Advances in MRI-based Motion Management for Radiation Therapy

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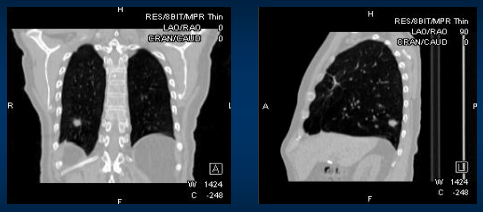
2017 AAPM 59th Annual Meeting, Denver, CO

Outline

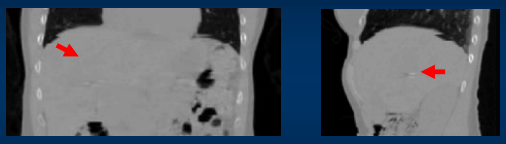
- Review of current MRI techniques for motion management
- Advances in MRI technique for simulation
  - 4D-MRI using 2D acquisition
  - 4D-MRI using 3D acquisition
- Advances in MRI technique for treatment delivery
  - 4D-MRI with highlighted vessels
  - On-board 4D-MRI
- Other advances
  - Hyperpolarized gas tagging MRI

Motion Imaging in RT



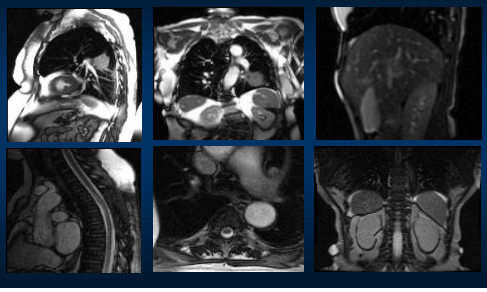
- 4D-CT is the current clinical standard for motion imaging
- Excellent contrast in the lung to reveal lung tumor motion

Limitations of 4D-CT in Imaging Abdominal Cancers

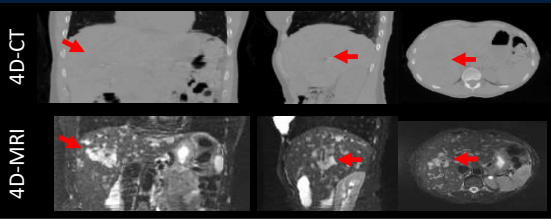


- 4D-CT suffer insufficient contrast in the abdomen to reveal tumor motion, leading to potential errors

Imaging Motion Using MRI

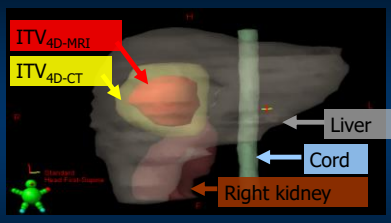


4D-MRI for RT



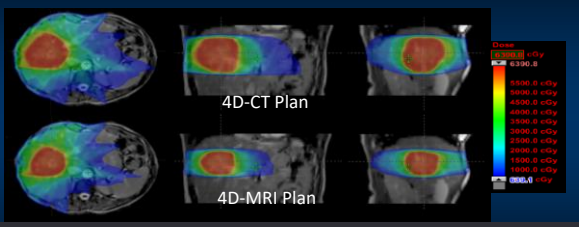
- Compared to 4D-CT, 4D-MRI improves tumor contrast and tumor motion measurement for abdominal cancers.

Target Volume: 4D-MRI vs 4D-CT



- 4D-MRI leads to smaller target volume (54.0 cc in 4D-MRI, 104.8 cc in 4D-CT) with reduced safety margin

Treatment Plan: 4D-MRI vs 4D-CT



- 4D-MRI plan spared more healthy liver tissue than 4D-CT plan.
- Mean dose to liver: 20.7 Gy ~ 34.2 Gy for 4D-MRI and 4D-CT.

Size Matters

Be SMART

4D-MRI Strategies

	2D Acquisition	3D Acquisition
Retrospective	I	II
Prospective	III	IV

Based on 2D Acqusition

- fast 2D MR sequence + breathing signal
- image processing, relatively easy to implement
- limited selections of usable MR sequences

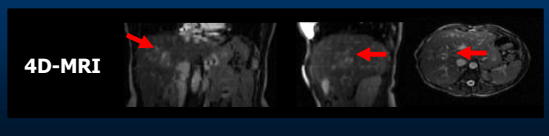
Based on 3D Acqusition

- fast 3D MR sequence + breathing signal
- more challenging, MR sequence development
- hardware and software demanding

4D-MRI Using Cine 2D Acquisition

True fast imaging with steady-state free precession (TrueFISP, FIESTA)

- T2/T1-w
- 3-10 frames/sec
- Phase sorting



4D-MRI Using Sequential 2D Acquisition

Single-Shot Fast Spin-Echo (SSFSE, HASTE)

