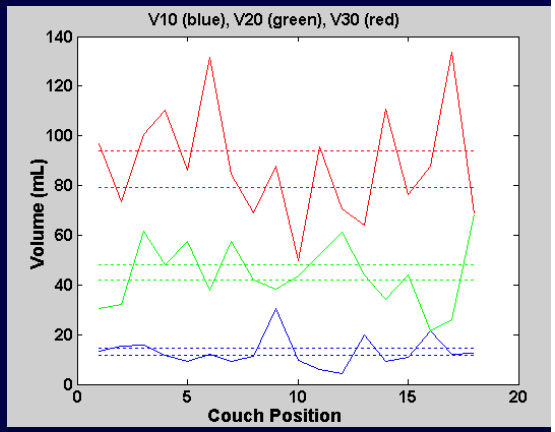
4D Data Reconstruction

12-slice CT Scan
using ciné mode

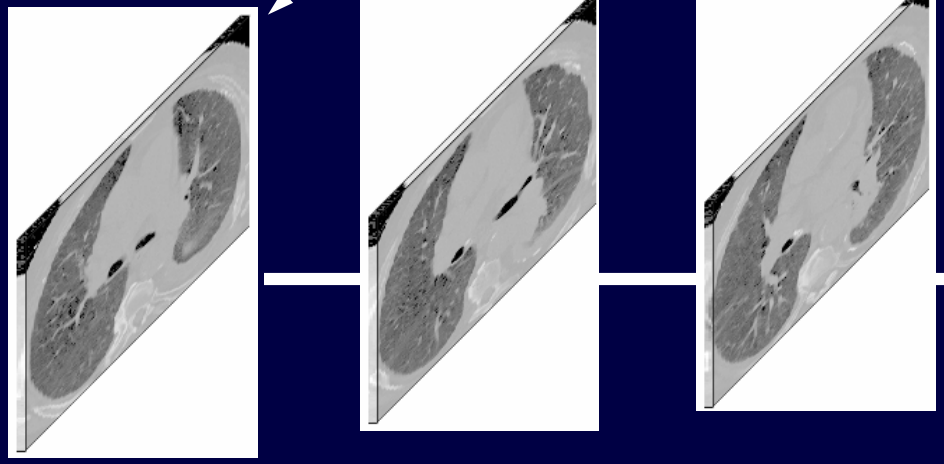
Simultaneous
spirometry
record



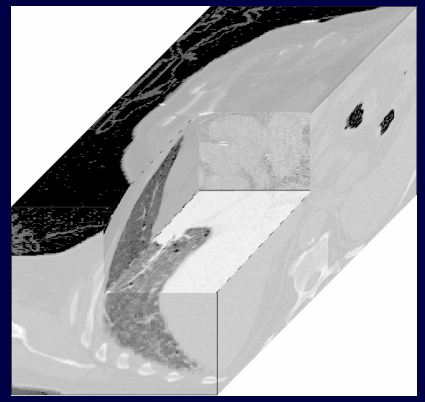
20% level



Statistical Review



CT scans
