Pre-treatment 4D-MRI at Johns Hopkins: methods development using an external surrogate

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(No conflicts)

4D-MRI developments at Johns Hopkins:

Motivation: "Breathing Motion" is highly subject to variation.

Hypothesis: Optimally for RT, "breathing motion" requires a more complete, statistically robust description. Existing techniques are deficient.

Overall Goal: Pre-treatment motion characterization for treatment planning and optimization

Method 1: 2D-to-4D sorting of dynamic MRI (dMRI) to derive a representation of the subjects' average breathing cycle

Method 2: 4D tumor tracking using orthogonal 2D dMRI slice planes

IRB-approved methods development study in volunteers nearing completion.

JHU method 1 goals:

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- With clinical workflow and practicality in mind, develop methods to derive a robust, representative "4D-MRI" for direct application to RTP similar to present utility of 4D-CT

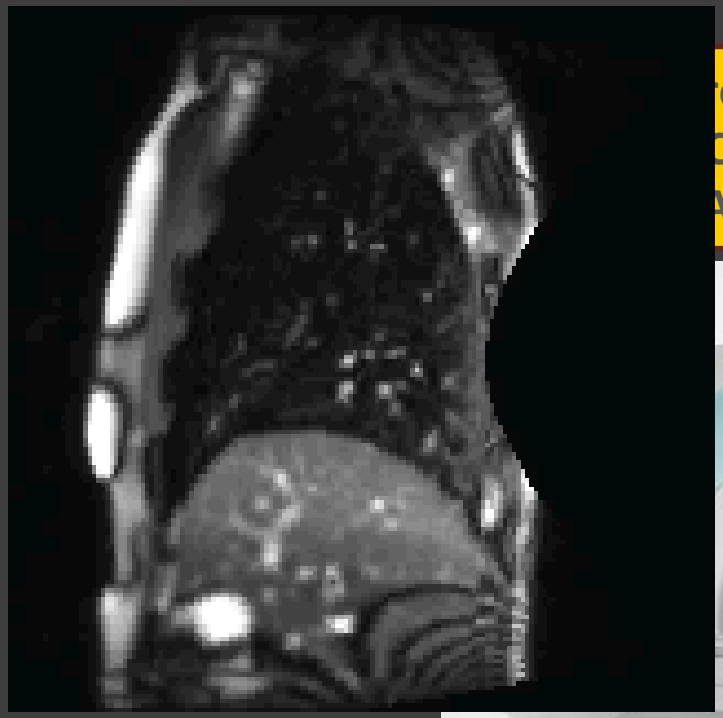
  Derived motion bins must be *probabalistic* so as to be employed for the various flavors of motion management

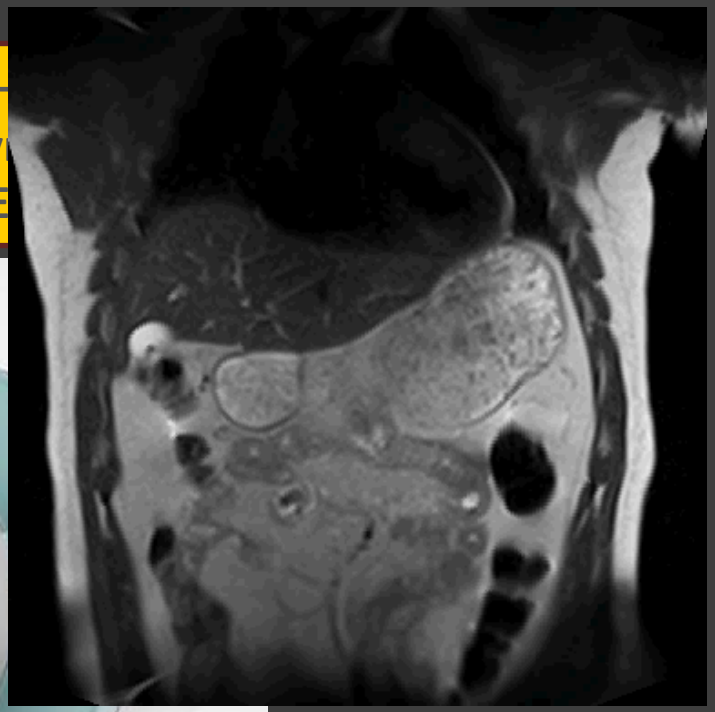
  E.g., phase-binned 4D-CT provides motion bins with equal probability

  Surrogate respiratory signal is used to provide a correlative link between external and internal motion, as in the application of 4D-CT with gating

- This "4D-MRI" method should, in particular, better address problems associated with variable breathing

JHU method 1: image acquisition





TrueFISP (bSSFP):

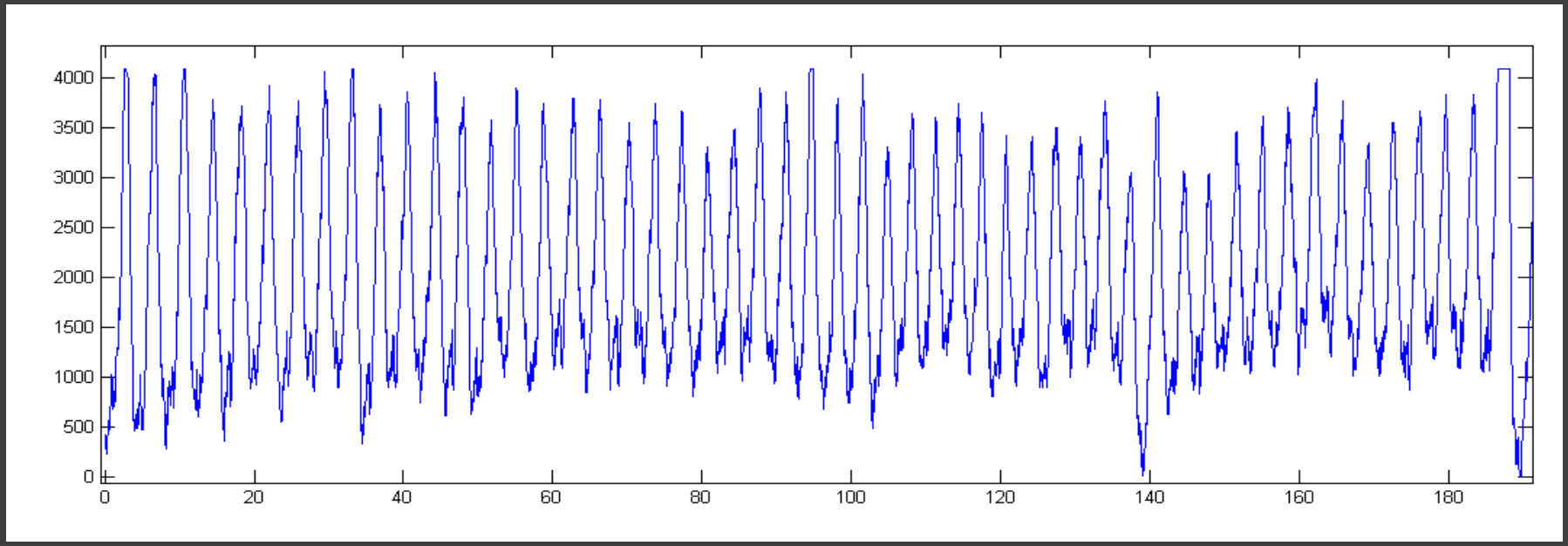
- stepped acquisition (slice 1,2,3…1,2,3
- 2x2 mm² pixels in plane
- 5 mm slice profile
- acquisition speed: 4 to 5 frames/sec (coronal and sagittal, respectively
- strong blood signal w/o contrast on board

HASTE (Half-Fourier Single-Shot Turbo Spin Echo):

- interleaved acquisition (slice 2,4,6…1,3,5…)
- 2x2 mm² pixels in plane
- 5 mm slice profile
- acquisition speed: 2.85 – 3.33 frames/sec. (coronal and sagittal respectively)
- strong fat signal; good abdominal contrast

JHU method 1: simultaneous respiratory monitoring

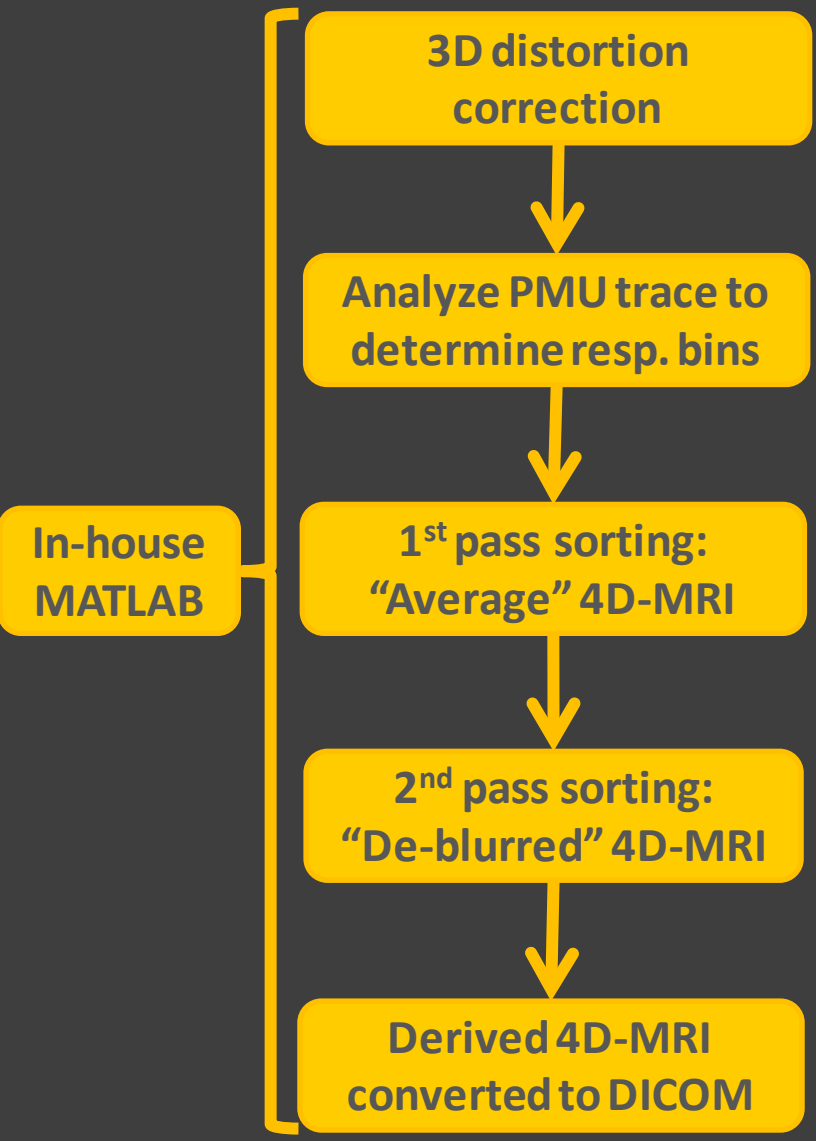
Acquire external respiratory signal (Physiological Monitoring Unit -- PMU)



