Resolving and characterizing breathing motion for radiotherapy with MRI

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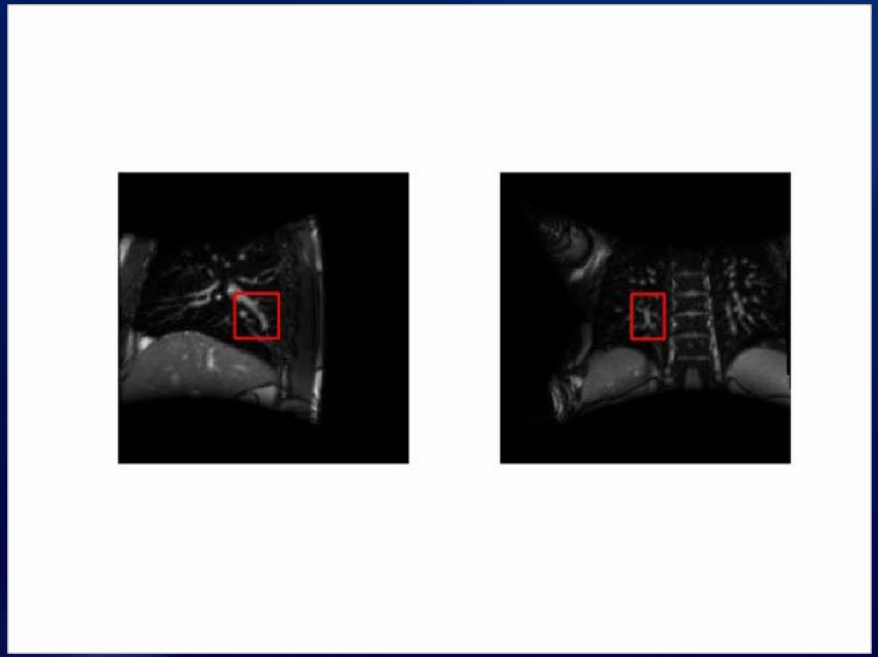

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Anaheim, CA

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Disclosures and Apologies

- No conflicts of interest
- Not an MRI scientist
- Only have 20 minutes

  Many investigators' relevant/current methods will not be mentioned

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Outline

I. Introduction
   a) Motivations
   b) Pitfalls
   c) 2D vs. 3D sequences

II. (Breathing) motion characterization offline
   a) Single-slice cine 2D MRI
   b) Orthogonal-slice cine 2D MRI
      i. Sequential
      ii. Interleaved
   c) Multi-slice cine 2D MRI to derive “4D-MRI”
      i. Retrospective binning
      ii. Un-binned for MIP generation

III. Motion monitoring online
   a) MRI-guided ^{60}Co unit
   b) MRI-guided linac

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Ia. Introduction: motivations for applying MRI to the motion problem

- MRI Offers the capability for 4D anatomical imaging, similar to 4D-CT
  - 4D-CT represents a snap-shot in time – not ideal
- MRI is non-ionizing → longer scans to characterize motion variability
- Sufficiently fast to minimize intra-scan motion
- Can scan in any orientation
- Flexibility in terms of achievable tissue contrast
  - Possibility to better visualize compared to CT for many disease sites (e.g., abdomen).
- Capability of 4D tumor tracking - useful for both online and offline applications:
  - Online:
    - Gated or motion-tracked therapies with reduction in treatment margins
  - Offline:
    - Validation studies of different management techniques (gating, breath-holding, tracking…)
    - Robust, patient specific margin determination

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Ib. Introduction: pitfalls of applying MRI to the motion problem

- Not widely available; cost-prohibitive?
- Flexibility in MRI technology has led to lack of a defined 4D-MRI standard
  - Development/adoption largely limited to academic centers with resources
  - No current support for 4D-MRI in treatment planning systems
- Geometric image distortion
- Spatial resolution is more limited than CT (SNR tradeoffs)
- "4D-MRI planning simulations" take longer than 4D-CT planning simulations
- Other practical issues
  - Body/surface/flex coils complicate the procedure/setup
  - Claustrophobia is more likely than with CT
  - Not all patients are MRI-safe

➔ Early adopters must continue to address these issues while demonstrating dosimetric/safety/clinical benefit to patients

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Ic. 2D vs. 3D sequences – primer

2D:

- Excitation of tissue slab (thickness dictated by slice profile) via slice selection gradient
- Duration per slice = TR × NPy × Nex
  NPy = number of phase encoding steps, hence number of rows
  Nex = number of (slab) excitations (or TR repetitions)
- Reconstruction via 2D Fourier transform
- (… Repeat over multiple slice locations to provide 3D image)

3D:

- Excitation slab = 3D volume at each (TR) repetition
- 3D spatial encoding via addition of phase encoding in another (3rd) dimension
- Duration per volume = TR × NPy × NPz × Nex
  NPz = Number of phase encoding steps in the z-axis
- Reconstruction via 3D Fourier transform

2D vs. 3D:

- 3D sequences provide better signal (SNR) for given resolution.
  → *Multi-planar viewing has higher fidelity with 3D*
- 3D volume takes longer to encode -- therefore 3D is subject to more intra-scan motion
  → *Methods exist to speed up 3D acquisition such as partial k-space filling*
- 2D sequences more practical "out of the box" given acquisition speed

[Hoa D., Spatial encoding in MRI. https://www.imaios.com/en/e-Courses/e-MRI/Signal-spatial-encoding/3D-spatial-encoding]

IIa&b. Offline motion tracking with 2D cine MRI

Single-slice-plane acquisition

1. Lung: Koch et al. [IJROBP 2004; 60 (5): 1459]
2. Lung: Cai et al. [PMB 2007; 52: 365]
   [IJROBP 2007; 60(3): 895]
3. Lung: Shi et al. [Med. Phys. 2014; 41 (3). 52304]

Orthogonal-slice-plane acquisition:

Sequential (sagittal-sagittal…; coronal-coronal…)

1. Liver: Shimizu et al. [IJROBP 2000; 48 (2); 471 (sagittal/coronal)
2. Liver: Kirilova et al. [IJROBP 2008; 71 (4): 1189] (sagittal/coronal/axial)
3. Liver: Akino et al. [Med. Phys. 2014; 41(11): 111704] (sagittal/coronal)
4. Pancreas: Feng et al. [IJROBP 2009; 74 (3): 884] (sagittal/coronal)

Interleaved (sagittal-coronal-sagittal-coronal…)

1. Lung/Abdomen: Tryggestad et al. [Med. Phys. 2013; 40 (9): 091712]
2. Kidney: Bjerre et al. [Phys. Med. Biol. 2013; 58 (14): 4943]

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IIa&b. Offline motion: tracking with 2D cine MRI

- **2D cine MRI example (bSSFP on Siemens 1.5T Espree)**

Interleaved orthogonal-slice cine acquisition:

- ~4 frames/second
- 2x2 mm^2 pixels in plane
- 5 mm slice profile

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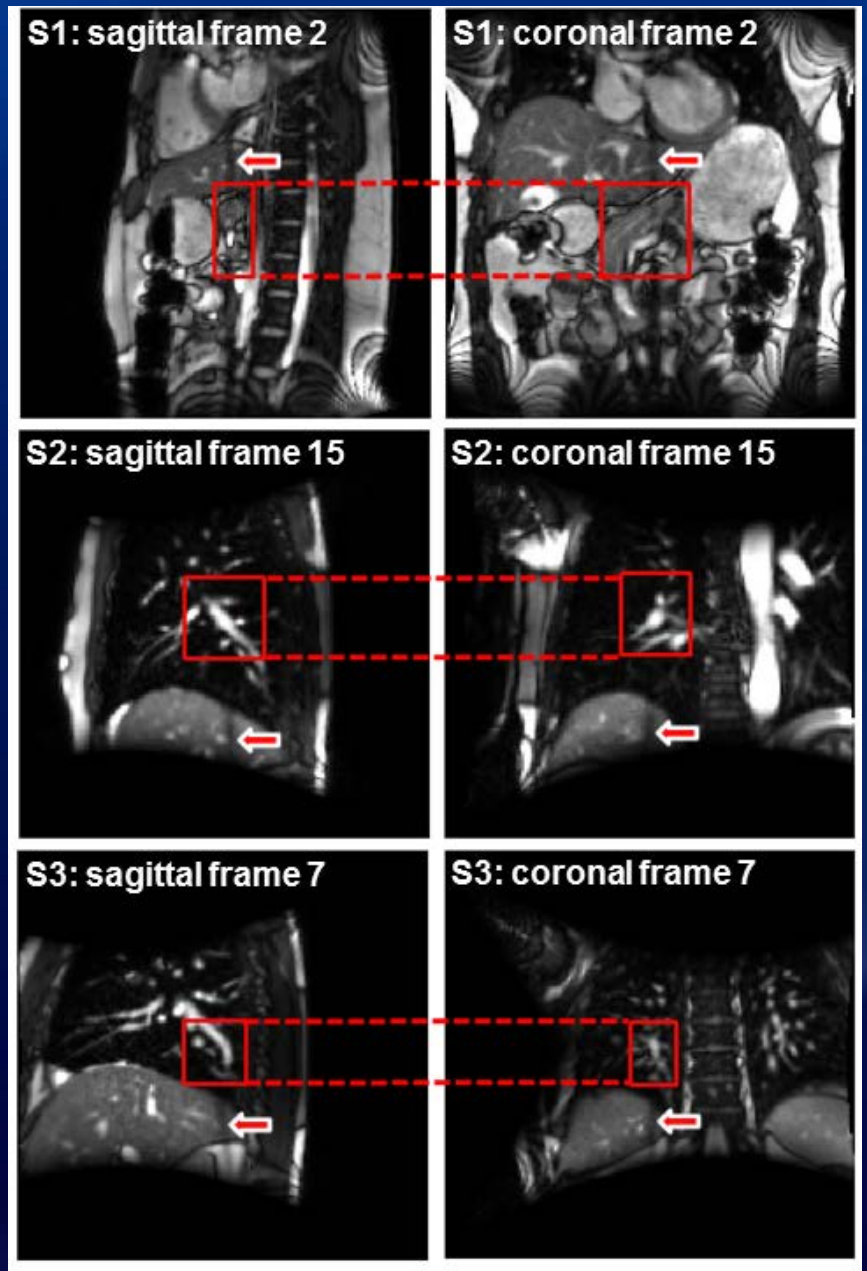
IIa&b. Offline motion: Template matching with orthogonal slice planes