closest to 20%-ile volume



Composite 3D
CT scan reconstructed
at 20%-ile free breathing
tidal volume

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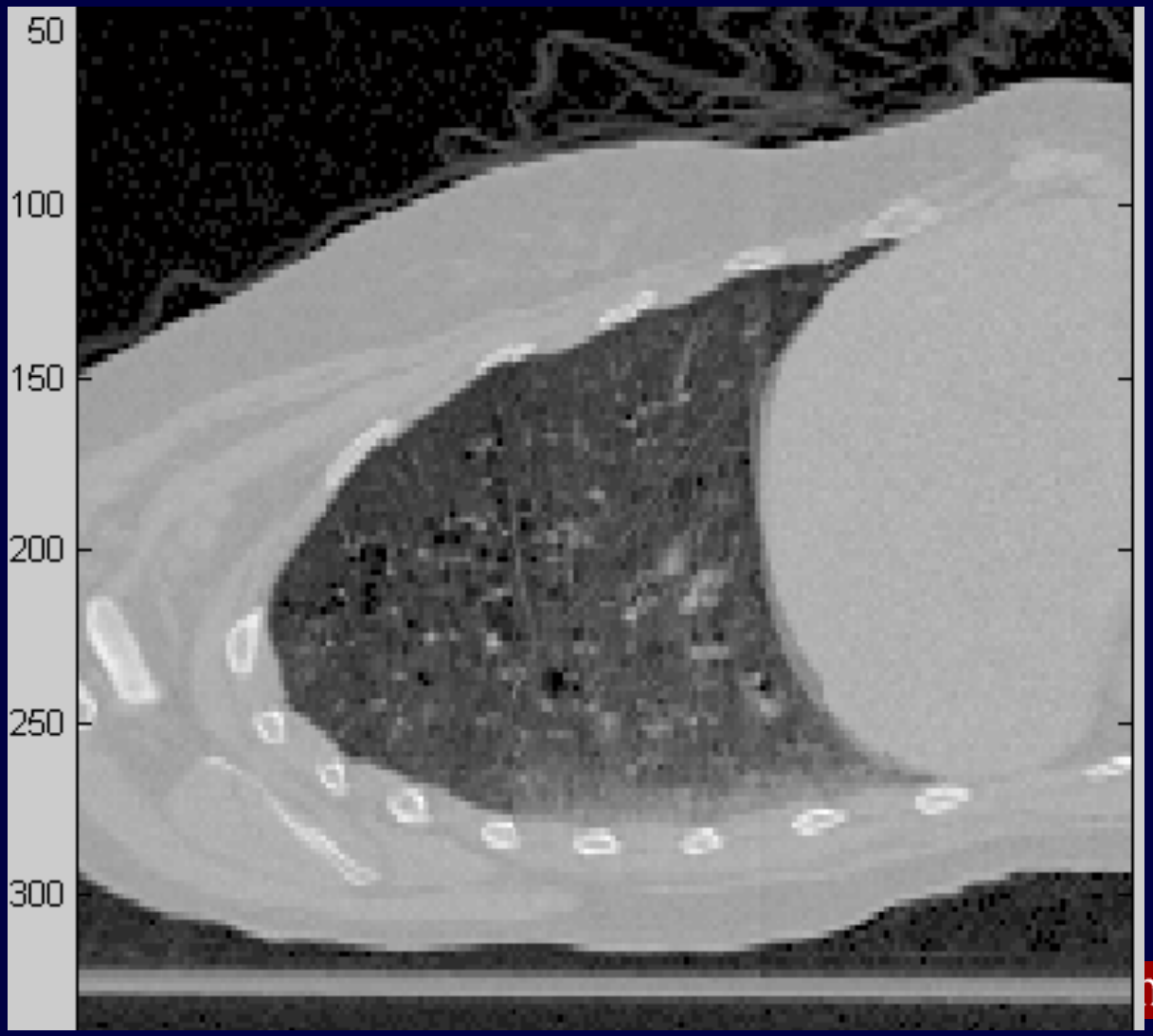
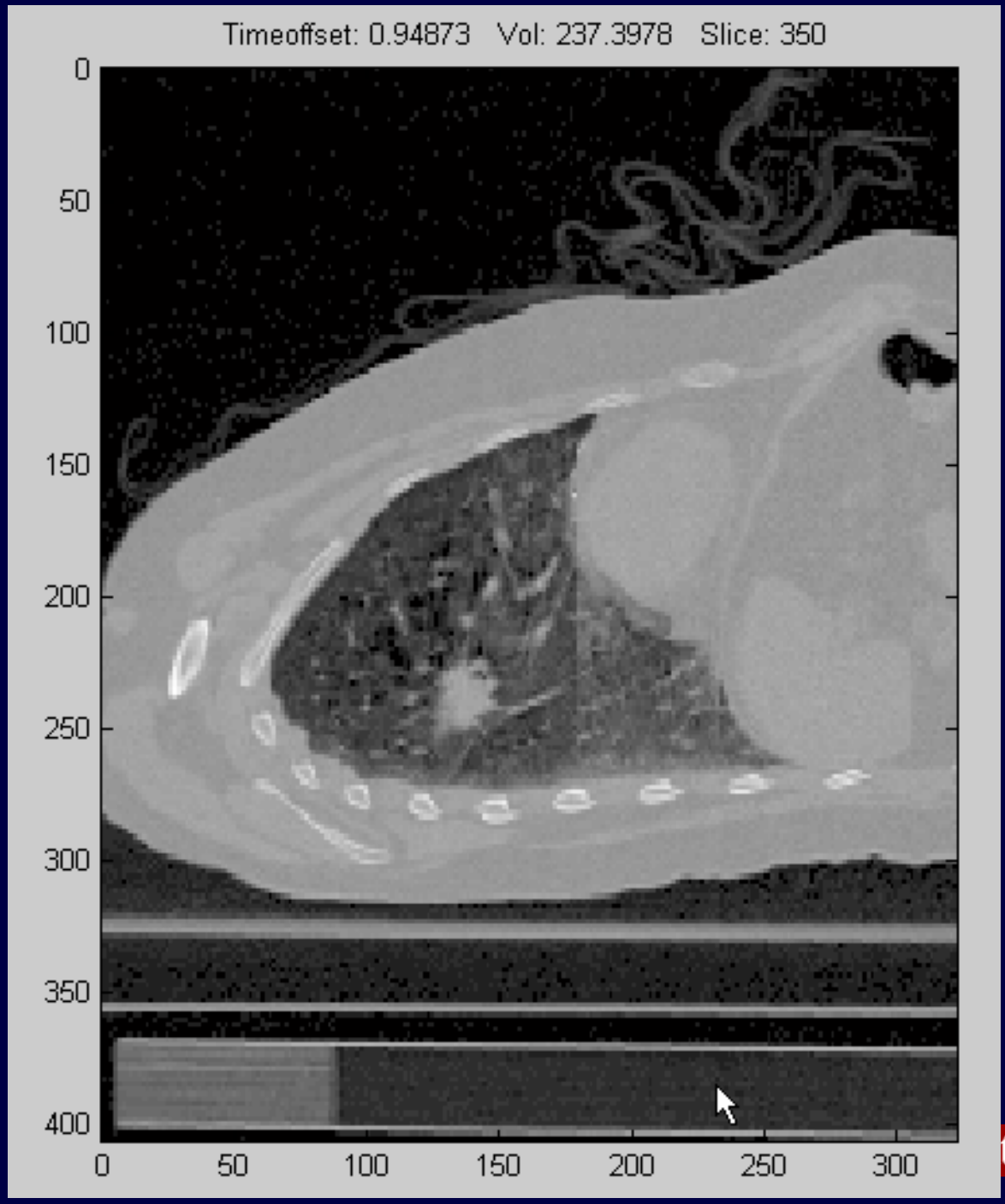
Images Reconstructed During Mid-Inhalation