PMU logging:

- synchronized with the image acquisition computer (well, in principle, anyway)
- auto started/stopped within sequence run
- sampled at ~50 Hz

JHU method 1: post-processing



1st-pass sorting:

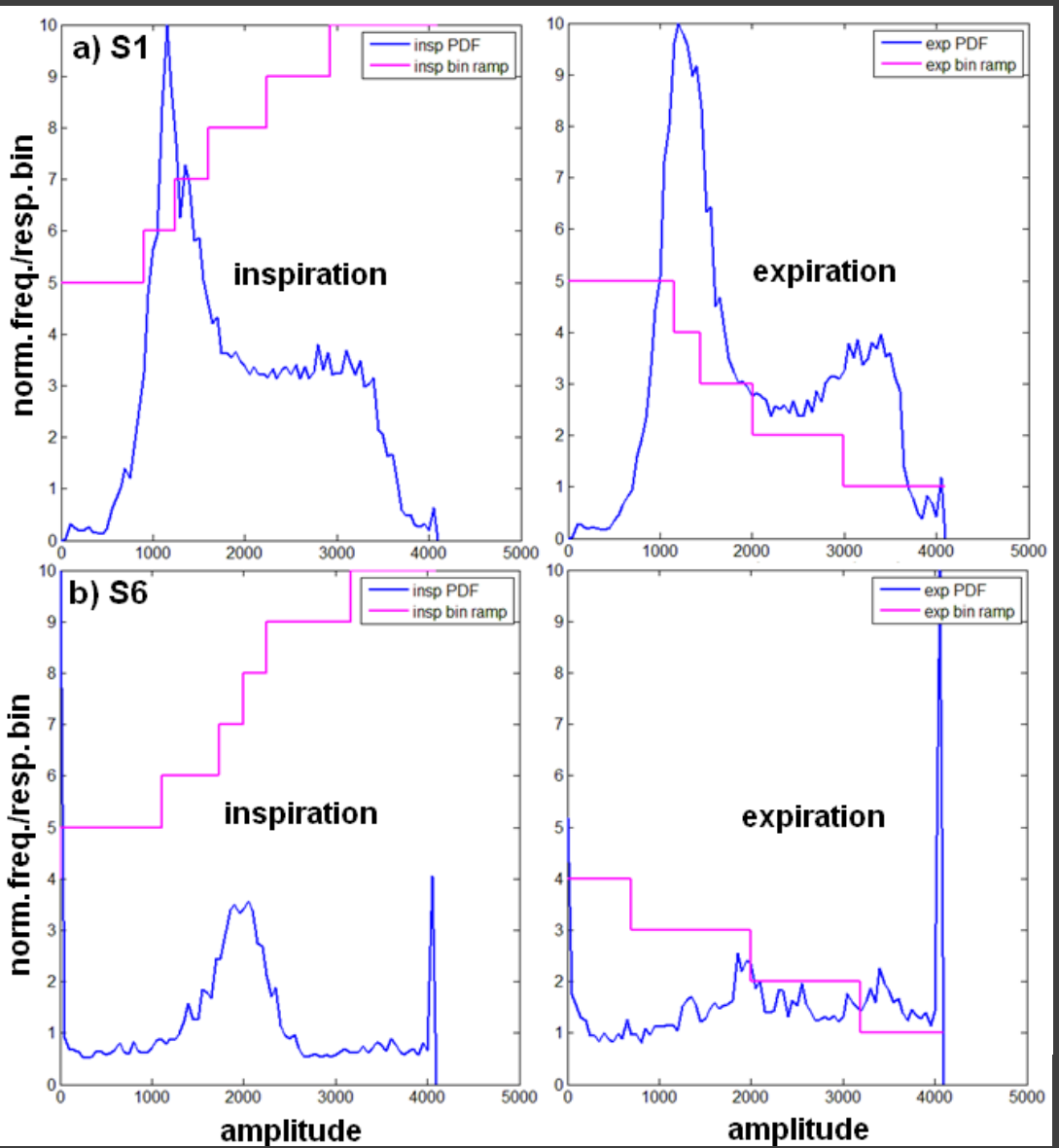
- Retrospective "slice stacking" employed:
- Each raw frame assigned to a respiratory bin based on PMU
- Each bin/slice of given binned 3D recon derived as an average image over all available frames
- Corresponding MIP and standard deviation images computed

2nd-Pass Sorting:

- Raw frames compared with 1st-pass result for corresponding slice across all respiratory bins
- 2D normalized cross-correlation-based comparison/selection of (N) best matching raw frames
- Only these N frames per slice location and respiratory bin are used for 2nd recon

JHU method 1:

Analysis of PMU surrogate to determine respiratory intervals

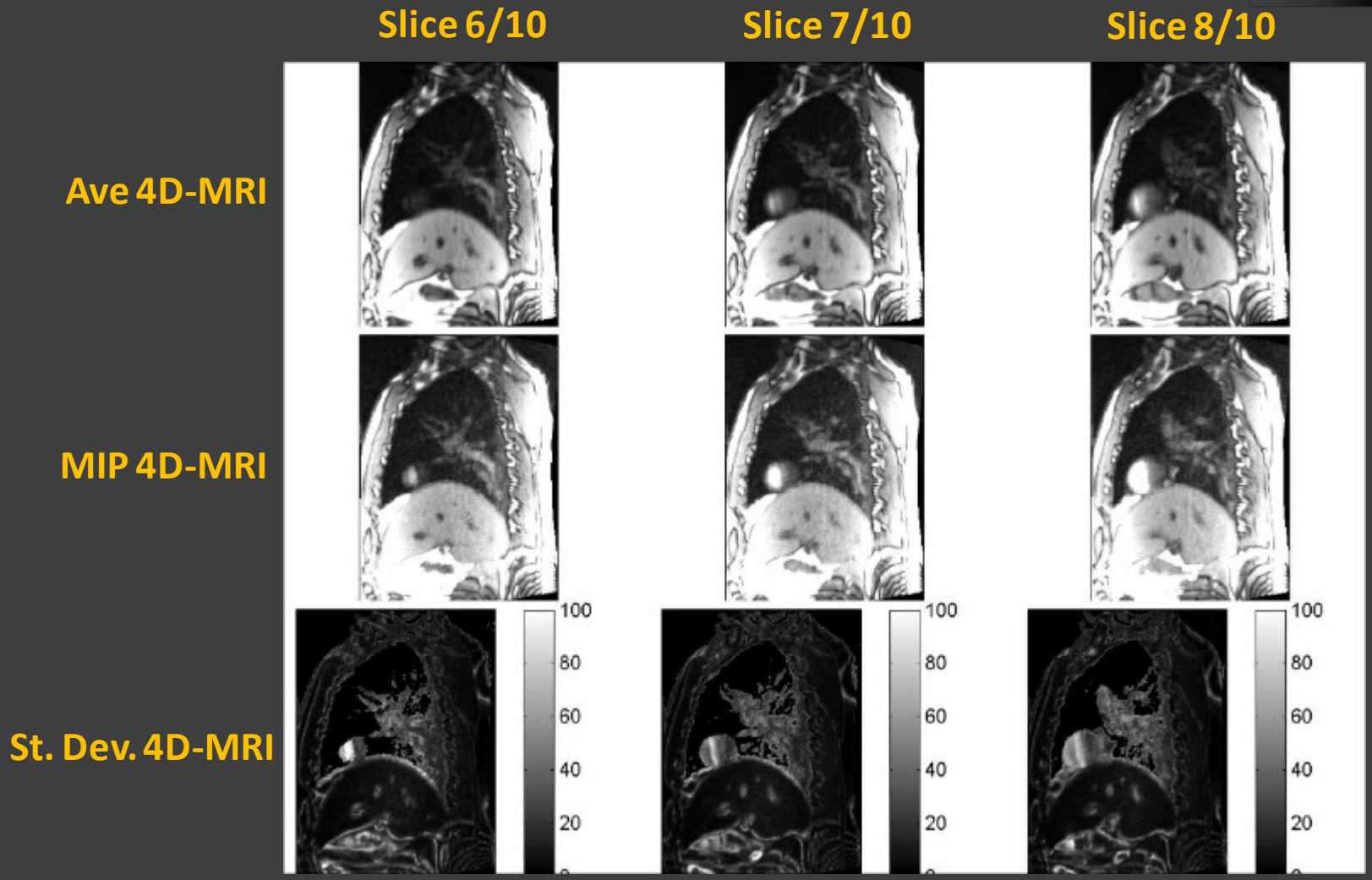


- The "Moving Average" [Lu et al., Med Phys. 2006; 33 (10)] is quantified to aid in identification of maxima/minima.

- Amplitude binning is based on "Amplitude Probability" which is being explored to potentially improve the first-pass sorting.