- T2-w
- ~ 2 frame/sec

Sequential / Interleave Acquisition

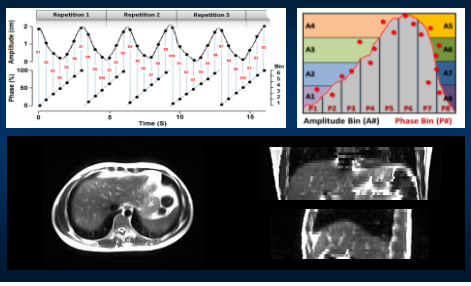
To obtain different phases at each slice

Repeat Volume Measurement

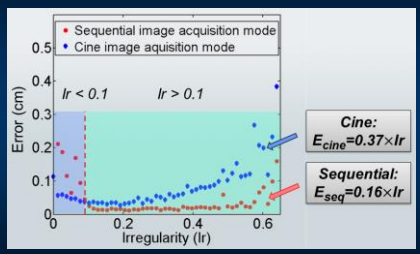
To satisfy data sufficient condition

Determine Minimal # of Repetitions (N_R)

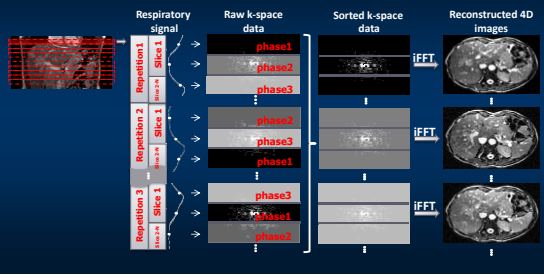
4D-MRI Using Sequential 2D Acquisition



4D-MRI Image Quality: Cine ~ Sequential



2D Acquisition with K-space Sorting



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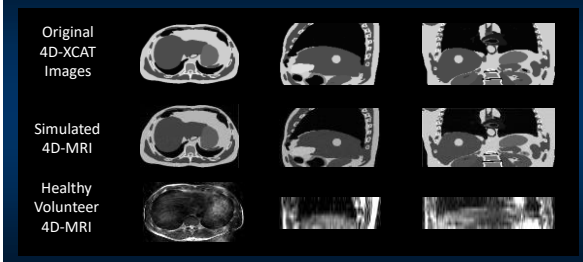
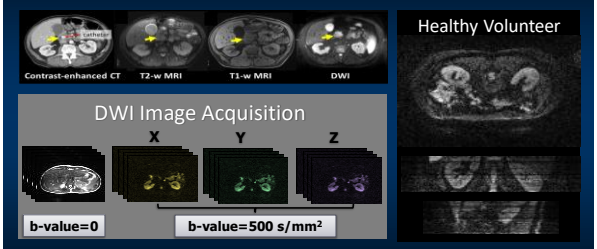
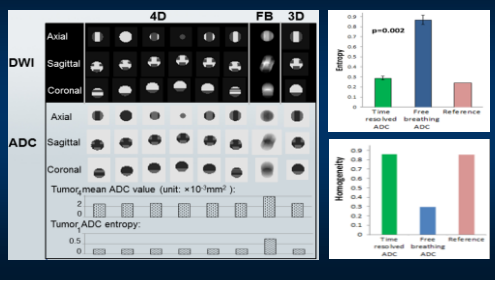


Diffusion-weighted 4D-MRI: 4D-DWI

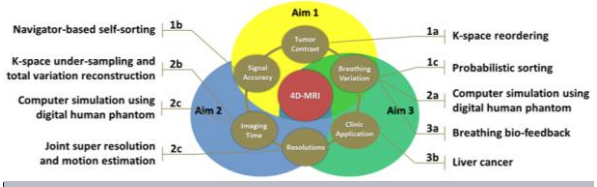


Collaboration with Siemens

Diffusion-weighted 4D-MRI: 4D-DWI

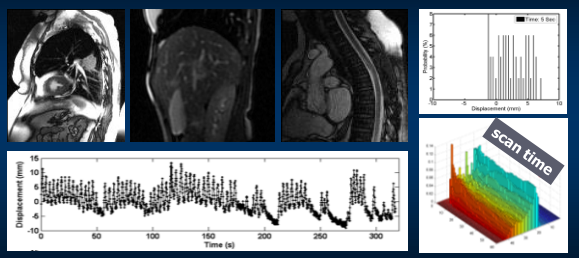


Challenges for 4D-MRI Development

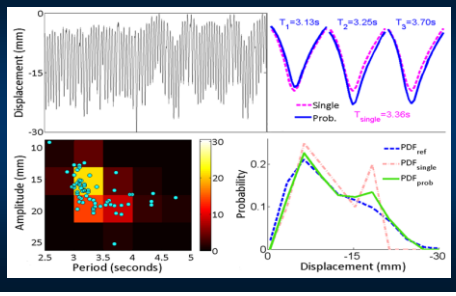


- suboptimal or inconsistent tumor contrast
- long image acquisition times
- insufficient temporal and spatial resolution
- inaccurate breathing signals
- poor handling of breathing variation
- lack of patient validation and applications