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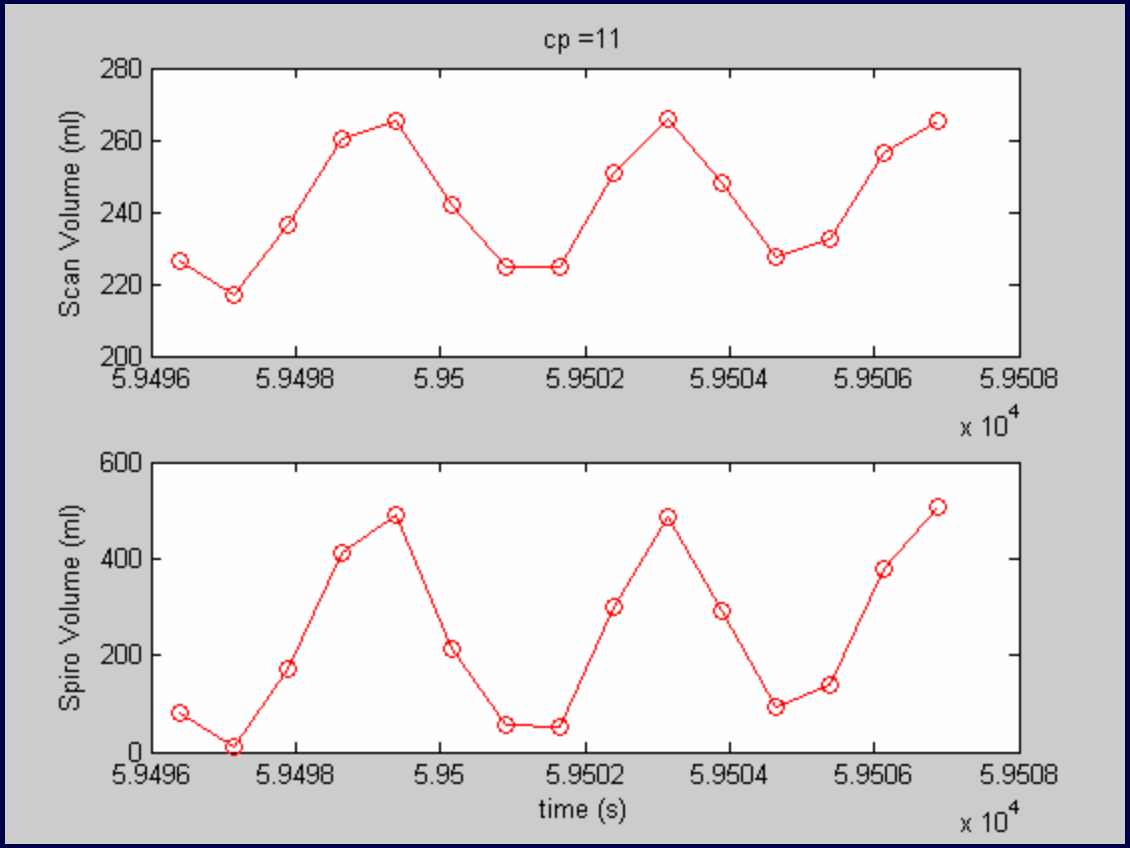
Data Quantitation