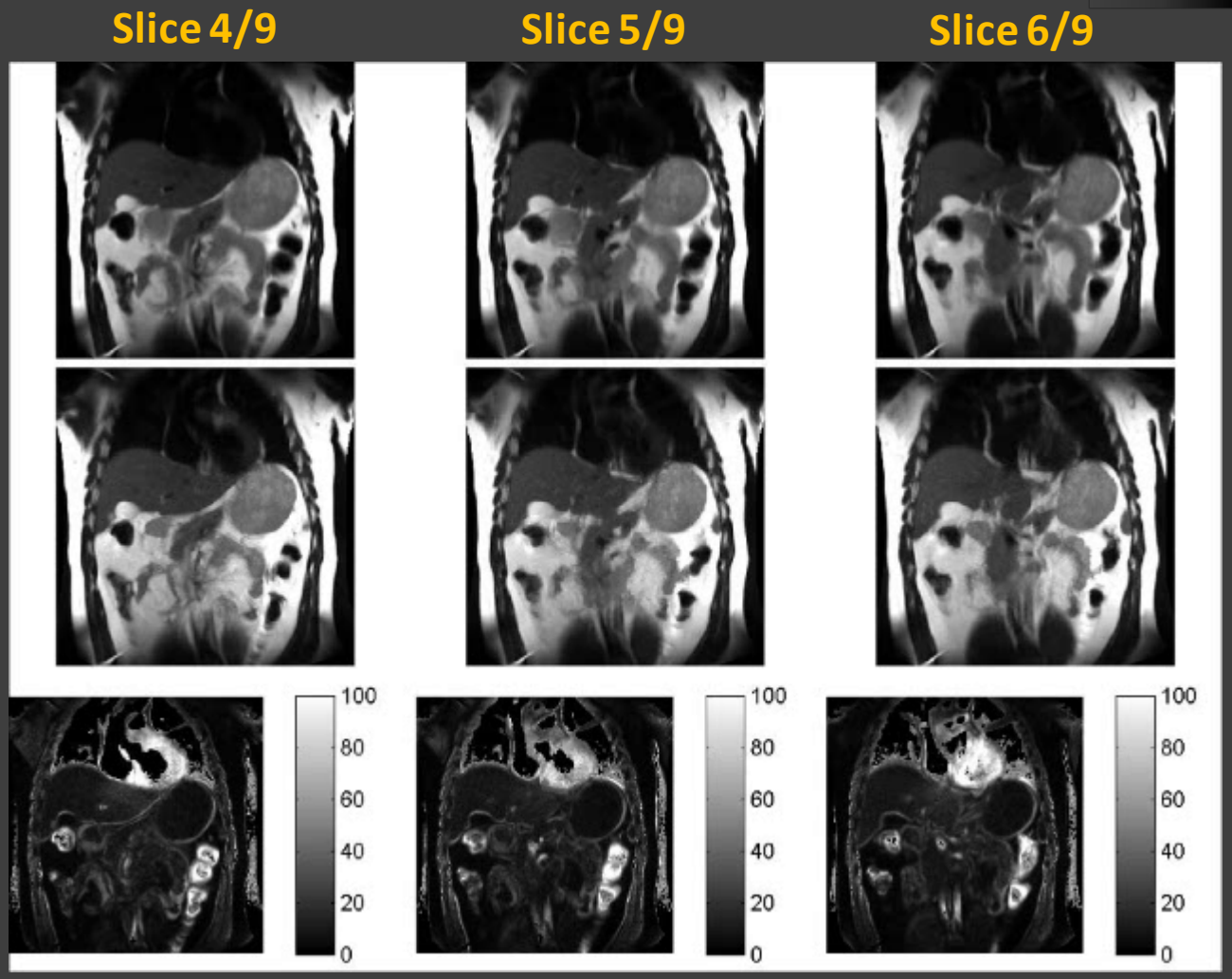
Note: this method is an adaptation of that presented by Olsen et al. [IJROBP 2008; 70 (1): 243]

JHU method 1: Example results for 1st-pass reconstruction



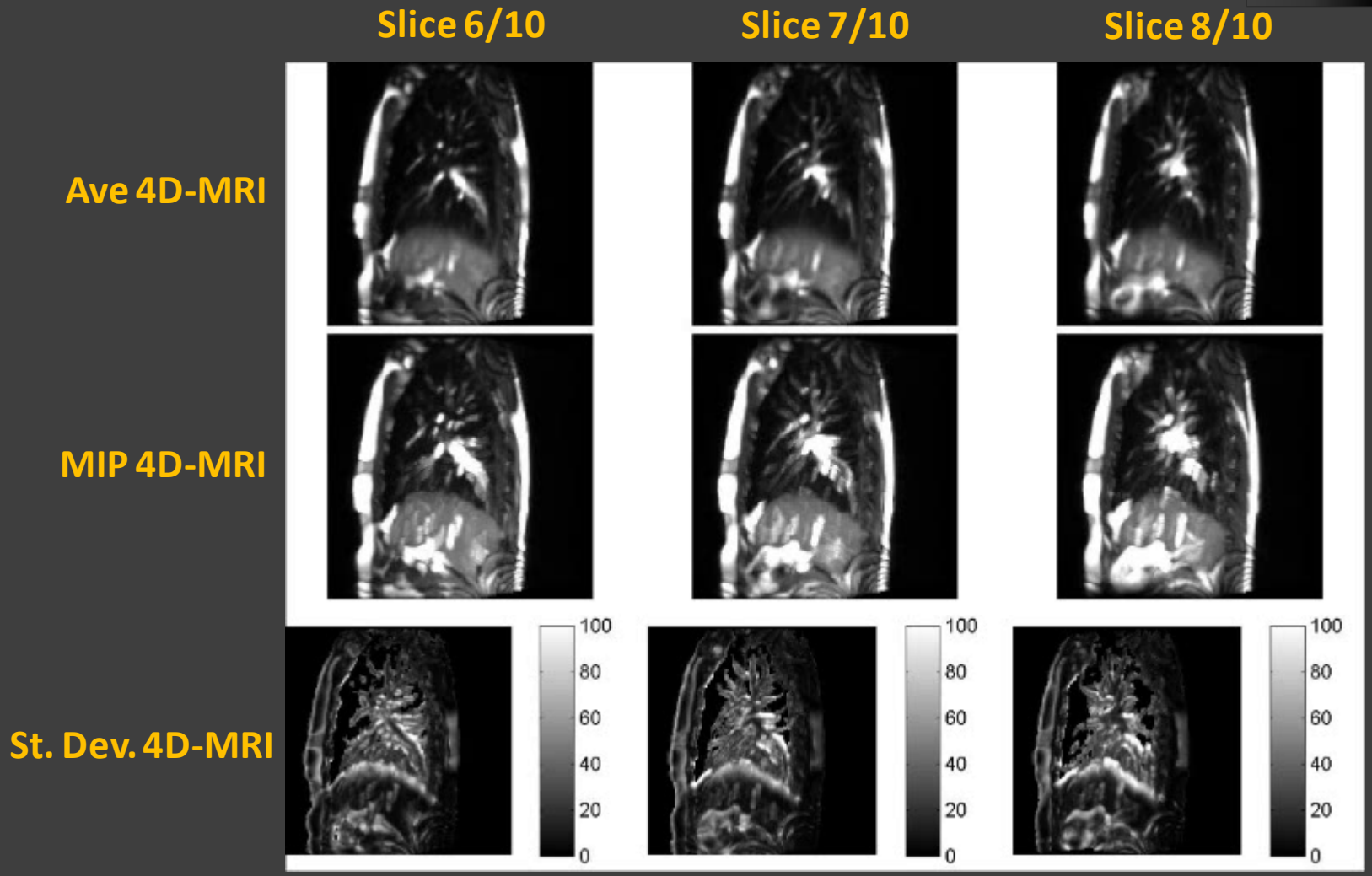
- 10-slice bSSFP-sagittal in lung volunteer (dark blood pulse on)
- 10-phase-bin reconstruction
- average frames/bin/slice = 17

JHU method 1: Example results for 1st-pass reconstruction



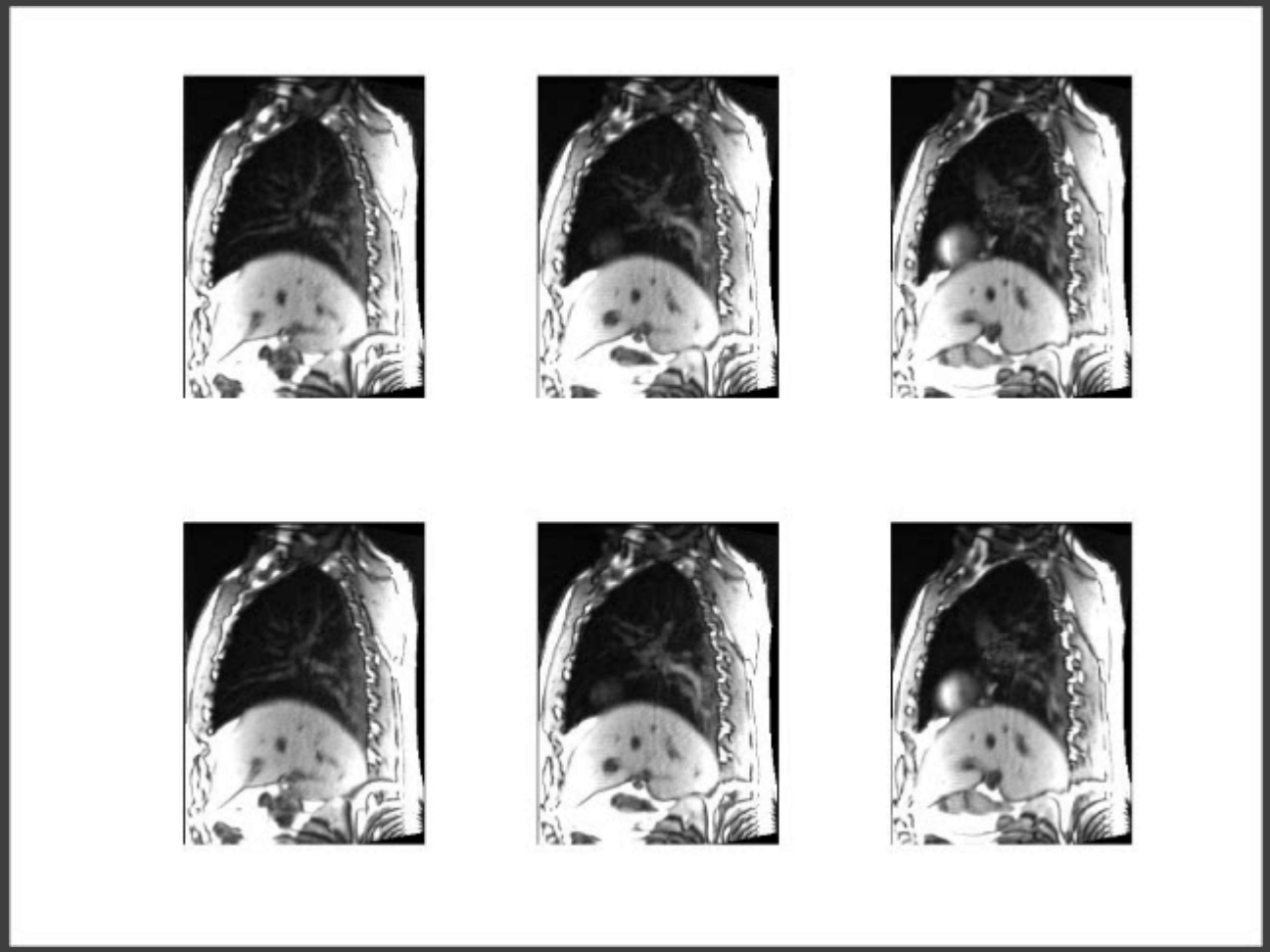
- 9-slice HASTE-coronal in lung volunteer
- 10-phase-bin reconstruction
- average frames/bin/slice = 26

JHU method 1: Example results for 1st-pass reconstruction



- 10-slice bSSFP-sagittal in lung volunteer – **highly variable breather**
- 10-phase-bin reconstruction
- average frames/bin/slice = 32

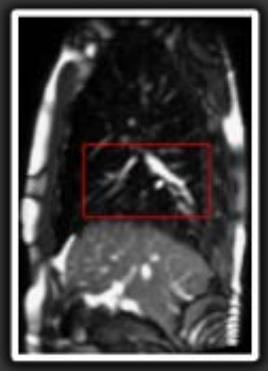
JHU method 1:
Example 1st pass result for amplitude-probability vs. phase binning



