Resolving and characterizing breathing motion for radiotherapy with MRI

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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
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
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
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
Ic. 2D vs. 3D sequences – primer

2D:
- Excitation of tissue slab (thickness dictated by slice profile) via slice selection gradient
- Duration per slice = \( TR \times NPy \times Nex \)
  
  \( NPy = \text{number of phase encoding steps, hence number of rows} \)
  
  \( Nex = \text{number of (slab) excitations (or TR repetitions)} \)
- 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 = \( TR \times NPy \times NPz \times Nex \)
  
  \( NPz = \text{Number of phase encoding steps in the z-axis} \)
- 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

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

Single-slice-plane acquisition
1. Lung: Koch et al. [IJROBP 2004; 60 (5): 1459]
   [IJROBP 2007; 60(3): 895]

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)

Interleaved (sagittal-coronal-sagittal-coronal...)
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
IIa&b. Offline motion: Template matching with orthogonal slice planes

- Cross-correlation-based template matching


Imaging time:
- 13 min.
- 12 min.
- 9 min.
IIb&c. What is a “cross-correlation” in image processing?

Normalized cross-correlation:

$$ncc_{k,N} = \frac{\sum_{i,j} (I_k \cdot I_N)}{\sqrt{\sum_{i,j} (I_k \cdot I_k) \times \sum_{i,j} (I_N \cdot I_N)}}$$
Ila&b. Offline motion: Template matching with orthogonal slice planes

- Results for volunteer “S3”

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

• Results from a numerical simulation:
  • 3 cm spherical lesion
  • $\text{ITV}_1$ was determined during first 60 seconds of tracking

Ilia&b. Simultaneous monitoring of motion surrogates

Respiratory bellows system [Picture: GE]

Example: PMU (Physiological Monitoring Unit, Siemens)
IIa&b. Simultaneous monitoring of motion surrogates

Diaphragmatic monitoring with edge detection filter
IIa&b. Simultaneous monitoring of motion surrogates

- **USE CAUTION** when employing bellows-type systems
IIa&b. Simultaneous monitoring of motion surrogates

- External markers (belts/tubes around patient)

Koch et al. [IJROBP 2004; 60 (5): 1459]
IIa & b. Simultaneous monitoring of motion surrogates

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

External markers providing 3D information from single-plane tracking
IIa&b. Simultaneous monitoring of motion surrogates

- Thresholded/segmented “Body Area”

Cai et al.

R. Farah and J. Lee [WIP / JHU]
“4D-MRI reconstruction using group-wise registration.”
AAPM 2015. Snap oral: SU-F-303-1
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)]
Ilc. 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 mm² pixels in plane
- 5 mm slice profile
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):**
3. Farah and Lee et al. [WIP JHU]
   "4D-MRI reconstruction using group-wise registration."
   **AAPM 2015. Snap oral: SU-F-303-1**
   *k-space binning*
   *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*
Ilc. 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
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.

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)*

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

- First-pass 4D-MRI (ROI for NormXCorr)
- First-pass 4D-MRI (Zoomed)
- Second-pass 4D-MRI (Zoomed)

- Slice 17/20
- Slice 19/20

- 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

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

- k-space binning with T2-weighted sequence

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?

\[
\%	ext{-completeness of k-space filling (over all slices/bins)}
\]

\[
\text{Number of repetitions required for 95\% completeness}
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Ilc. Offline motion: 3D MIP generation using multi-slice cine 2D MRI

- Potentially very practical, low-tech solution for ITV delineation

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
III. Motion online: Example ViewRay “MRIdian” 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
III. Motion online: Example from hybrid linac-MRI

Cross Cancer Institute, Edmonton, Canada


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
Conclusion:

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