- Examine internal air content and correlate to spirometry-measured tidal volume
- Simultaneous acquisition of 12 slices (1.8 cm) = can inspect large internal volumes
- Abutting regions
- Use digital movies of abdomen height and compare against spirometry
- Internal motion automation and quantitation

Step 1: Segmentation, Air Content

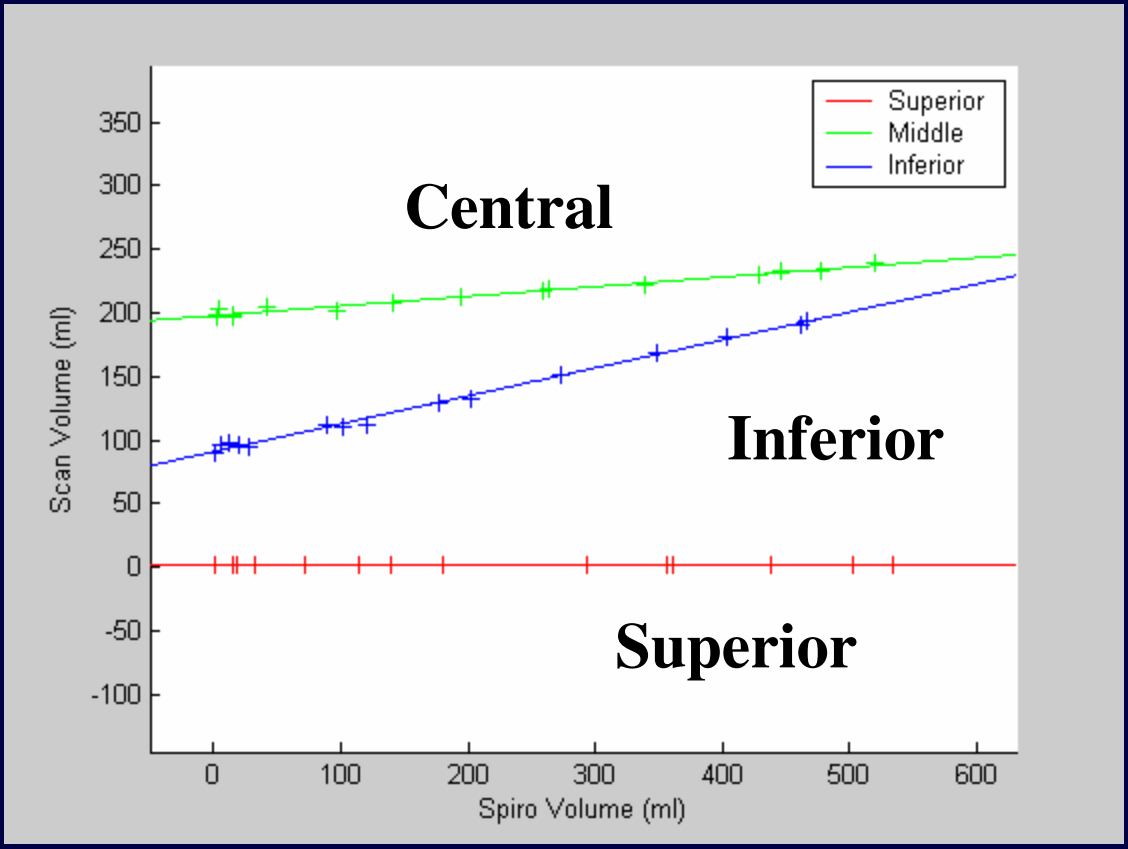
Correlation Results



CT Volume (this couch position)

Spirometry Volume

Correlation Results



3 couch positions

$$\sum \frac{dV}{dv} = \frac{\rho_{room}}{\rho_{lungs}} = 1.05$$

What are the Sums (accuracy)?

Slope Sum
1.05
1.08
1.08
1.02
1.18
1.16
1.11
1.09
1.03
1.07
1.12
0.96
Mean (SD) = 1.08 (0.06)