•Example lung volunteer exhibiting highly regular breathing

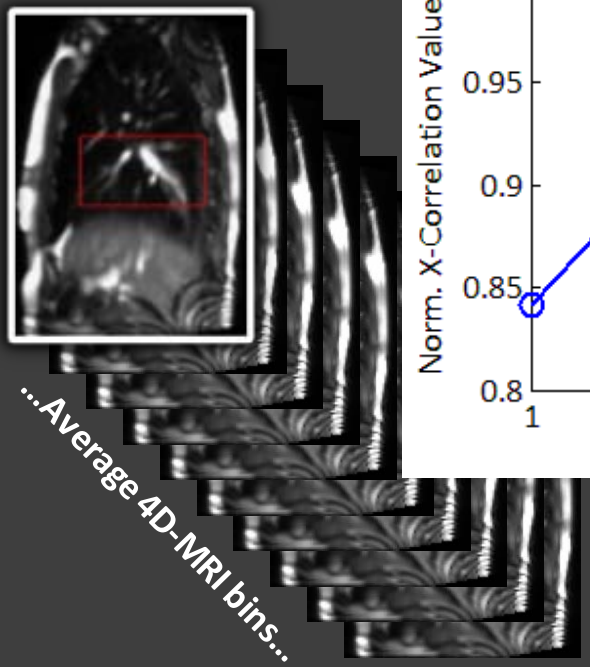
JHU method 1:

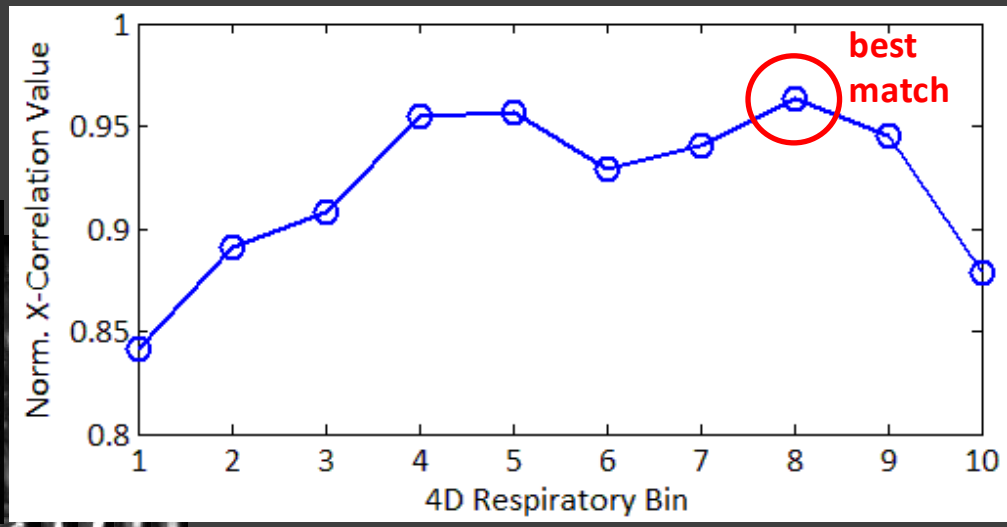
Normalized cross-correlation based scoring to determine best matching frames for 2nd pass reconstruction



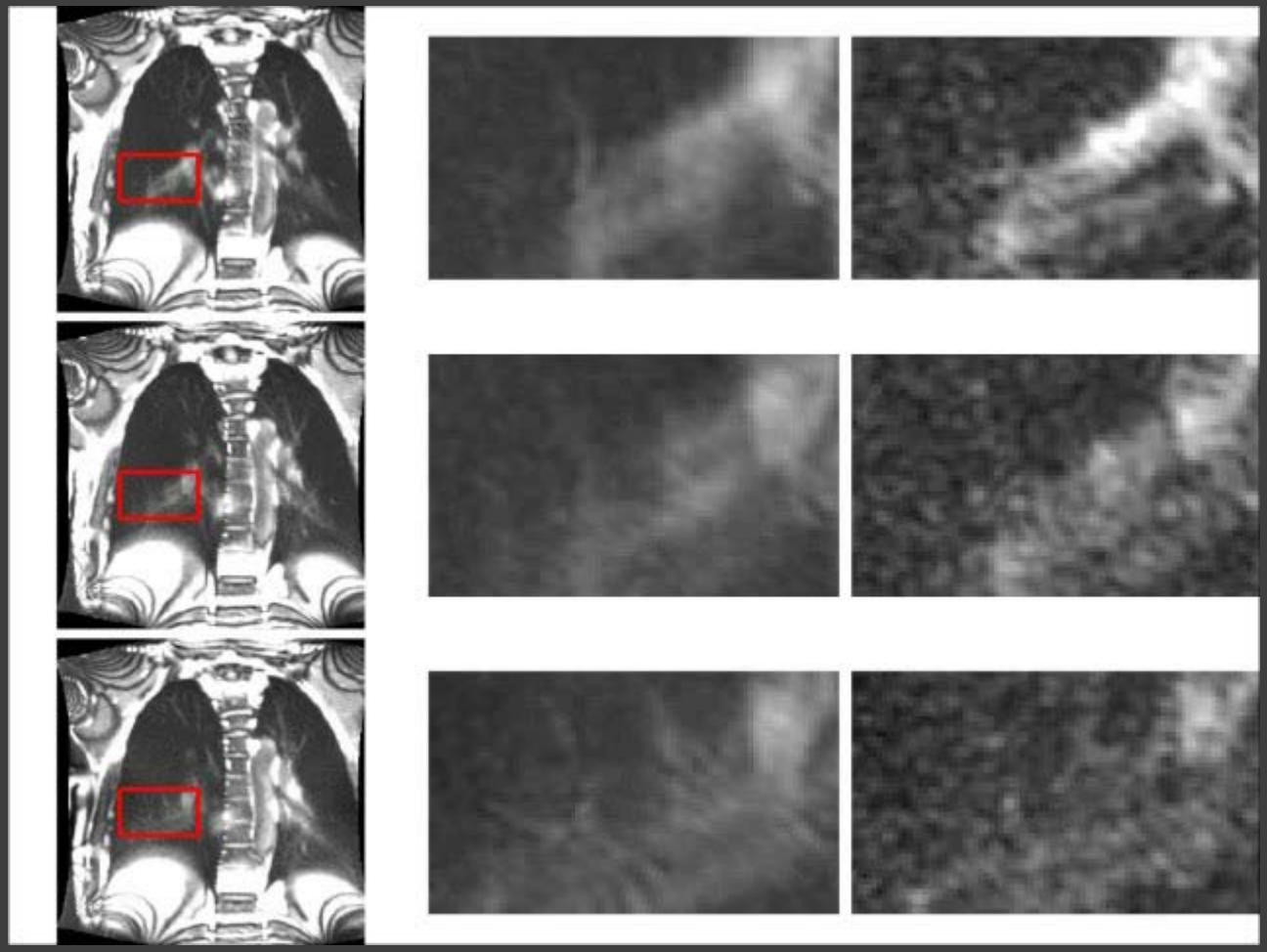
Raw Frame 166

Norm. X-Corr.



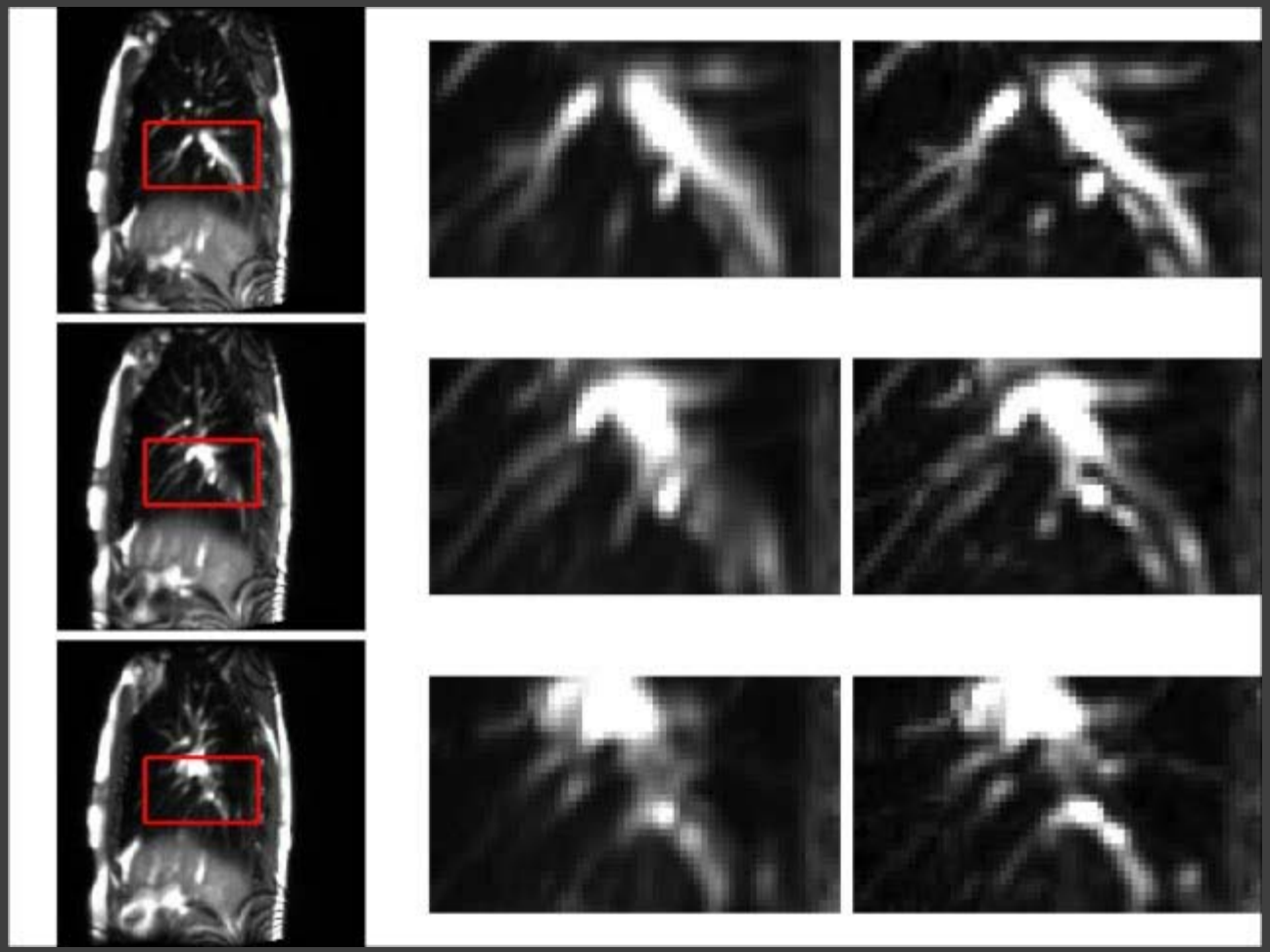


JHU method 1: Example results for 2nd-pass reconstruction



- bSSFP in lung volunteer (dark blood pulse on) - 30 min. acquisition
- 10-phase-bin reconstruction
- average frames/slice/bin = 30