- **Cross-correlation-based template matching**

Tryggestad et al. [Med. Phys. 2013; 40 (9): 091712]



Imaging time

13 min.

12 min.

9 min.

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IIb&c. What is a “cross-correlation” in image processing?

Live image (k)

<pixel-wise (*i,j*) comparison>

Template image (N)

Normalized cross-correlation:

$$ncc_{k,N} = \sum_{i,j} (I_k \cdot I_N) \; / \; \sqrt{\{\sum_{i,j} (I_k \cdot I_k) \times \sum_{i,j} (I_N \cdot I_N)\}}$$

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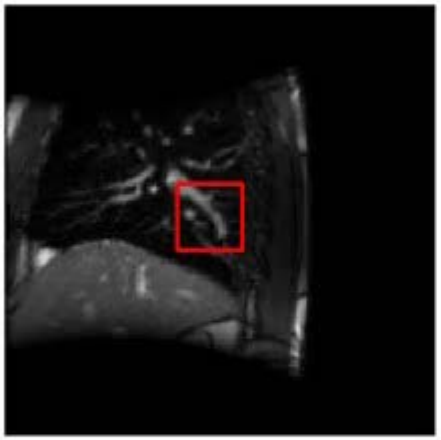
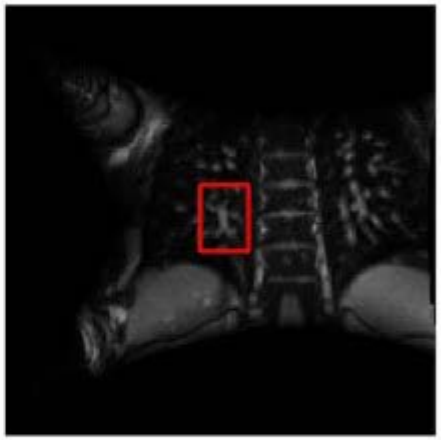
IIa&b. Offline motion: Template matching with orthogonal slice planes

- **Results for volunteer “S3”**





Tryggestad et al. [Med. Phys. 2013; 40 (9): 091712]

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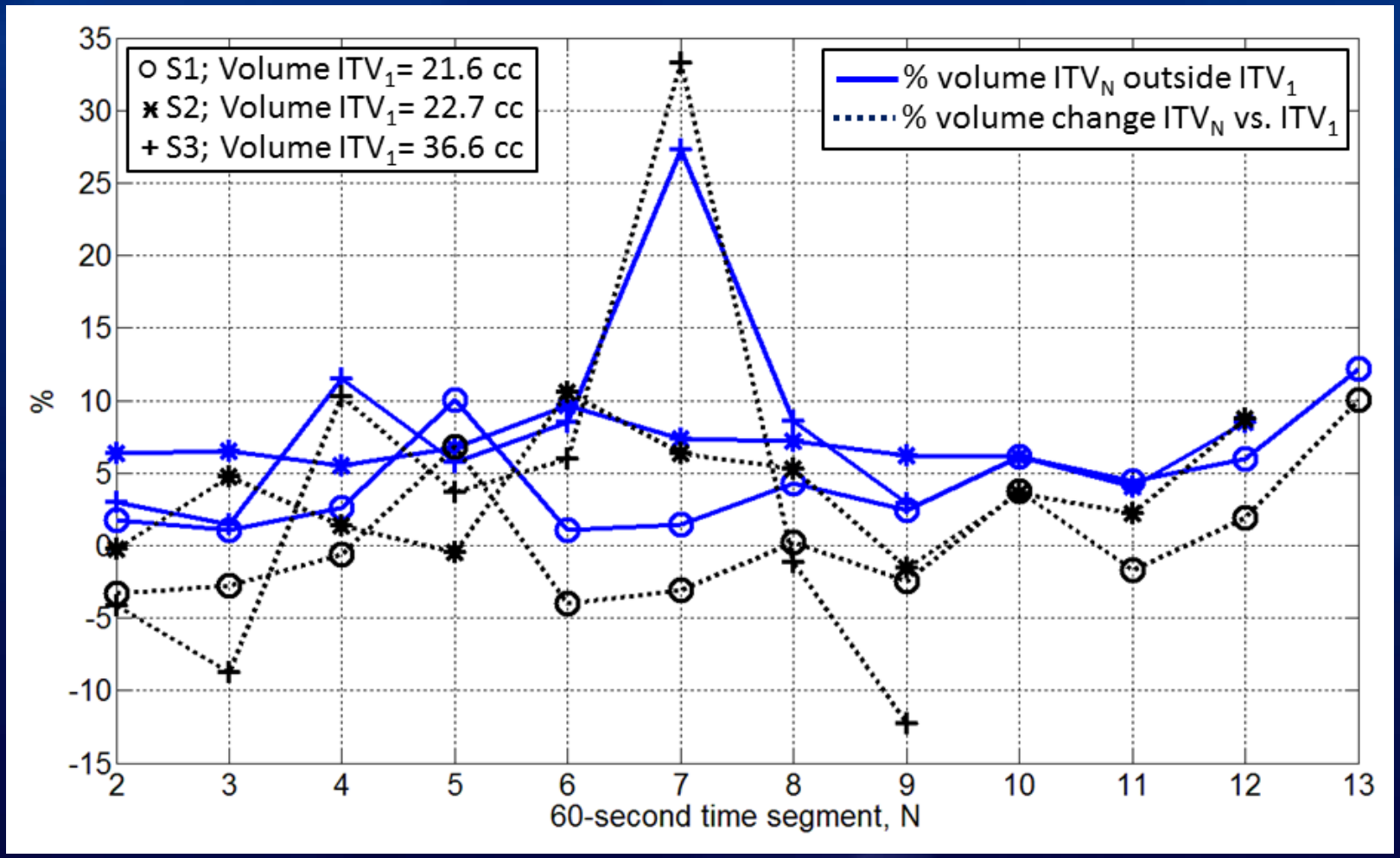
IIa&b. Offline motion: Template matching with orthogonal slice planes

- **Results from a numerical simulation:**
  - **3 cm spherical lesion**
  - **ITV_1 was determined during first 60 seconds of tracking**