This is one reason why spirometry is important

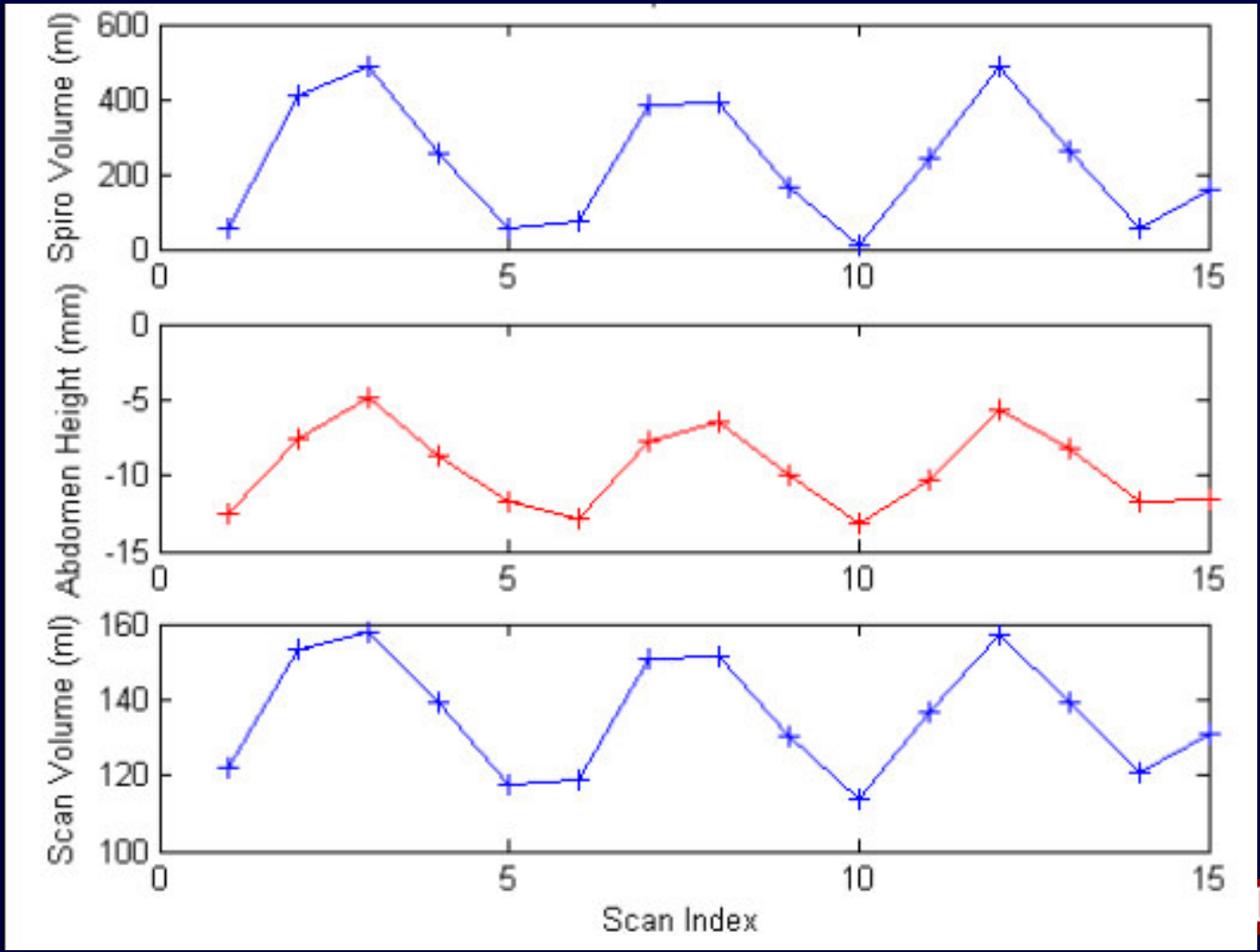
Spirometry Precision

Precision (%)
3.5
4
6
8
5
5
4
4
8
3
3
8
Mean (SD) = 5.13 (1.93)

Metrics: Abdomen Height vs Spirometry

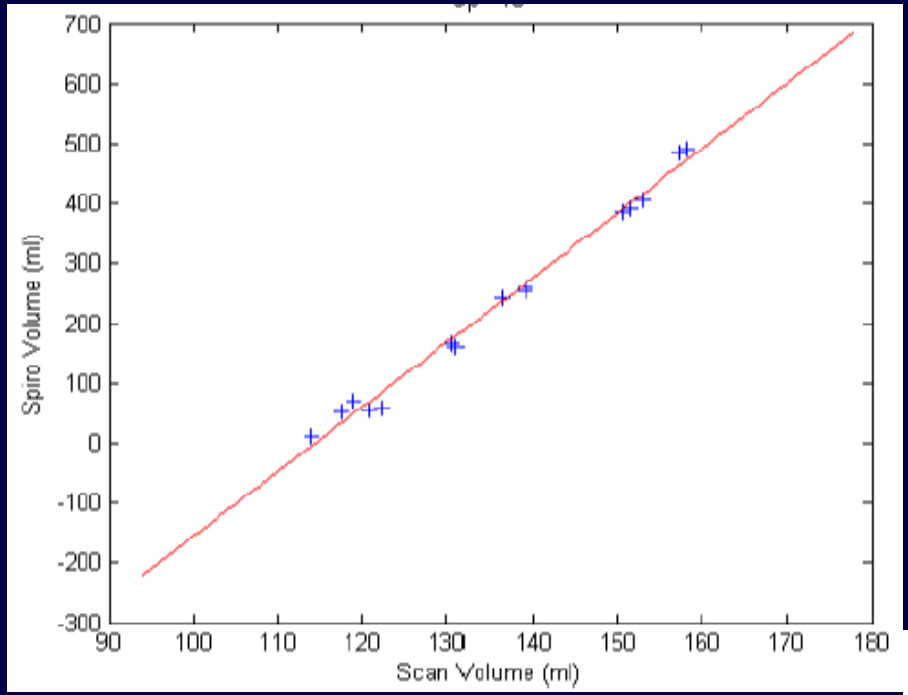
- Spirometry drifts
  - We need a drift-free metric
  - How well does abdomen height compare against spirometry correlations?