JHU method 1: Example results for 2nd-pass reconstruction



- bSSFP in lung volunteer
- 10-phase-bin reconstruction
- average frames/slice/bin = 32

Conclusions for JHU method 1:

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- We have successfully demonstrated feasibility of this method in volunteers using two readily-available sequences

- Diaphragm signal or other similar image-based surrogates can be used as surrogate for sorting

- Technique will be ready for prime-time when PMU issues (not discussed) are resolved

- If we assert: 50 sagittal slices covering patient w/ 10 bins ; 15 frames/bin/slice
  → 7500 raw 2D frames, about 30 minutes required

Hence, increased frame rates would be beneficial for scanning commensurate anatomical volumes (as 4D-CT), potentially in multiple orientations, in a realistic MRI simulation appointment (30-60 minutes)

JHU method 2 goals/applications:

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Goal:

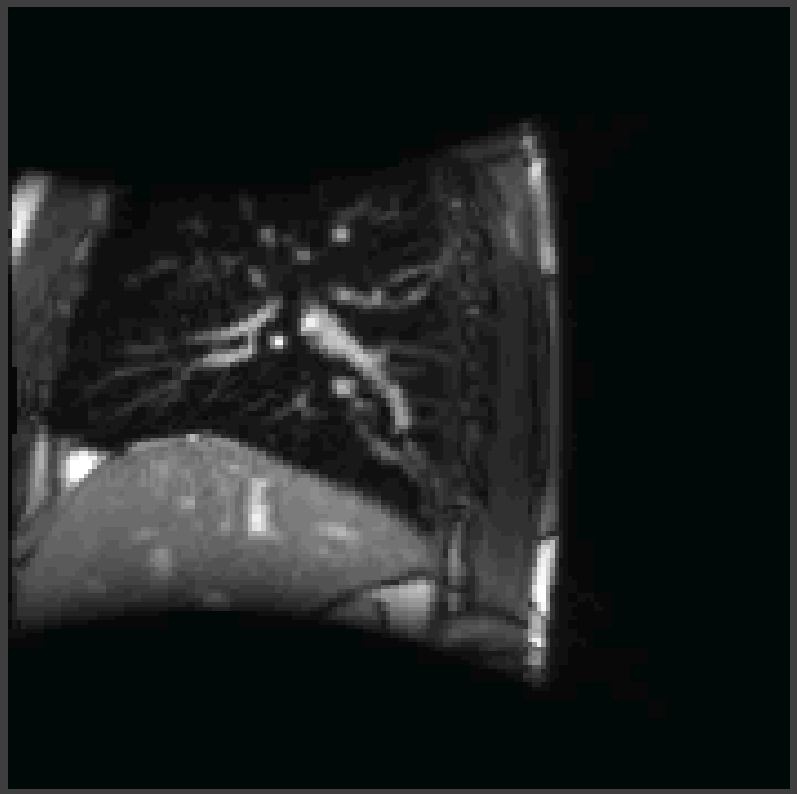
Pre-treatment, perform "true" 4D tracking of the tumor (center of mass) using dMRI over a sufficiently long duration to adequately characterize "breathing motion" (variability)

Example Applications (not exhaustive list!):

- Derive the "dynamic internal margin" Coolens et al. [PMB 53(16) 2008]
- Derive the spatial-3D probability density function for tumor motion
- Study of spatial-temporal correlations of traditional target motion surrogates such as an external respiratory trace or skin/surface markers
- Determine which potential breathing management strategy is best suited for the given patient, e.g., motion-encompassing (ITV), 4D-probabalistic, gating, breath-holding or tracking

JHU Method 2: image acquisition

Acquire orthogonal 2D (Sagittal + Coronal) dMRI Siemens MAGNETOM Espree 1.5T



TrueFISP (bSSFP):

- interleaved acquisition (sag, coronal, sag…)
- 2x2 mm^2 pixels in plane
- slice thickness adjusted for motion out-of-plane
- Acquisition speed: ≈4 frames/sec.

JHU method 2: simultaneous respiratory monitoring

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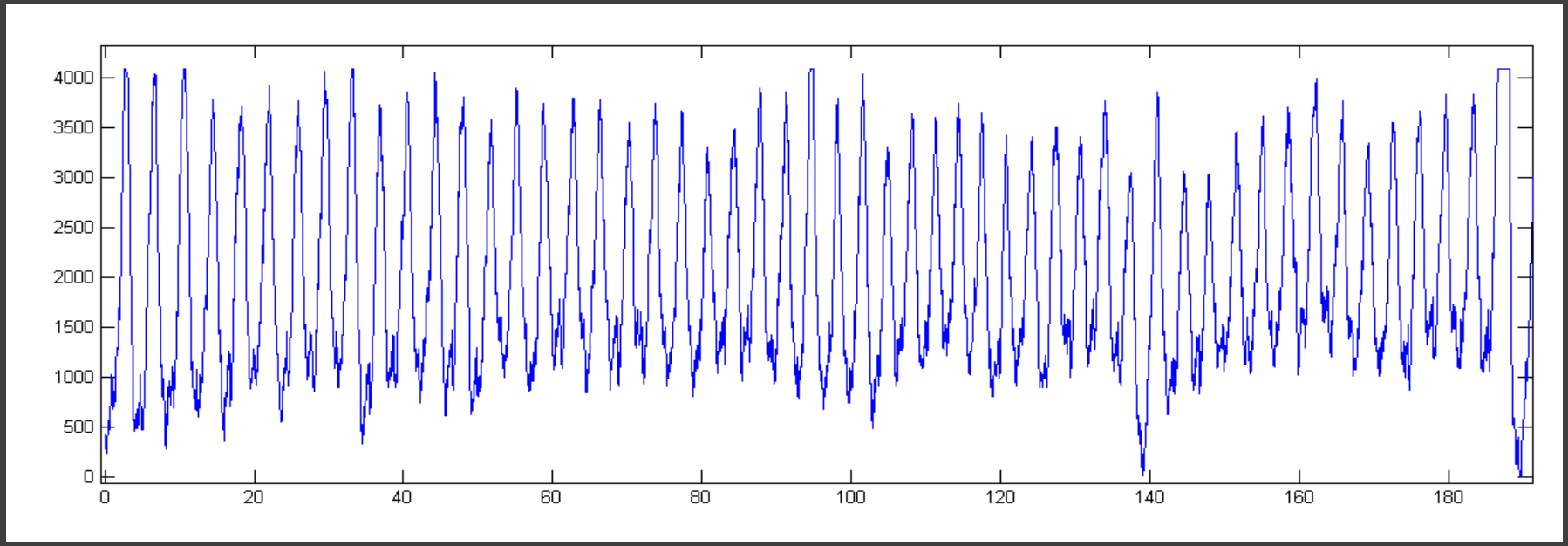
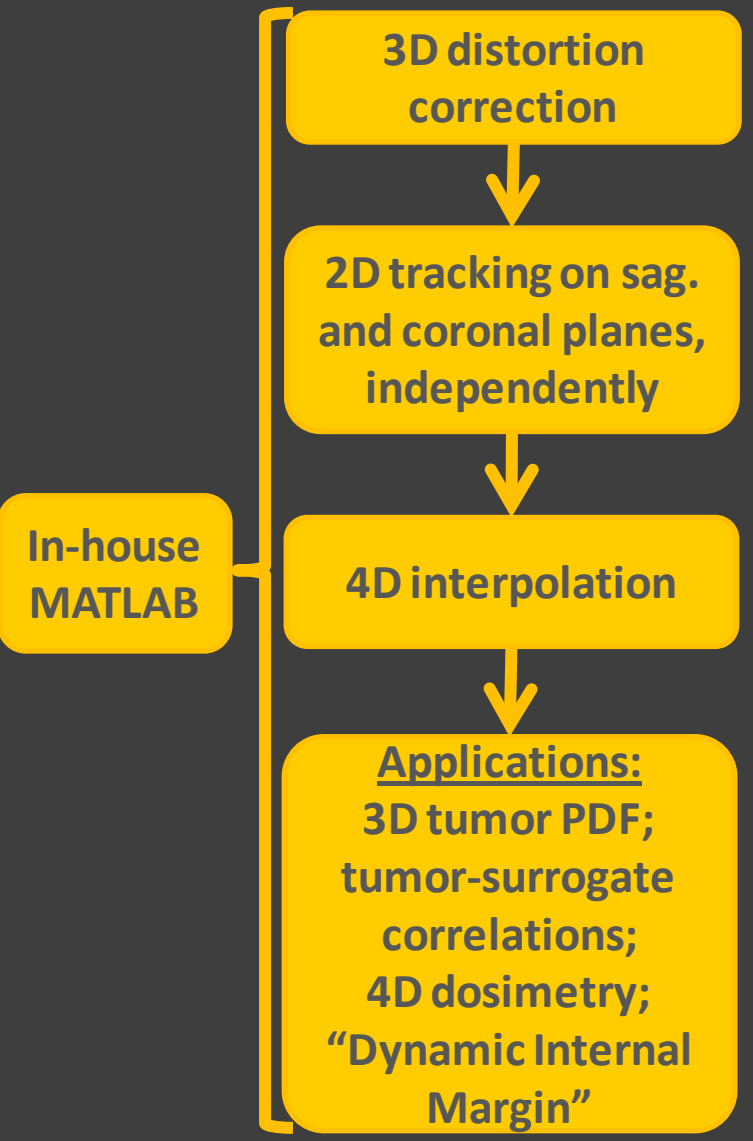
Acquire external respiratory signal (Physiological Monitoring Unit -- PMU)



PMU logging:

- synchronized with the image acquisition computer
- auto started/stopped within sequence run
- sampled at 50 Hz

JHU Method 2: post processing



2D sag/coronal tracking:

- User draws ROIs interactively looking at MIP images
- Sup.-inf. border of sag. and coronal ROIs is matched
- Based on ROIs, template images chosen from an arbitrary frame
- 2D normalized cross-correlation-based tracking/optimization
- Images up-sampled 4× to provide higher (spatial) tracking resolution

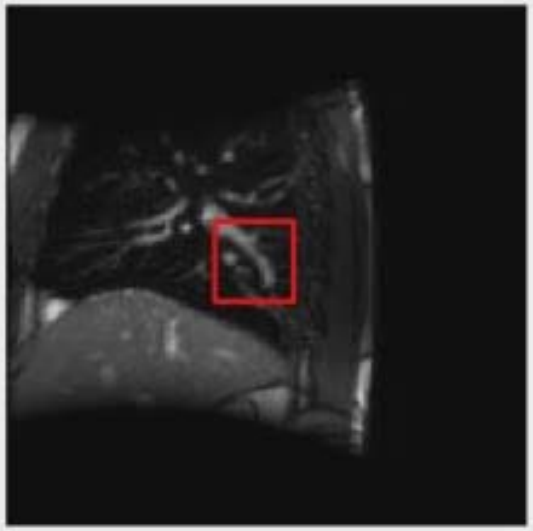
4D interpolation:

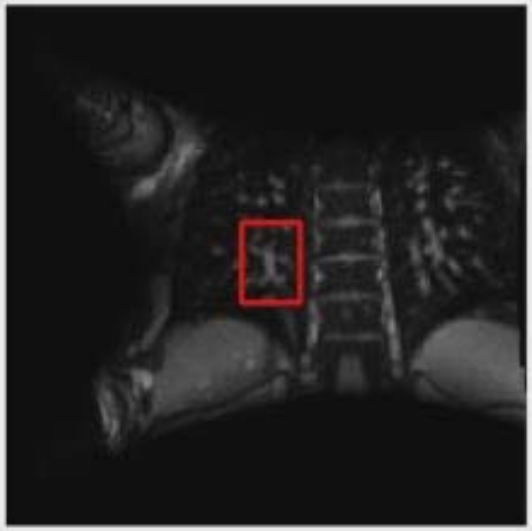
- stitch 2D vs. time data from each plane into contiguous 4D trajectory
- Interpolation of position data onto regular temporal grid (matching raw frame rate) using spine interpolation

Works in progress!