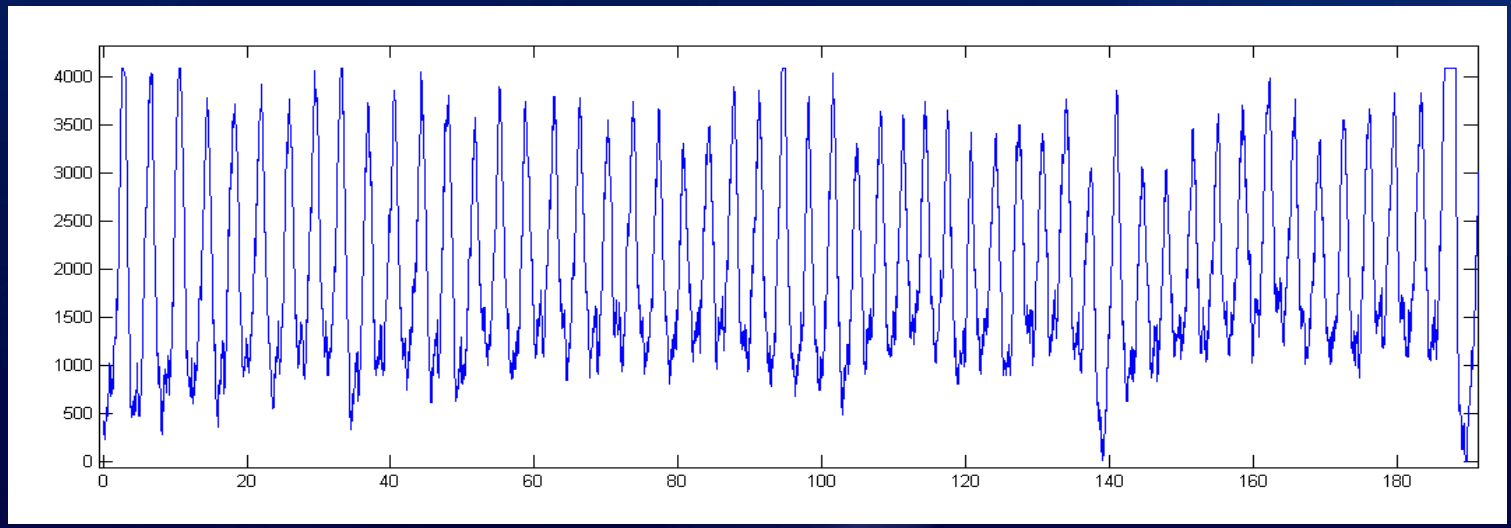


Tryggestad et al. [Med. Phys. 2013; 40 (9): 091712]

IIa&b. Simultaneous monitoring of motion surrogates

Respiratory bellows system [Picture: GE]

Example: PMU (Physiological Monitoring Unit, Siemens)



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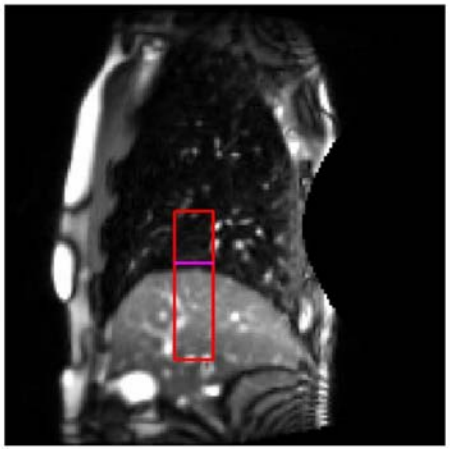
IIa&b. Simultaneous monitoring of motion surrogates



Diaphragmatic monitoring with edge detection filter

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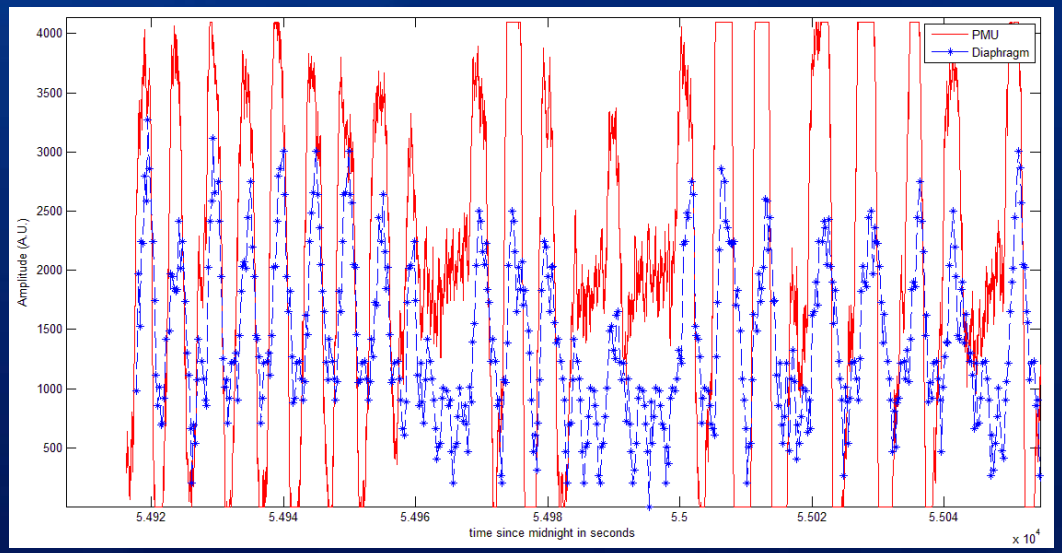
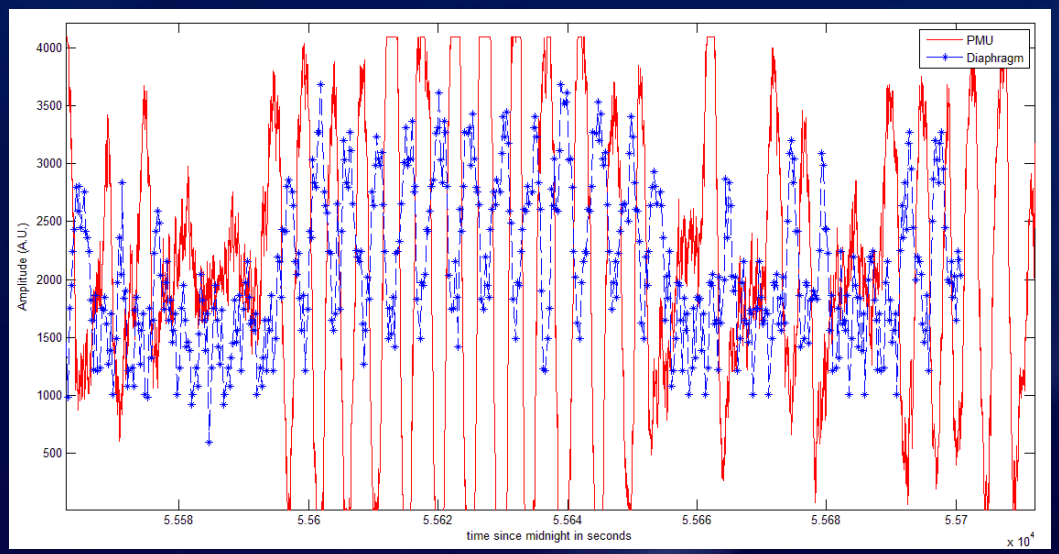
IIa&b. Simultaneous monitoring of motion surrogates

- **USE CAUTION when employing bellows-type systems**



@start of acquisition

Amplitude (A.U.)



@end of acquisition

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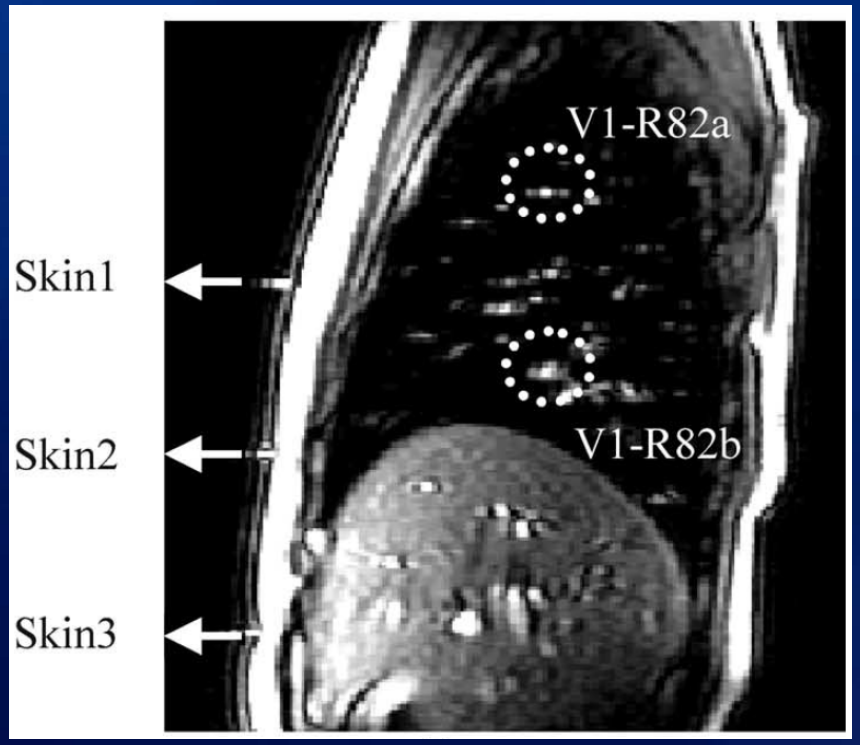
IIa&b. Simultaneous monitoring of motion surrogates

- **External markers (belts/tubes around patient)**



Koch et al. [IJROBP 2004; 60 (5): 1459]