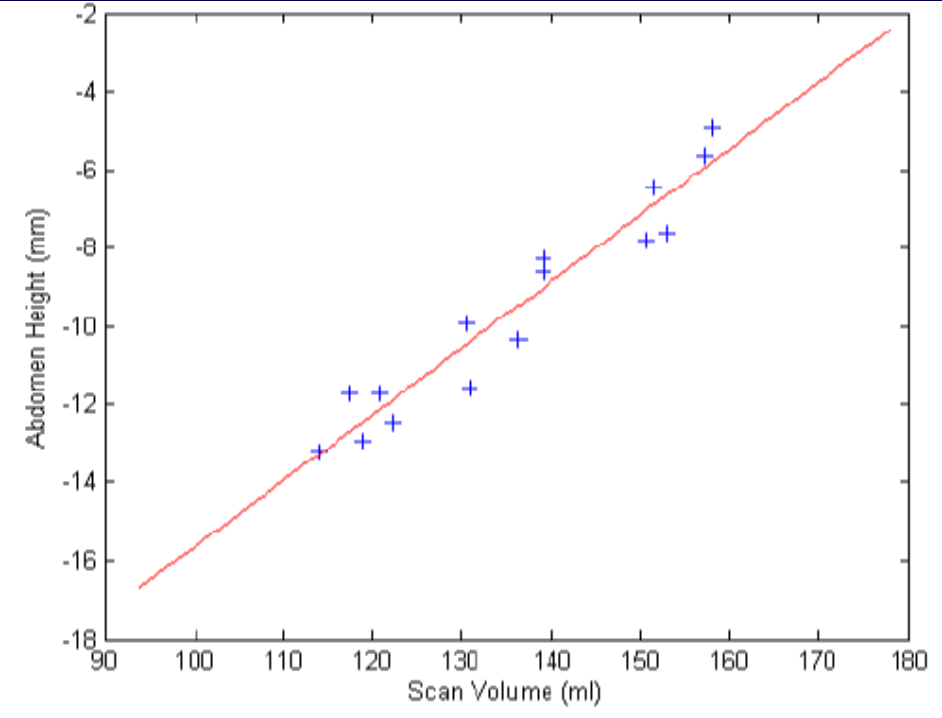
Spirometry, Abdomen, Air Content



Louis

Correlations With Air Content





Automation of Trajectory Mapping

- Many groups investigating automation of motion mapping

Lu (U Wisc) PMB 49 3067 (2004)

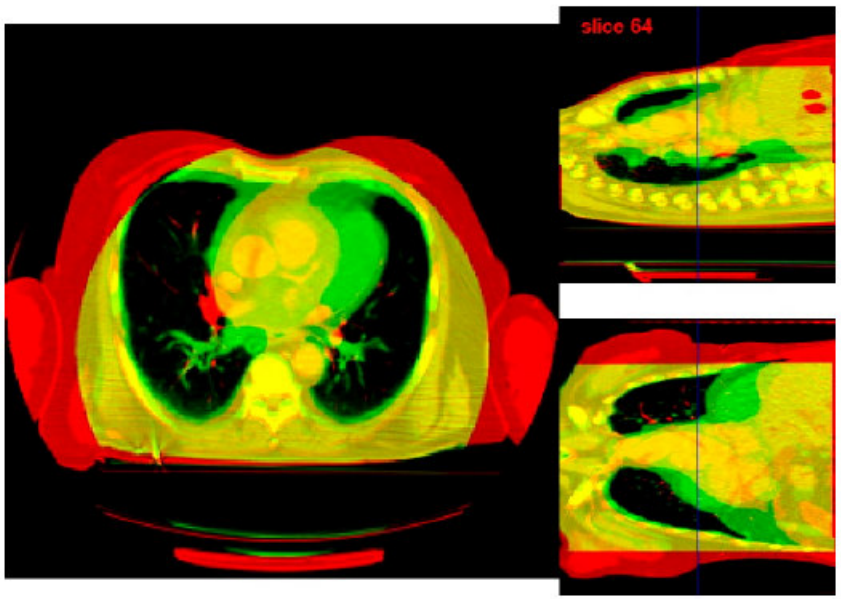


Figure 12. Overlapped orthogonal views of the intra-fraction CT images. The red component is the inhale image, which is used as reference image. The green component is the exhale image, which is used as test image.