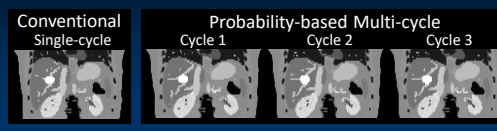
Motion Probability Density Function (PDF)

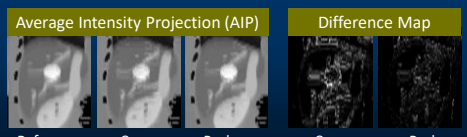


PDF-driven Sorting Multi-cycle Recon

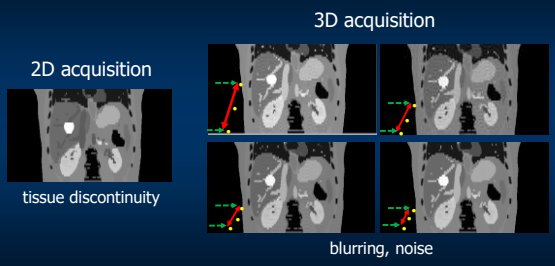


PDF-driven Sorting Multi-cycle Recon: 2D

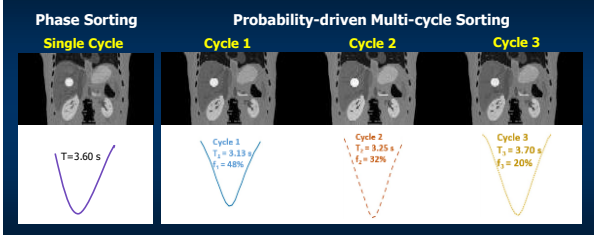


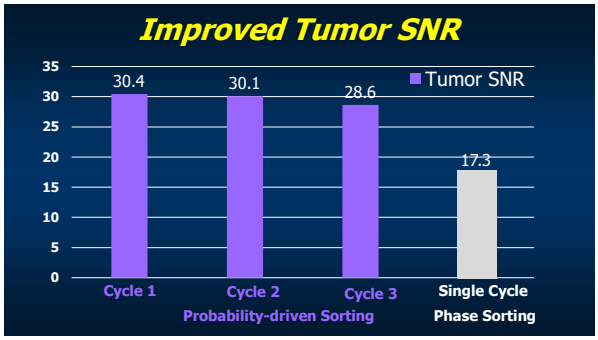


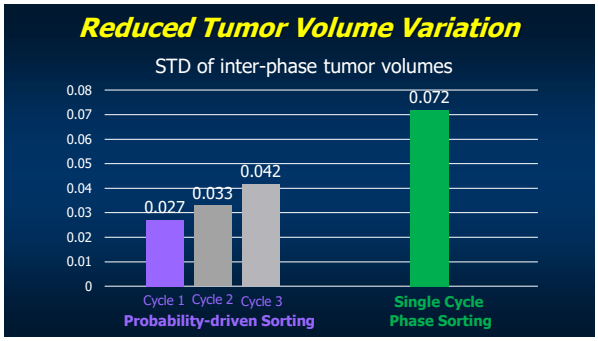
PDF-driven Sorting Multi-cycle Recon: 3D

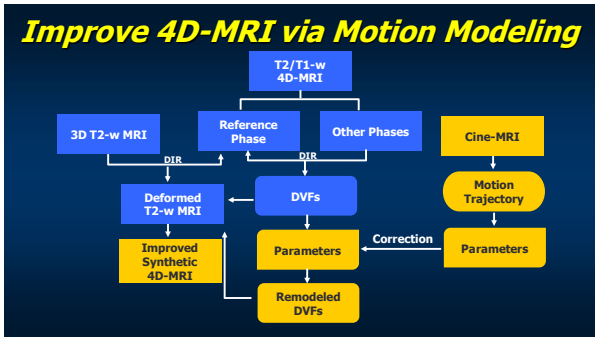


PDF-driven Sorting Multi-cycle Recon: 3D

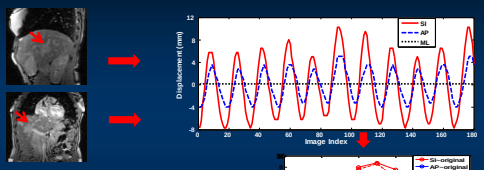


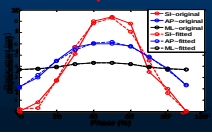

Improved Tumor SNR
Tumor SNR
35
30
25
20
15
10
5
0
30.4
30.1
28.6
17.3
Cycle 1
Cycle 2
Cycle 3
Probability-driven Sorting
Single Cycle
Phase Sorting