JHU method 2:

Example lung volunteer tracking result

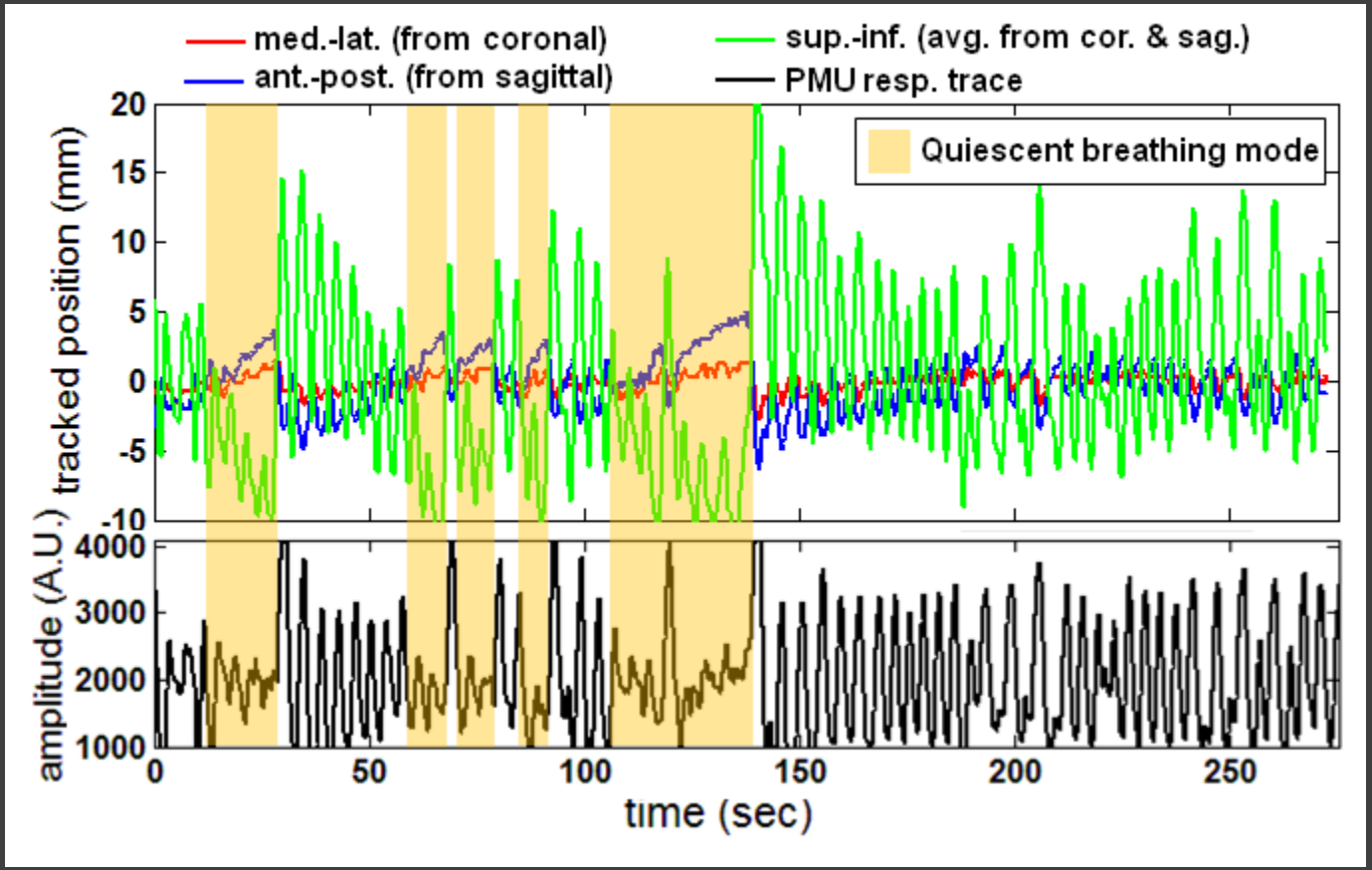




JHU method 2:

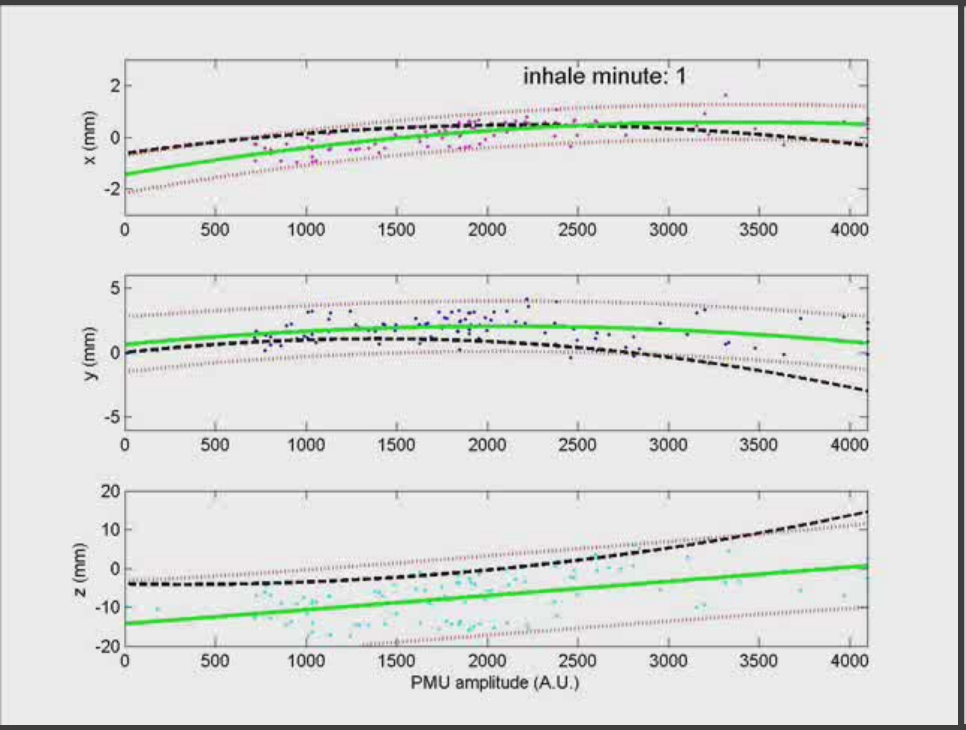
Example lung volunteer tracking result, cont'd.

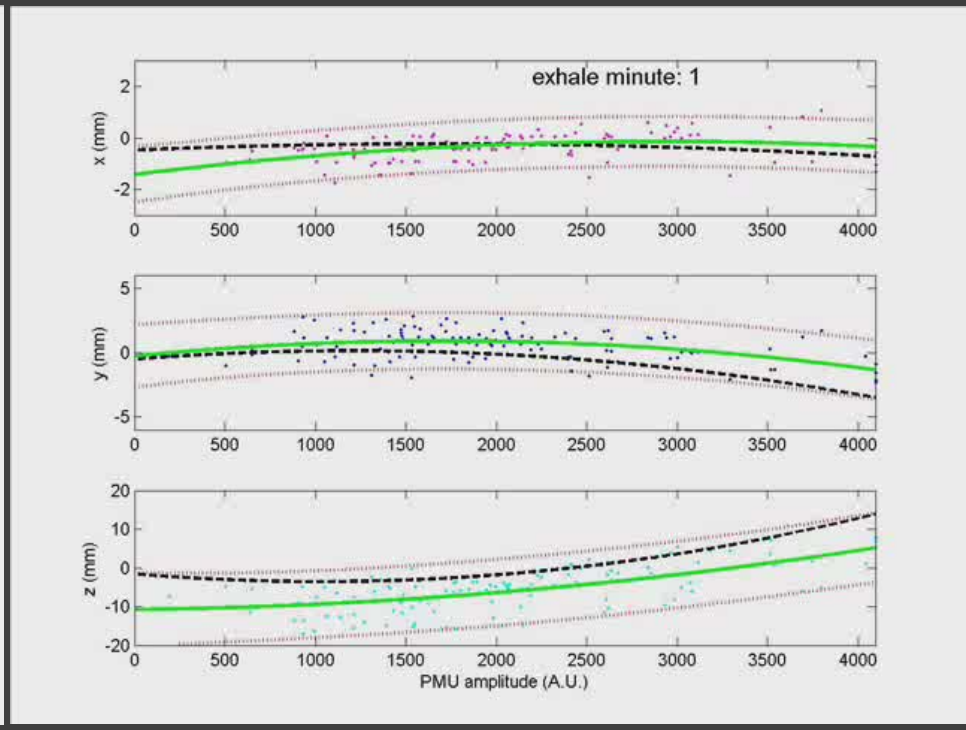
- Tracking over last 4.5 minutes of 9.1 minute study
- Volunteer instructed to relax and breathe normally – breathing motion is highly variable
- Two discernable breathing modes detected
- In the "quiescent" state, the PMU correspondence is essentially lost



JHU method 2:
Example lung volunteer tracking result, cont'd.