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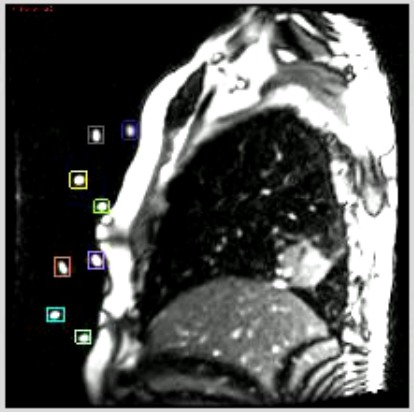
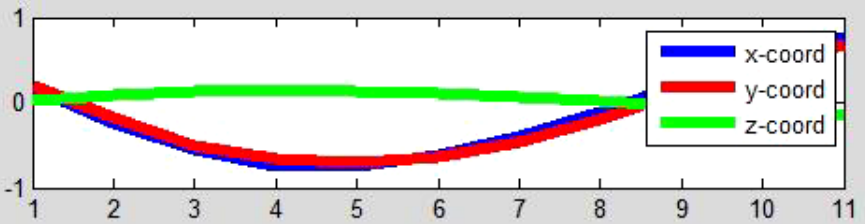
IIa&b. Simultaneous monitoring of motion surrogates

R. Farah and J. Lee [JHU / WIP]

External markers providing 3D information from single-plane tracking





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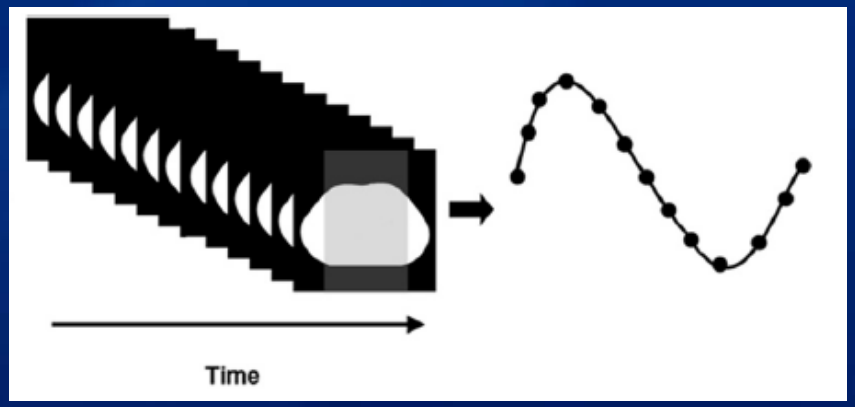
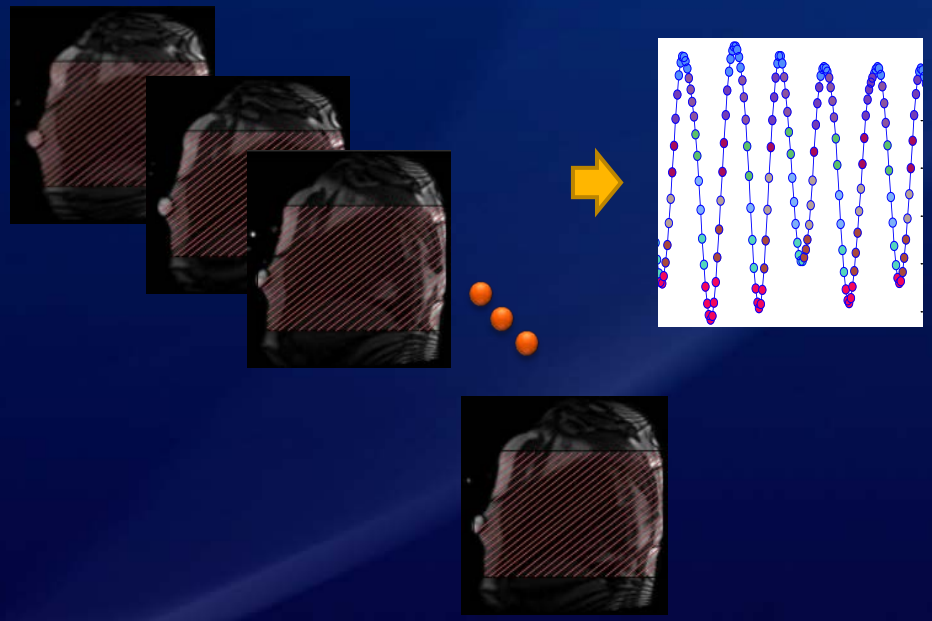
IIa&b. Simultaneous monitoring of motion surrogates

- **Thresholded/segmented "Body Area"**



Cai *et al.*
[Med. Phys. 2011; 38 (12): 6384]

R. Farah and J. Lee [WIP / JHU]
"4D-MRI reconstruction using group-wise registration."
AAPM 2015. Snap oral: SU-F-303-1



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IIa&b. Offline motion tracking with 2D cine MRI

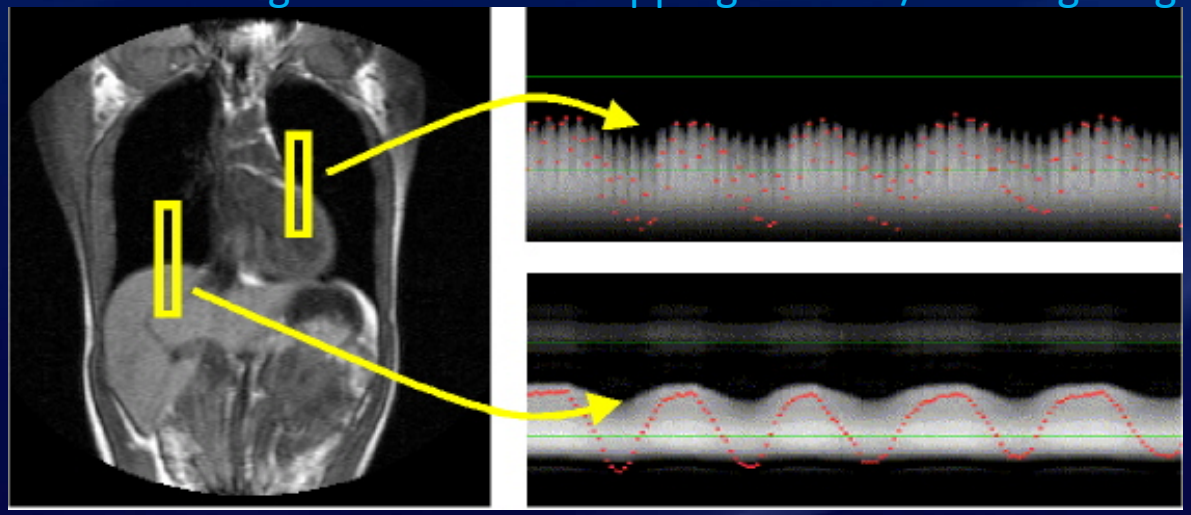
Opportunities for simultaneous monitoring of motion surrogates

- **Pencil Beam Navigators:**

  [Ehman and Felmlee, Radiology 1989; 173: 255]

  [Pauly, Nishimura and Makovski, JMRI 1989; 81: 43-56]

  - Excitation of a column of tissue and generation of a corresponding 1D image, i.e., spatial intensity profile
  - Can be inserted into sequence progression, e.g., in between 2D frames (or in between phase encoding steps)
  - Oriented arbitrarily relative to the 2D/3D imaging orientation
  - Commonly used in commercial sequences to trigger acquisition during a portion of breathing (amplitude-based)
  - Can produce banding artifacts if overlapping with 2D/3D image region



[Nehrke and Manke, IJBEM 2000; 2(2)]

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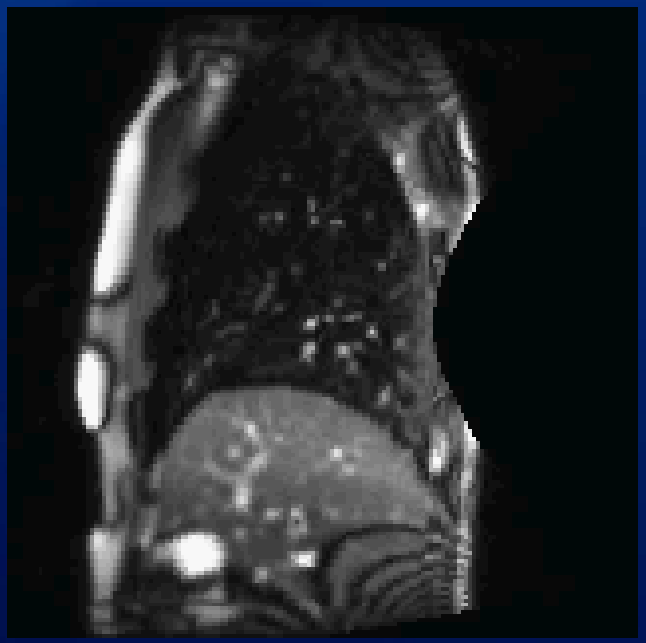
IIc. Offline motion:
Retrospective binning of multi-slice cine 2D MRI to derive “4D-MRI”

- **2D cine MRI example (bSSFP on Siemens 1.5T Espree)**



“Sequential” multi-slice:

- ~5 frames/second
- 2x2 mm^2 pixels in plane
- 5 mm slice profile

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IIc. Offline motion: Binning of multi-slice 2D MRI to derive "4D-MRI"