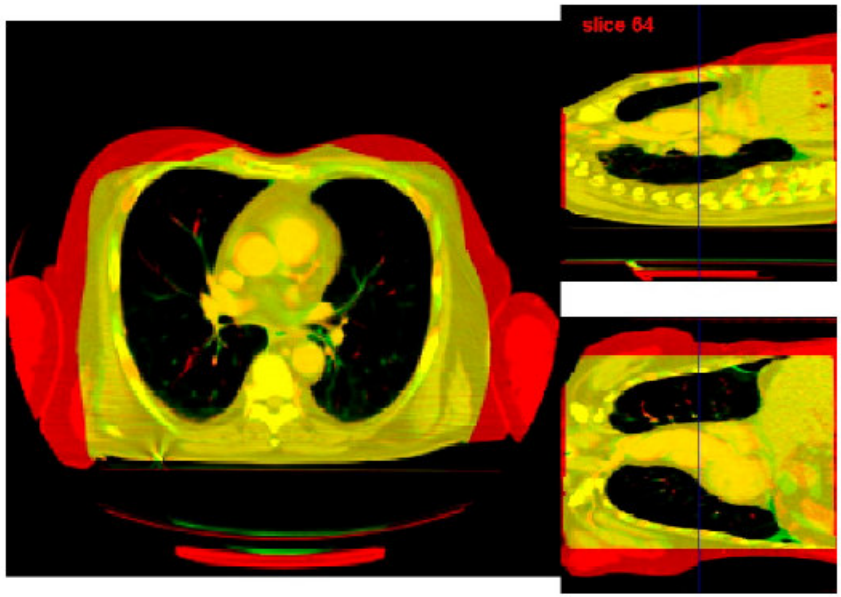
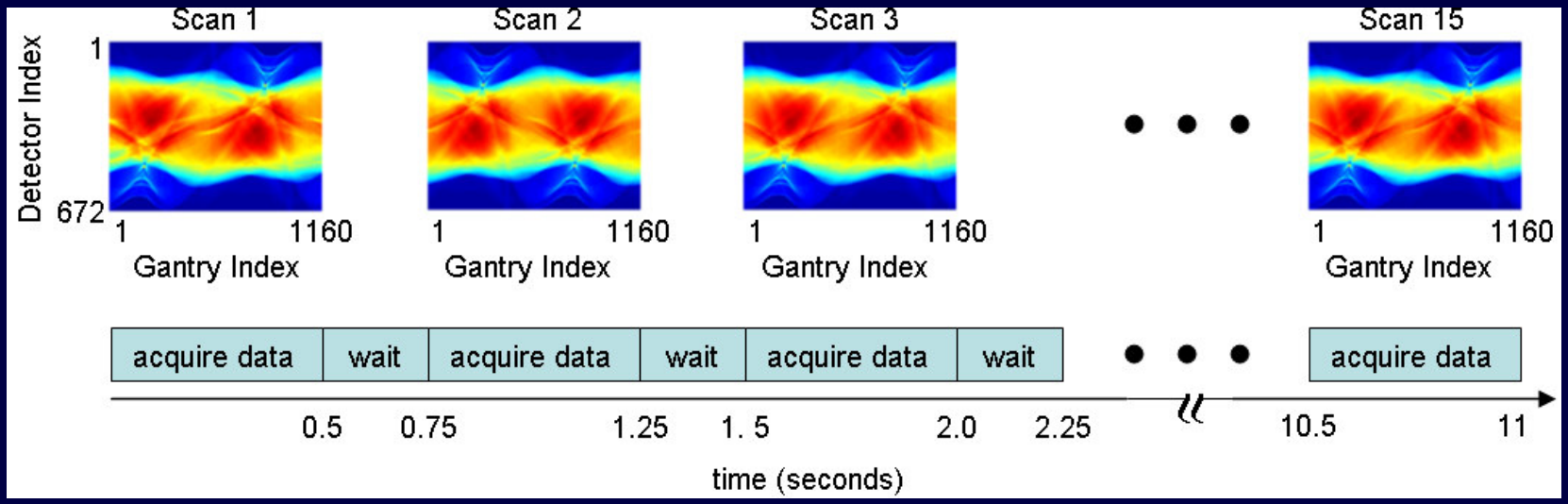