Here in same volunteer we investigate the correlation between the PMU amplitude and the internal motion of the tracked vessels:



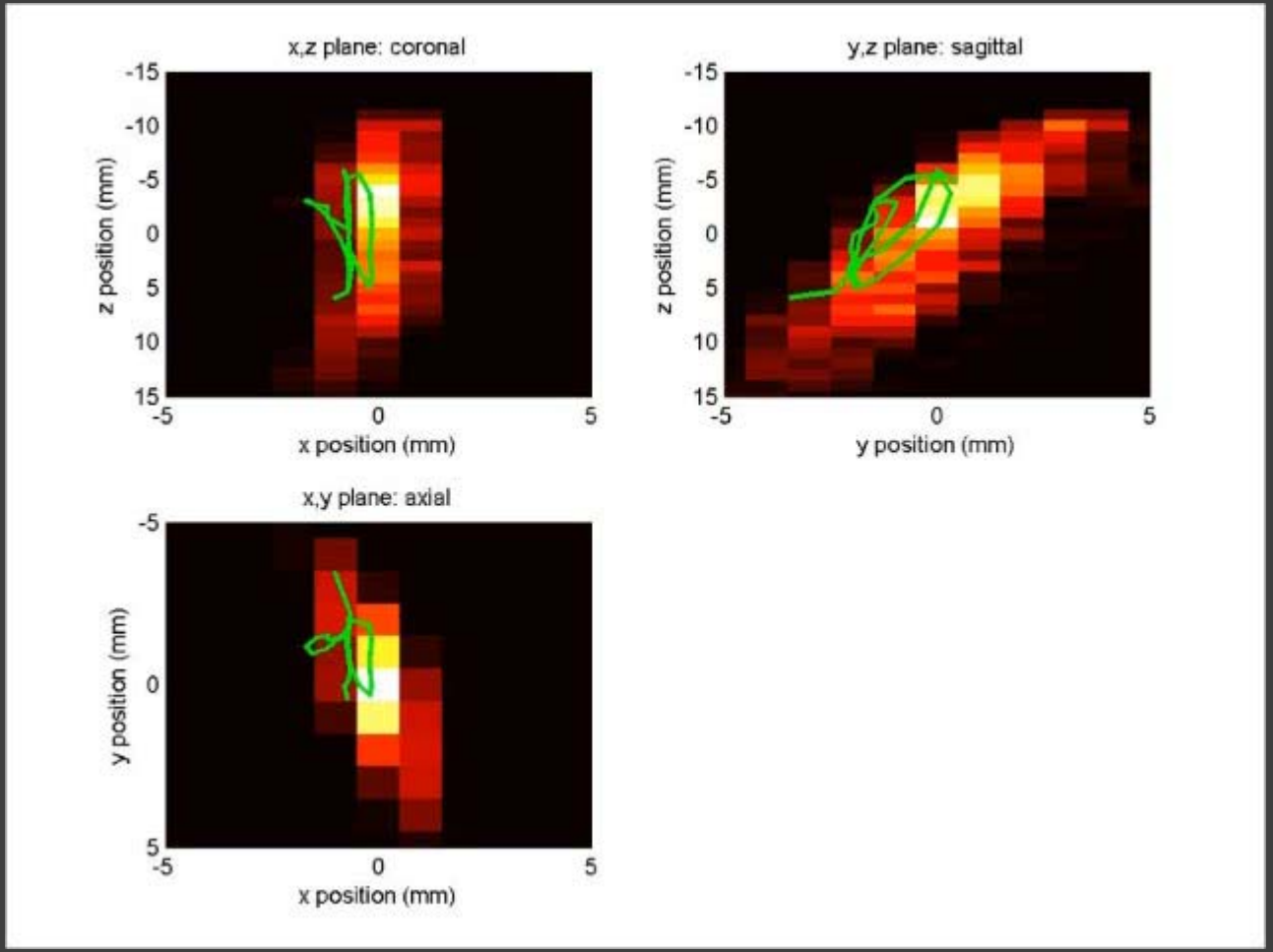


•Each frame compares data/fit from 1 min. portion of tracking data to fit over full 9.1 min.

JHU method 2:

Example lung volunteer tracking result, cont'd.

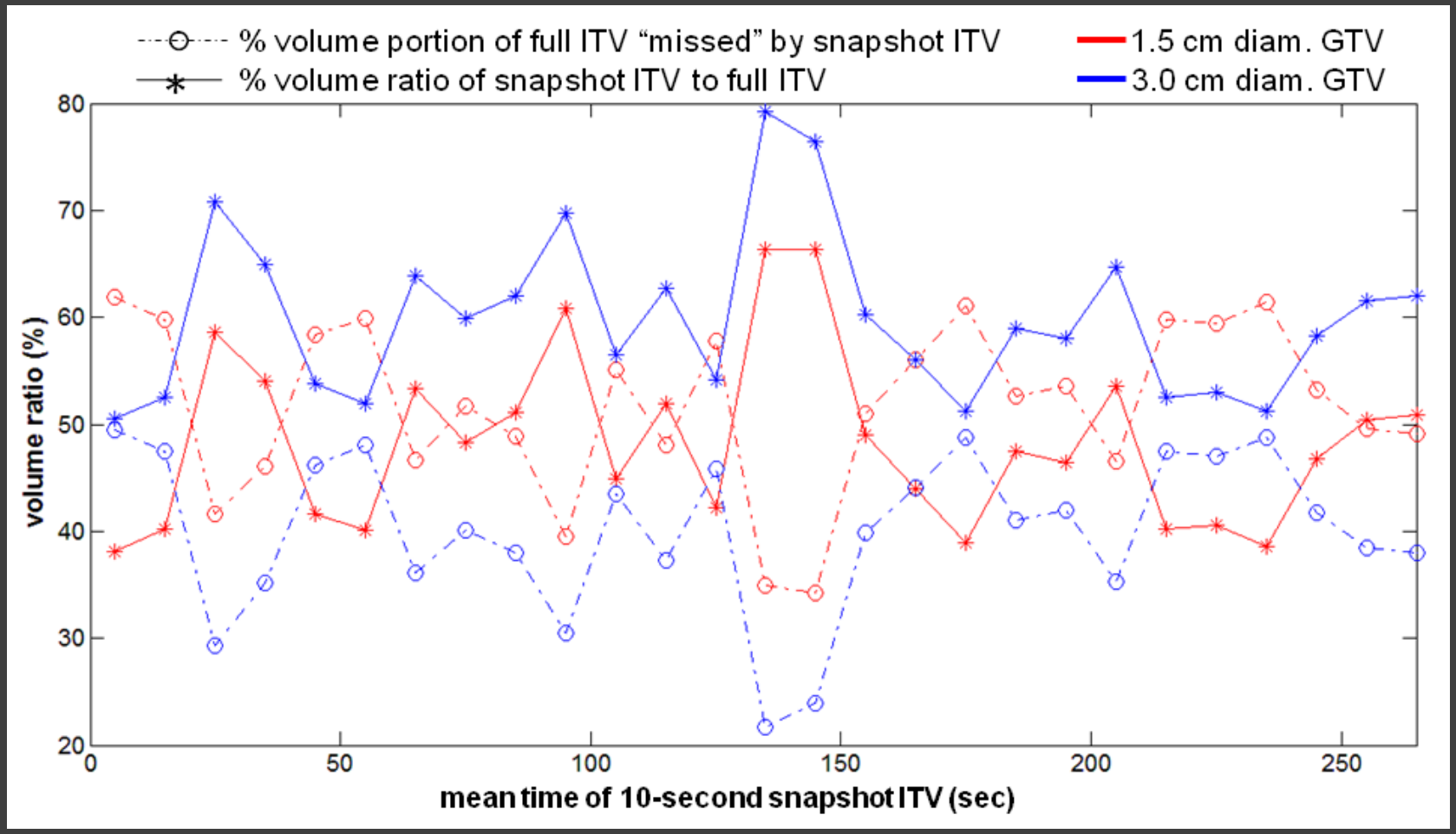
- Tracking over last 4.5 minutes of 9.1 minute study
- A typical 4D-CT scan may scan through the tumor in ~10 seconds
- Suppose we compare the full-duration PDF vs. 10-second trajectories:



JHU method 2:

Example lung volunteer tracking result, cont'd.

- A typical 4D-CT scan may scan through the tumor in ~10 seconds
- Suppose we compare the full motion ITV vs. 10-second snapshot ITVs for a 1.5 and 3.0 cm (diameter) hypothetical GTV

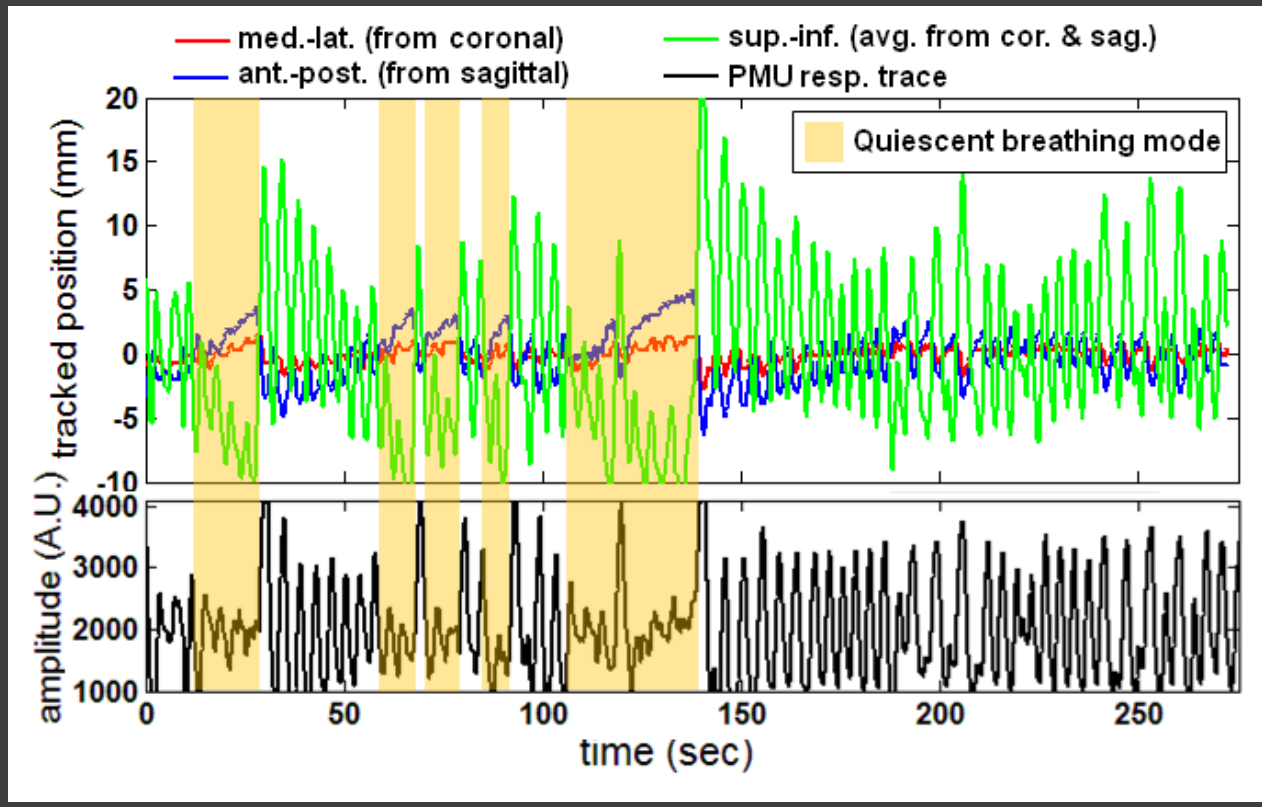


JHU method 2:
Example lung volunteer tracking result, cont'd.