Two general constructs:

Virtual cine 3D (over duration of exam):

1. von Siebenthal et al. [PMB 2007; 52 (6): 1547]

Representative single-cycle cine 3D (analog to 4D-CT):

1. Cai et al. [Med. Phys. 2011; 38 (12): 6384]

2. Tryggestad E. et al. [Med. Phys. 2013; 40 (5): 051909]

3. Farah and Lee et. al. [WIP JHU]
   "4D-MRI reconstruction using group-wise registration."
   AAPM 2015. Snap oral: SU-F-303-1
4. Liu Y. et al. [Med. Phys. 2015; 42 (2): 534]
   k-space binning
5. Phantom and Liver: Tokuda et al. [Mag. Res. Med. 2008; 59 (5): 1051]
   navigator echoes to determine respiratory state and trigger acquisition
6. Hu et al. [IJROBP 2013; 86 (1): 198]
   bellows to determine respiratory state and trigger acquisition

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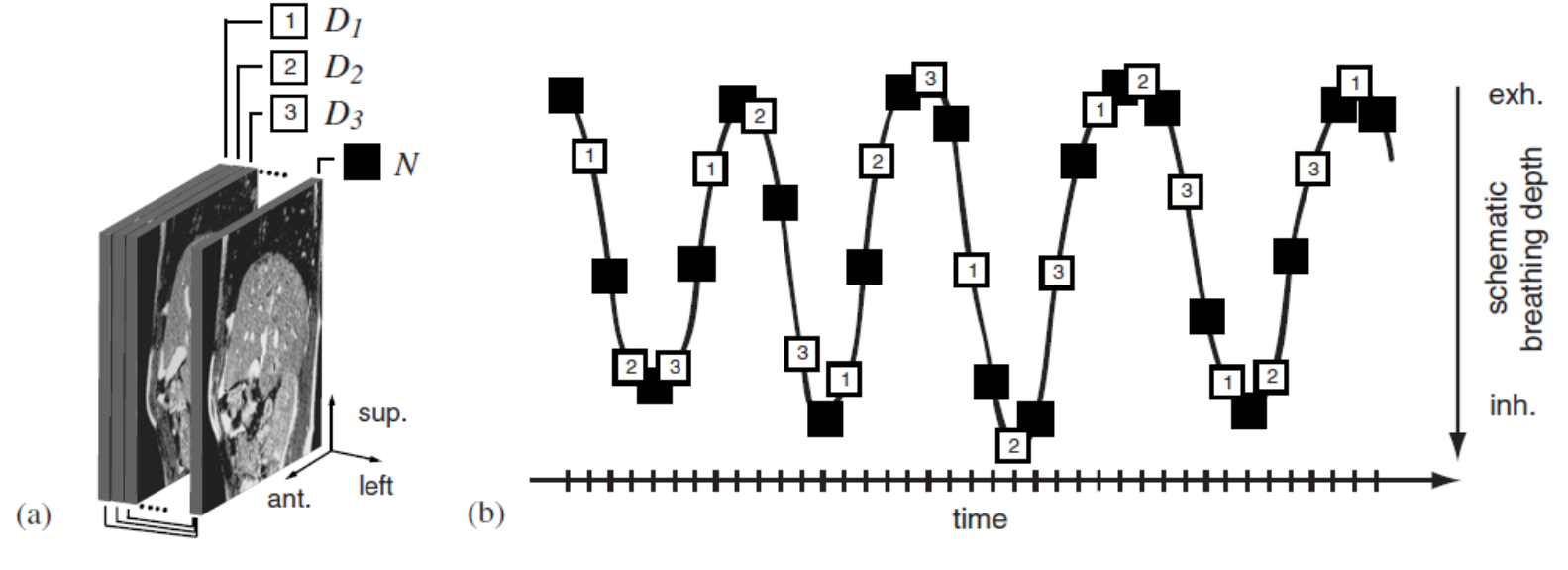
IIc. Offline motion:
Retrospective binning of multi-slice 2D MRI to derive virtual 3D cine MRI

- **Multi-slice abdominal 2D cine study in volunteers**
- **Demonstrated principle of "navigator slice"-based retrospective sorting**

[von Siebenthal et al. PMB 2007; 52 (6): 1547]



- 1.5 T (Philips Achieva)
- Custom bSSFP sequence
- Pixel size: 1.8^2 mm^2
- Slice profile (~thickness): 3-4 mm

- Acq. speed: 5.3-5.6 frames/sec.
  ➔ Effective acq. speed: 2.6-2.8 frames/sec.
- Sequential sagittal slice acquisition
- Continuous acquisition over tens of minutes

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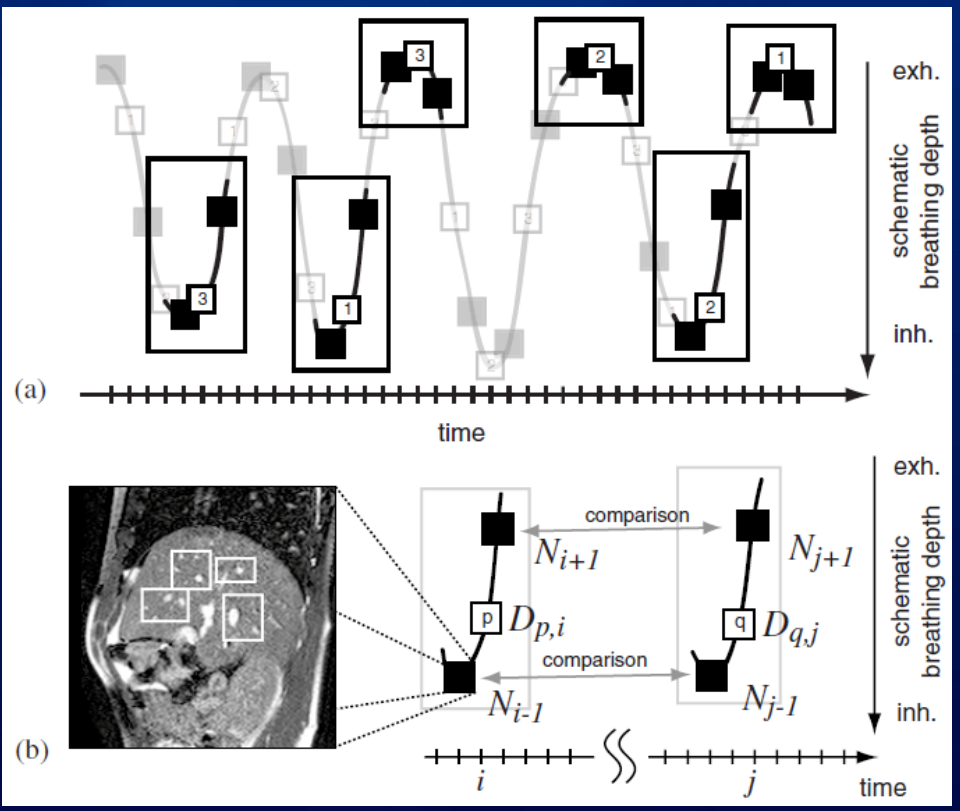
IIc. Offline motion:
Retrospective binning of multi-slice 2D MRI to derive virtual 3D cine MRI

- **Each pair of consecutive or "embracing" navigator frames defines a liver "state" for sorting from which an entire 3D volume can be reconstructed.**



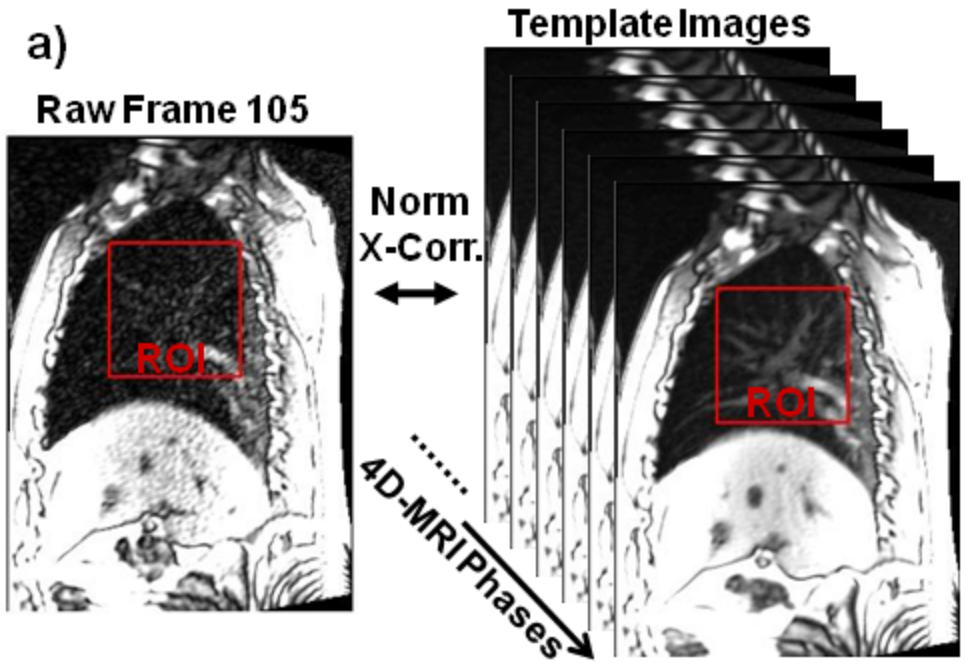
$$c(i,j) = \sum_{r=1}^{P} \left\| \begin{pmatrix} x^r_{j-1} - x^r_{i-1} \\ y^r_{j-1} - y^r_{i-1} \end{pmatrix} + \begin{pmatrix} x^r_{j+1} - x^r_{i+1} \\ y^r_{j+1} - y^r_{i+1} \end{pmatrix} \right\|$$