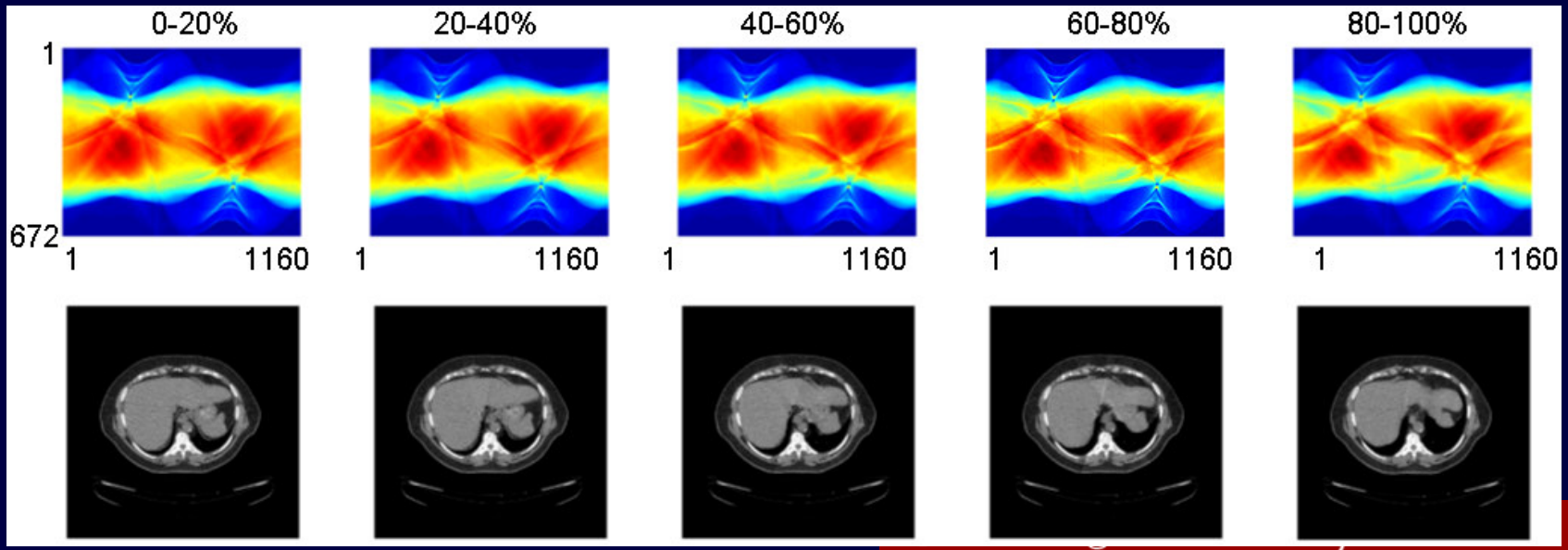
Figure 13. Overlap of inhale and the exhale image after registration.

Future of 4DCT

- We have been using the CT data as is
- Reconstruction provided by Vendor
- 0.5 s resolution
- Artifacts in diaphragm area
- Blurring of smaller internal objects
  - These objects are important for automated registration algorithms
- Acquire projection data over multiple breaths
  - Redistribute sinogram data within single breathing phase

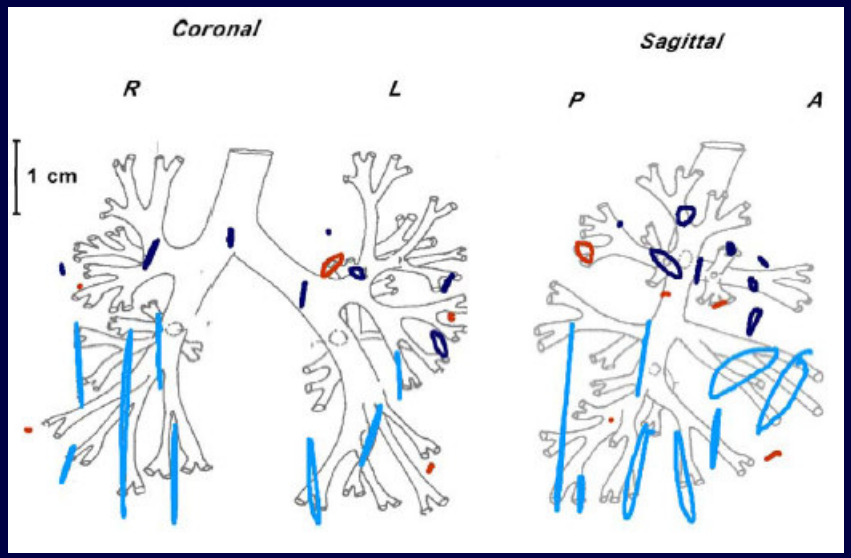
Sinogram Redistribution





Challenges

- Accurate metrics
- Internal Hysteresis
- Reproducibility



Shirato et al Semin Rad Onc 14 10 (2004)

Conclusions

- 4D imaging (breathing timescales) has many uses:
  - Portal customization
  - Gating
  - PET removal
- Important to emphasize quantitation in imaging processes
- Multislice/Cone-beam CT likely to dominate 4D imaging for few years
- Reproducibility of 4DCT still required