- **Numerical 4D dose accumulation simulations**

Suppose we "scan through" the tumor at times t=130-140 sec. and generate an ITV plan:

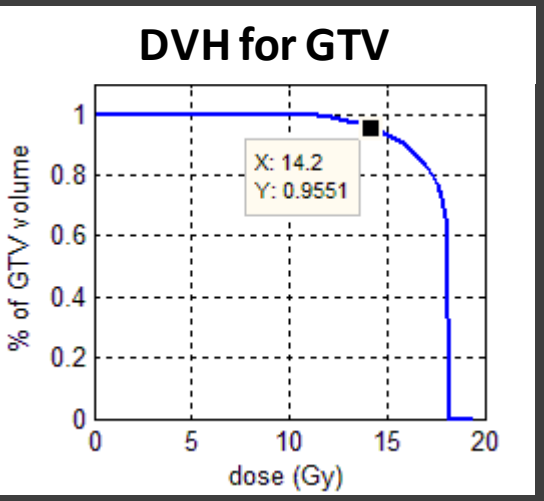
- GTV diameter = 1.5 cm
- PTV = ITV + 1 mm uniform expansion
- $D_{Rx,\,PTV}$ = 18 Gy
- Quasi-realistic dose cloud: uniform in PTV; dose fall-off given by Gaussian tail with 3.5 mm sigma
- Assume "shift invariance"



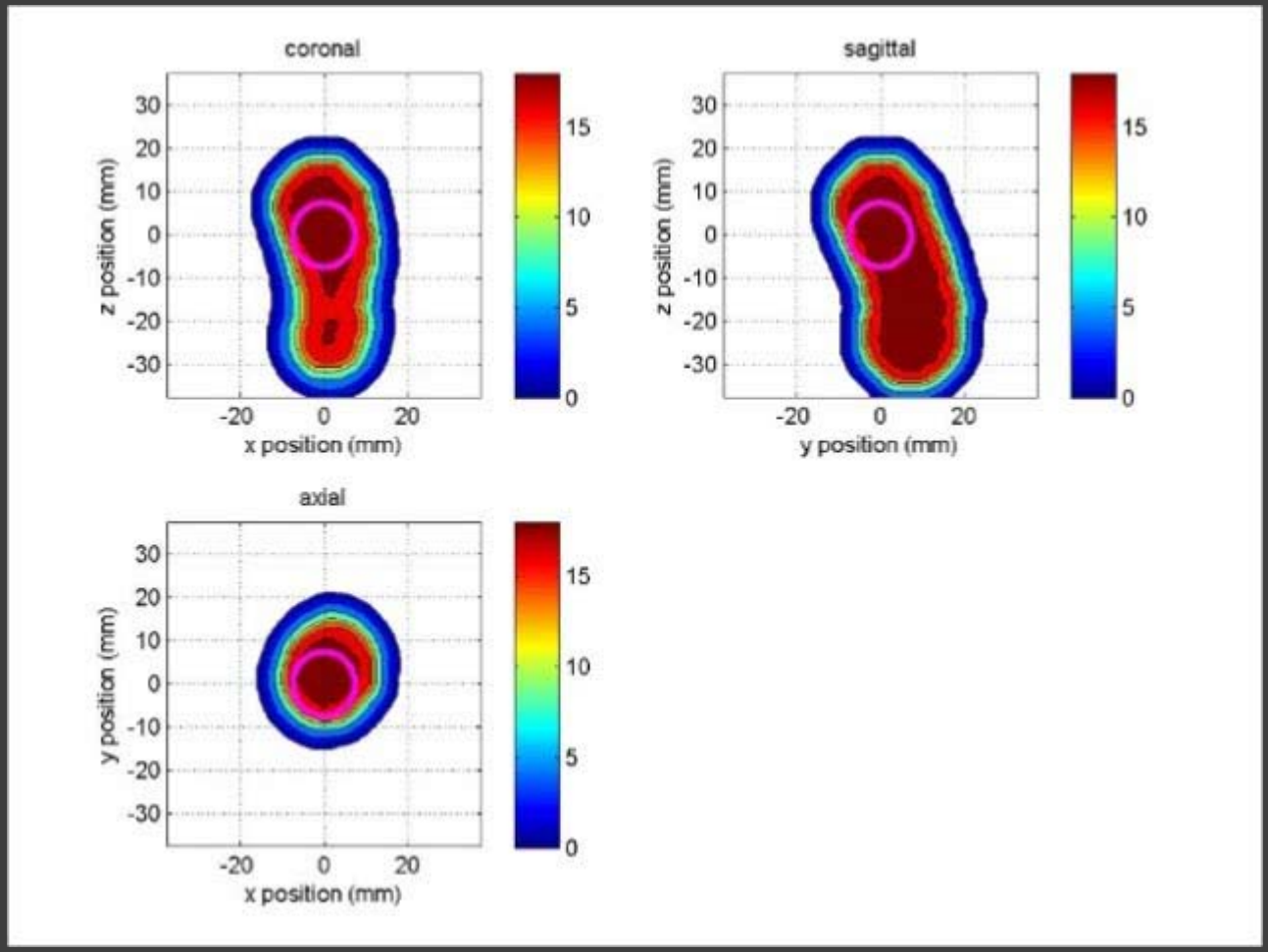
JHU method 2:
Example lung volunteer tracking result, cont'd.

- Numerical 4D dose accumulation simulations to illustrate utility

Suppose we now treat the patient over time, t=30-60 sec:

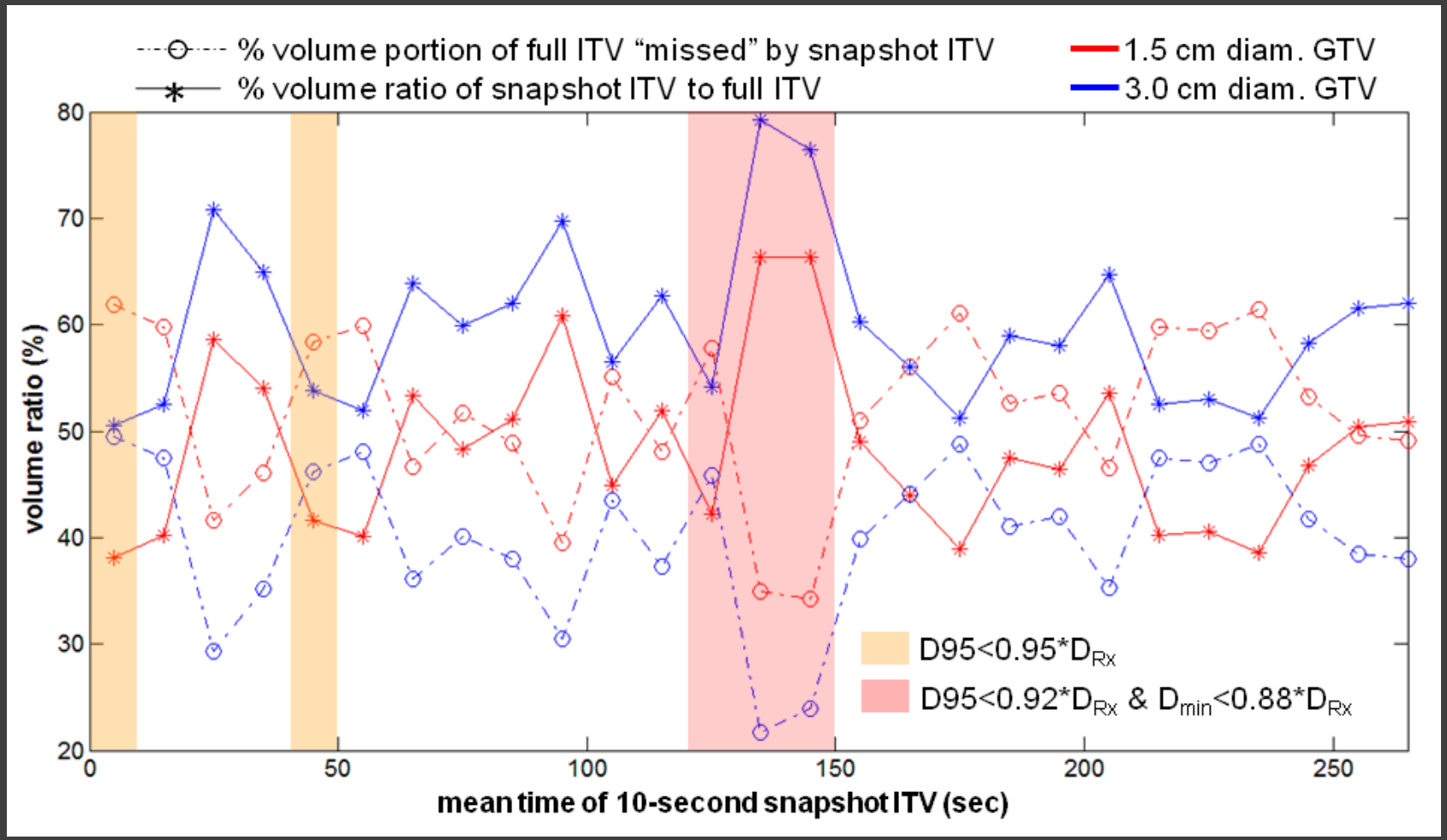


- $D_{min,GTV}$ = 10.4 Gy
- D95 = 14.3 Gy



JHU method 2:
Example lung volunteer tracking result, cont'd.

- Suppose we now move our 10-second snapshot ITV target definition time window iteratively across the entire tracking duration
- For each iteration perform a 4D dose accumulation for the dose cloud derived from the trial ITV (1.5 cm GTV) using the motion information from the entire duration



Conclusions for JHU method 2:

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- We have successfully demonstrated feasibility of this method in volunteers.

- Current focus is on finding practical ways to incorporate this information into clinical workflow.

- Truly 3D dMRI is highly desirable : e.g., tumor deformation can also be tracked and characterized; more complete study of potential internal/external surrogates can be performed. Tradeoffs between image quality and speed currently challenge this approach.

General concluding remarks:

- Dynamic MRI has matured and is ripe for more widespread application in radiotherapy

- More investigation is needed to dosimetrically (and perhaps clinically) demonstrate that "4D-MRI" provides advantages over our present 4D imaging (4D-CT) so as to justify the required investments

- Realistic phantom studies are needed to evaluate the geometrical robustness of the dMRI sequences