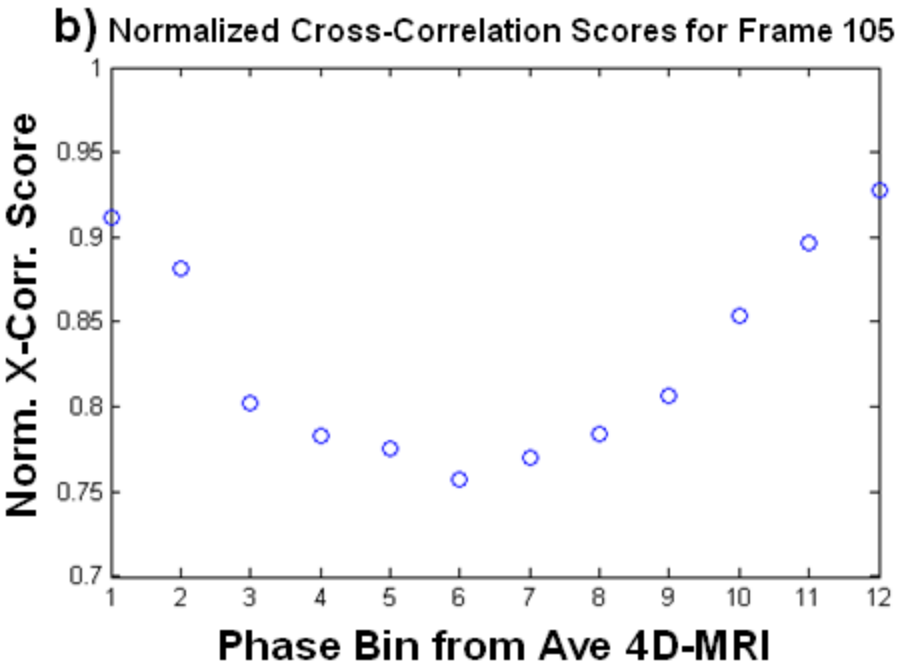
$$= \sum_{r=1}^{P} \left\| \Delta \vec{X}^r_{-1} + \Delta \vec{X}^r_{+1} \right\|.$$

Cost function:
combines template-matching-derived shifts from multiple ROIs within the 2D navigator

IIc. Offline motion:
Retrospective binning of multi-slice cine 2D MRI to representative "4D-MRI"

- **First pass reconstruction based on bellows – all frames/bin were averaged**
- **Normalized cross-correlation based scoring to determine best matching frames for 2nd pass reconstruction:**





- **Clear indication of best matching phase (despite poor SNR in raw image in this case)**

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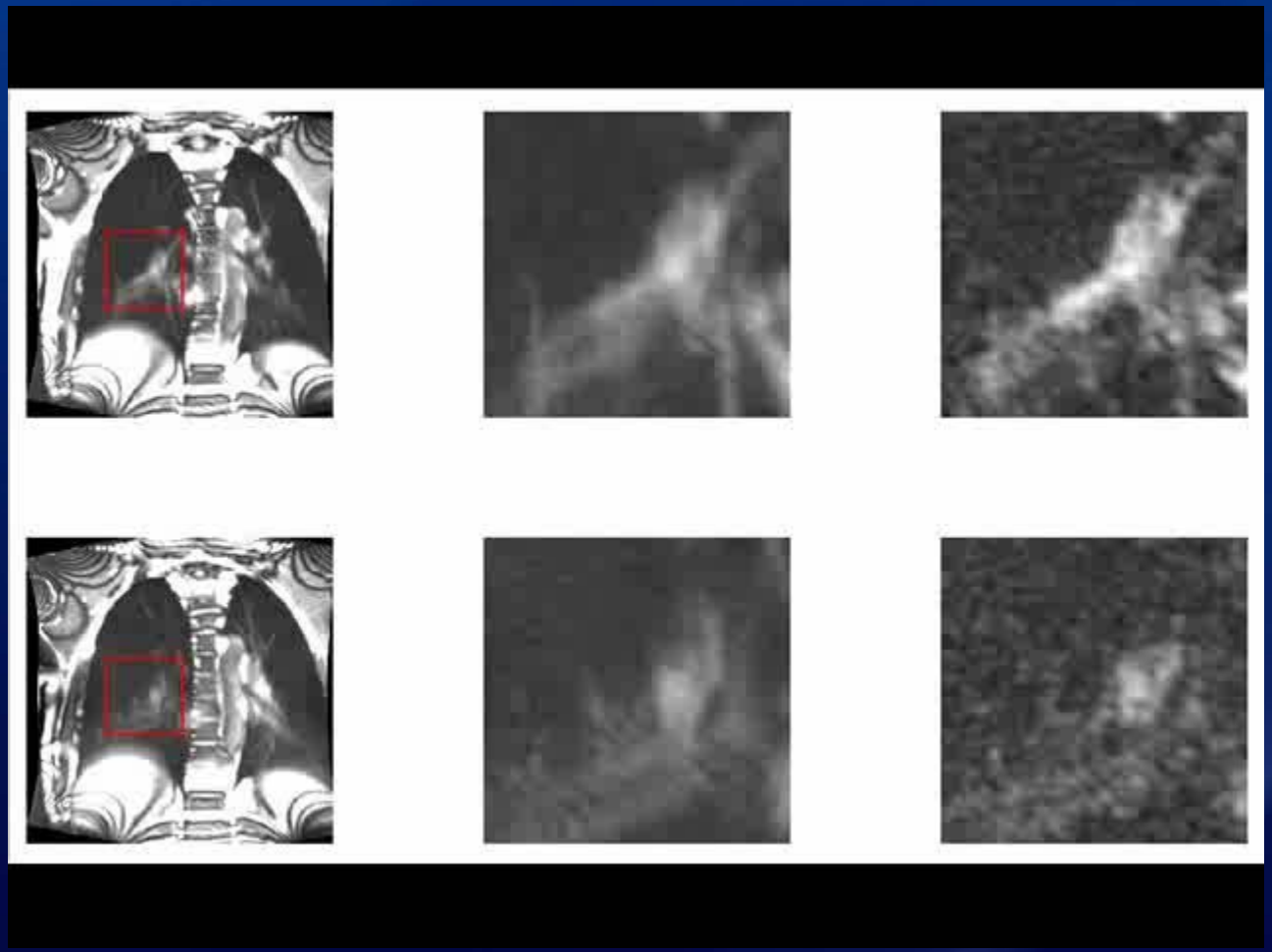
Tryggestad E. et al. [Med. Phys. 2013; 40 (5): 051909]

IIc. Offline motion:
Retrospective binning of multi-slice cine 2D MRI to representative "4D-MRI"

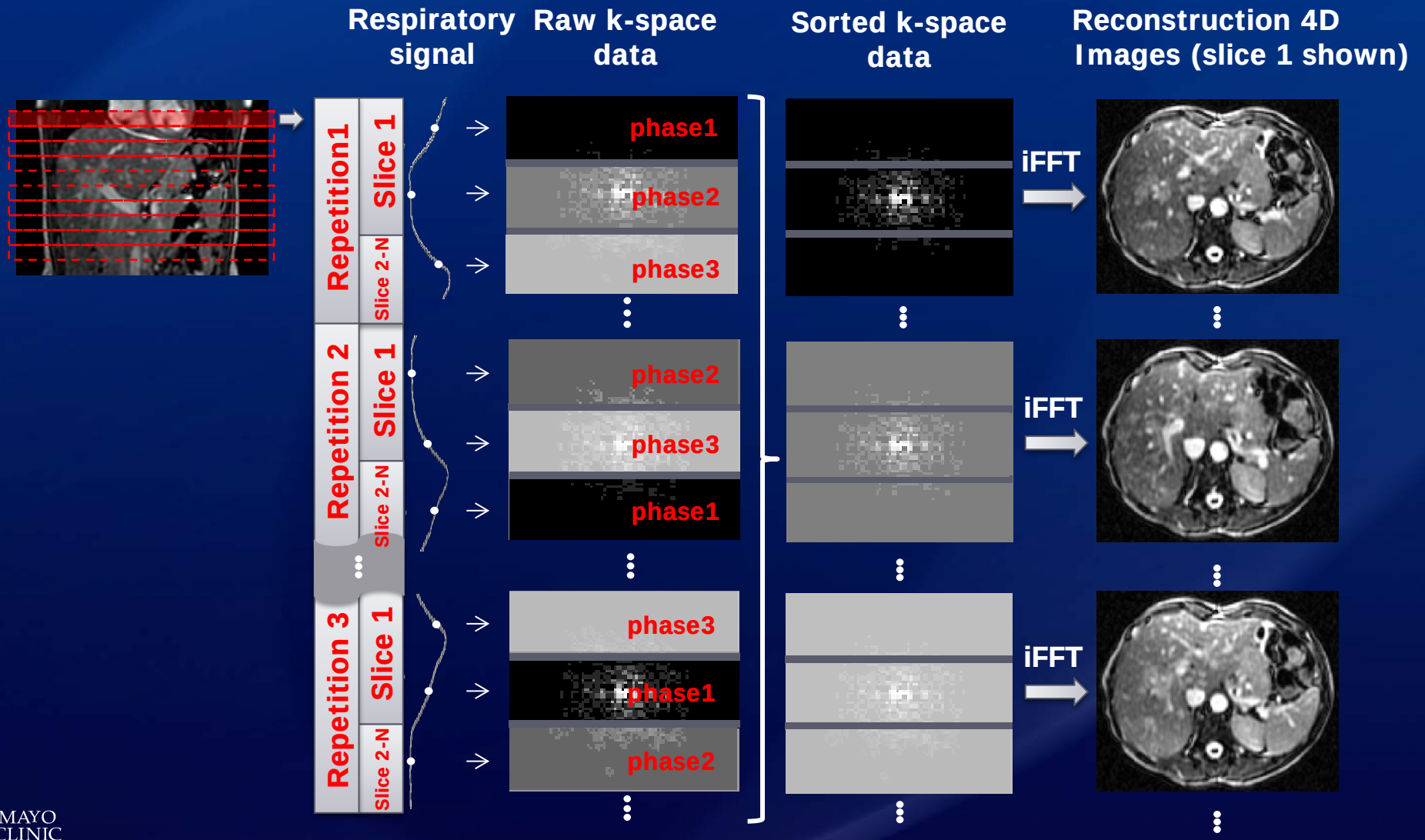


- bSSFP in lung volunteer (dark blood pulse on)
- Subject imaged for 30 minutes continuously
- 1st- Pass result derived from respiratory phase binning
- 10-phase reconstruction

Tryggestad E. et al. [Med. Phys. 2013; 40 (5): 051909]

IIc. Offline motion:
Retrospective binning of multi-slice cine 2D MRI to representative “4D-MRI”

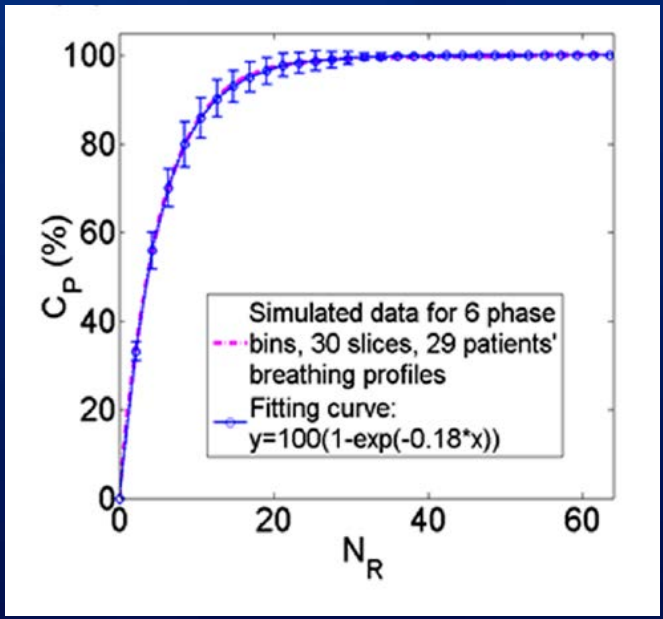
- **k-space binning with T2-weighted sequence**



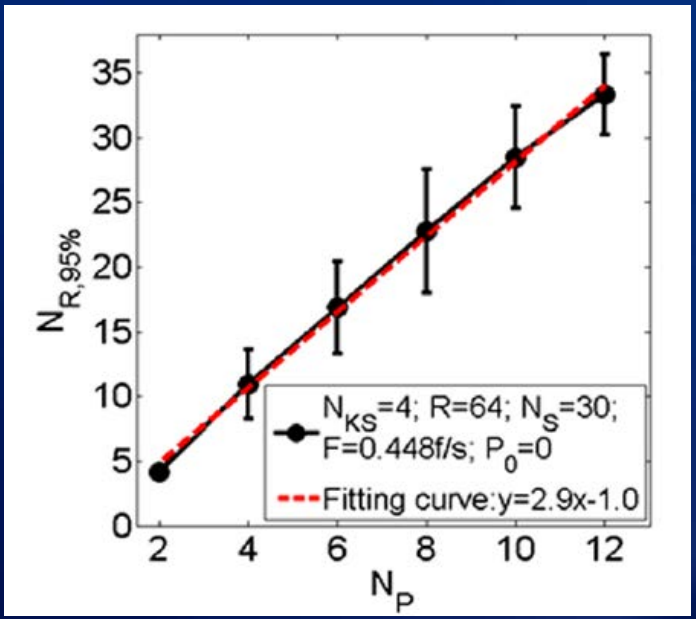
Liu Y. et al. [Med. Phys. 2015; 42 (2): 534]

IIc. Offline motion:
Retrospective binning of multi-slice cine 2D MRI to representative "4D-MRI"

- **For retrospective binning with un-triggered cine 2D multi-slice acquisition, how do we know how many repetitions over set of slices to fill all 4D bins per slice location?**



%-completeness of k-space filling (over all slices/bins)



Number of repetitions required for 95% completeness

Liu Y. et al. [Med. Phys. 2015; 42 (2): 534]

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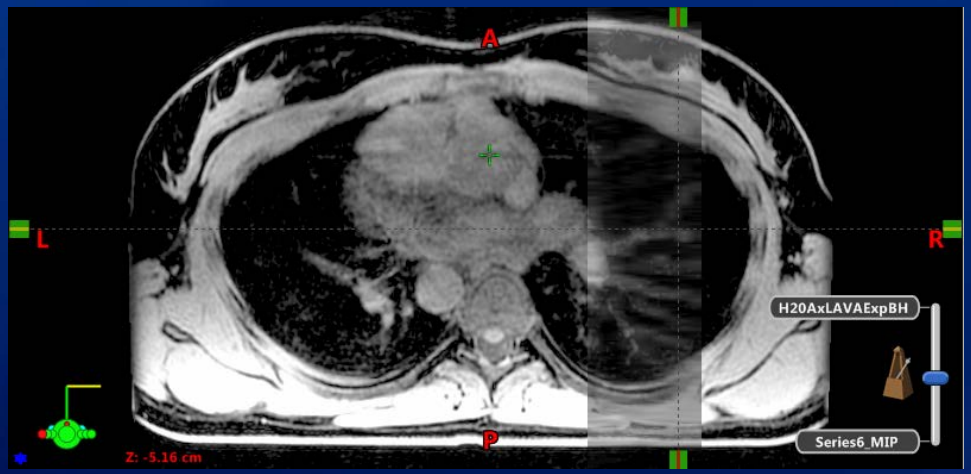
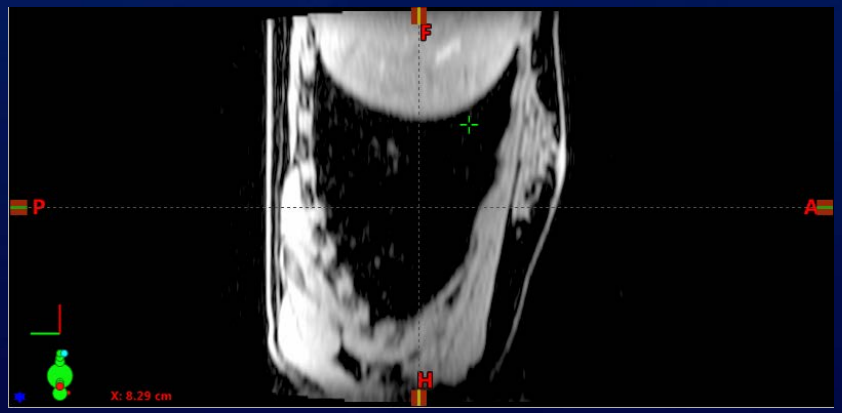
IIc. Offline motion:
3D MIP generation using multi-slice cine 2D MRI

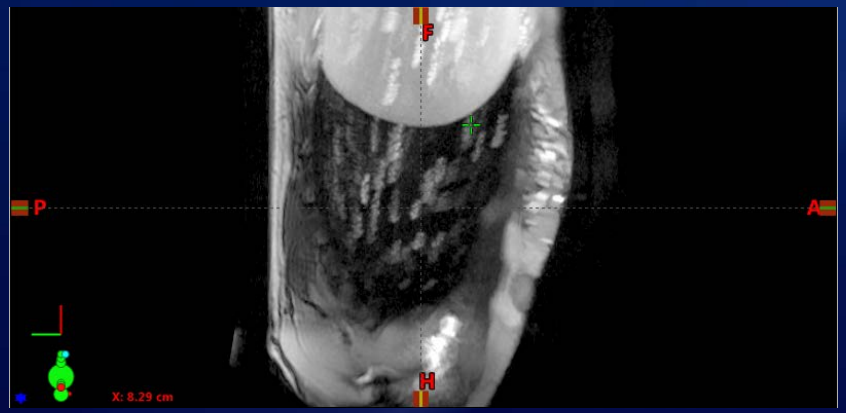
- **Potentially very practical, low-tech solution for ITV delineation**
- **Previously demonstrated by Adamson et al. [Med. Phys. 2010; 37 (11): 5914]**

In-house example using GE 750w 3T





3D LAVA Flex
breath-hold at end expiration



MIP from Sagittal FIESTA Multiphase
8 slices; 30 dynamics/repetitions

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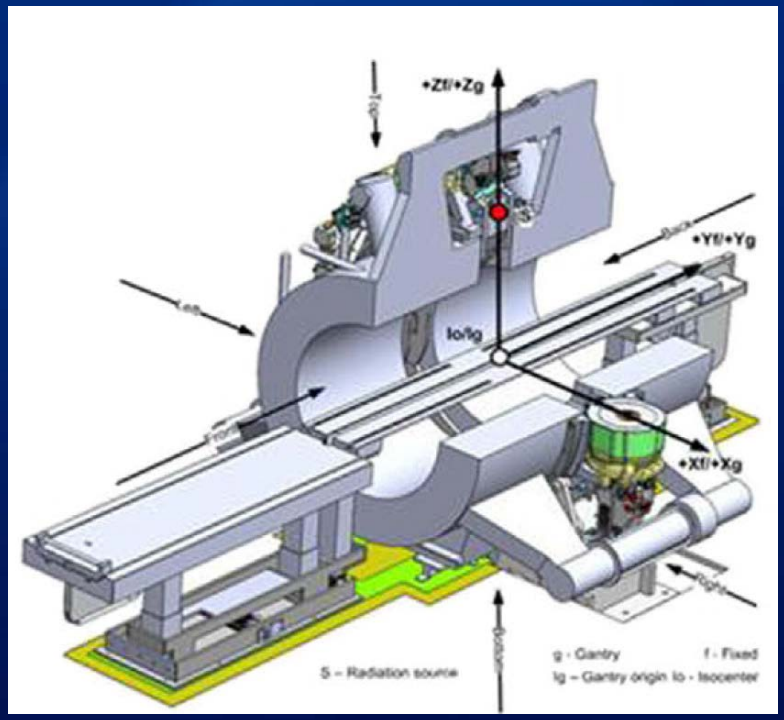
III. Motion online: Example ViewRay "MRIdian" system

Mutic and Dempsey [Semin. Radiat. Oncol. 2014; 24(3): 196]



[http://www.viewray.com/system]

- **Three-head ^{60}Cobalt teletherapy unit delivering IMRT**
- **On-board 0.35T MRI**
- **Cine 2D MRI and DIR-based real-time tracking for beam gating:**
  - Single sagittal plane at 4 frames/second
  - Three sagittal planes at 2 frames/second

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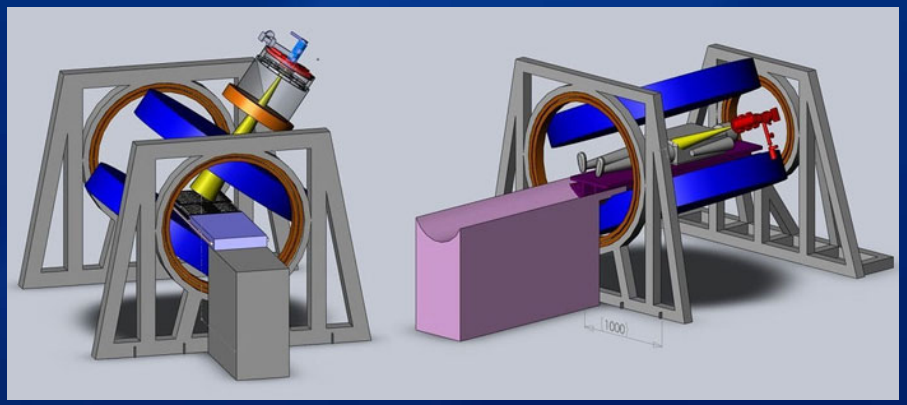
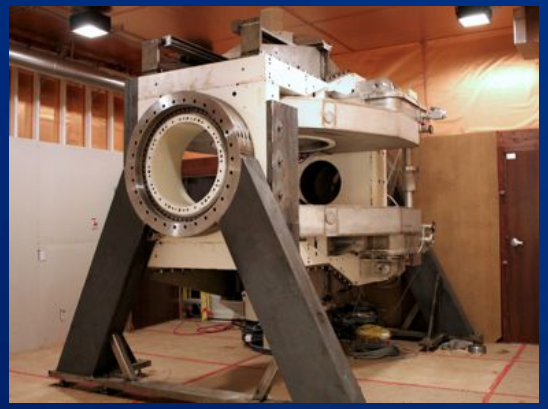
III. Motion online: Example from hybrid linac-MRI

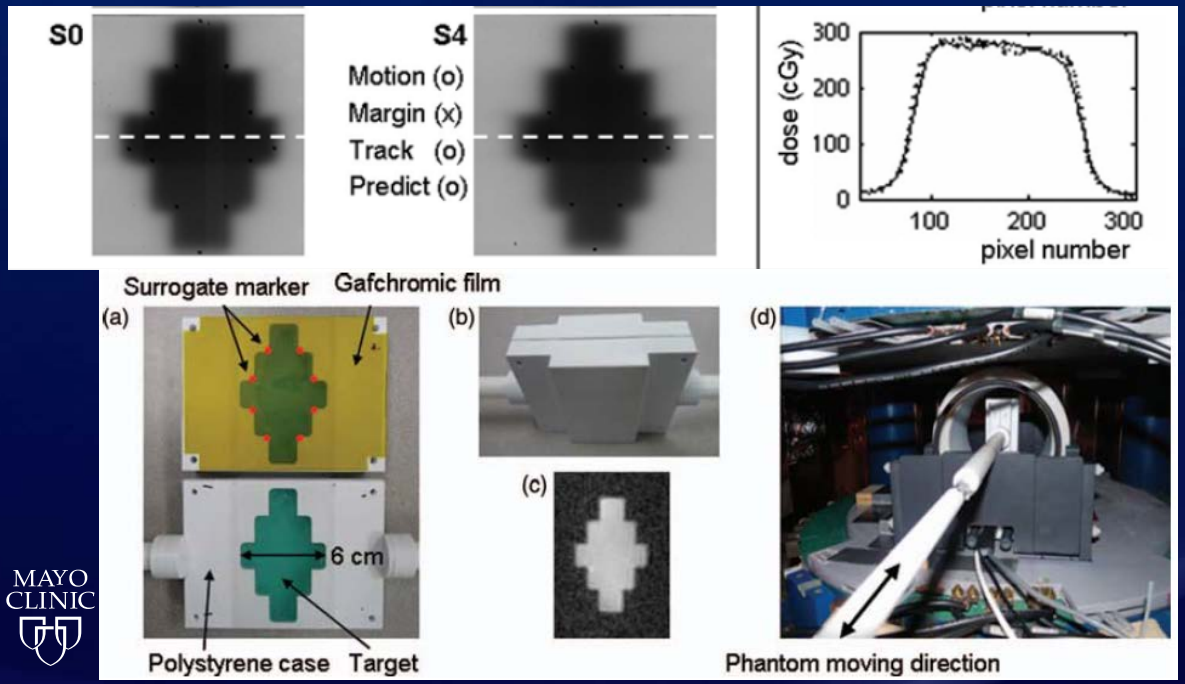
Cross Cancer Institute, Edmonton, Canada

[http://medicalphysicsweb.org/cws/article/research/50521] *[http://www.mp.med.ualberta.ca/linac-mr/index.html]*





Yun et al. [Med. Phys. 2013; 40 (5): 051718]



Demonstration of MLC-tracked delivery to 1D motion phantom:

- **0.2 Tesla B0 Field**
- **Varian 52-leaf MK-II MLC**
- **Cine 2D (single-slice) bSSFP sequence**
- **Predictive tracking algorithm**

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Conclusion:

We are at the dawn of a new era in clinical implementation of MRI-based motion characterization and management!