Reduced Tumor Volume Variation
STD of inter-phase tumor volumes
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.027
0.033
0.042
0.072
Cycle 1
Cycle 2
Cycle 3
Probability-driven Sorting
Single Cycle
Phase Sorting


Improve 4D-MRI via Motion Modeling
T2/T1-w
4D-MRI
3D T2-w MRI
Reference
Phase
Other Phases
Cine-MRI
DIR
DIR
Deformed
T2-w MRI
DVFs
Motion
Trajectory
Improved
Synthetic
4D-MRI
Parameters
Correction
Parameters
Remodeled
DVFs

Improve 4D-MRI via Motion Modeling





- **Normalized cross correlation (NCC) based tracking technique**
- **A quartic polynomial formula was used to fit the motion trajectories**

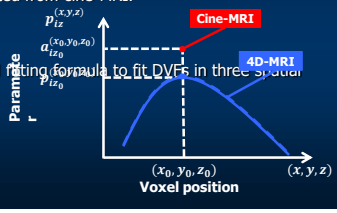
Improve 4D-MRI via Motion Modeling

- DVF temporal fitting

  To correct the motion estimated from 4D-MRI DVFs by incorporating motion information extracted from cine-MRI.

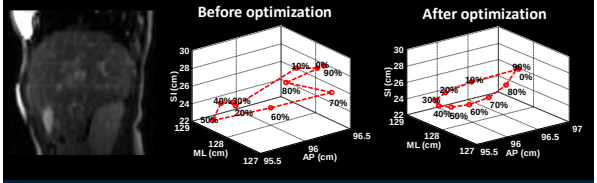
- DVF spatial fitting

  Using a quartic polynomial fitting formula to fit DVFs in three spatial dimensions.



Improve 4D-MRI via Motion Modeling

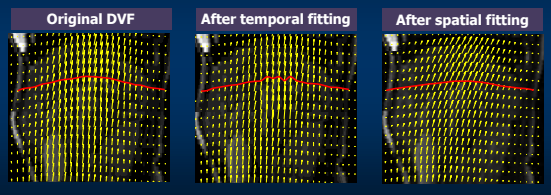
Temporal fitting



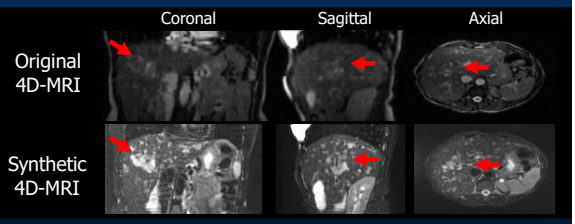
- Voxel-wise motion modeling and optimization

Improve 4D-MRI via Motion Modeling

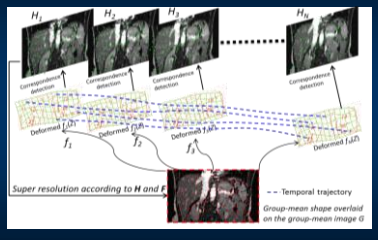
Spatial fitting



Improve 4D-MRI via Motion Modeling Patient Example



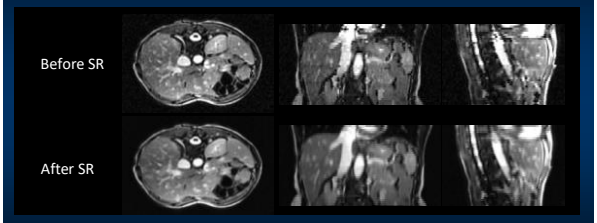
Super Resolution 4D-MRI



Groupwise registration for motion estimation and spatiotemporal resolution enhancement

Collaboration with Dr. DG Shen, UNC Chapel Hill

Super Resolution 4D-MRI



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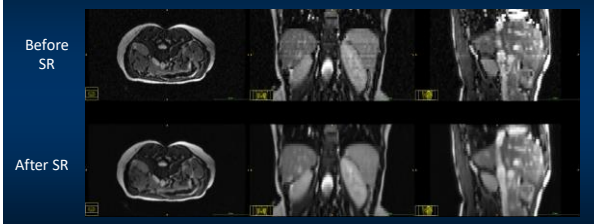
Super Resolution 4D-MRI



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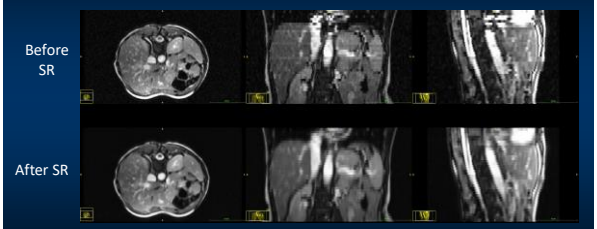
Super Resolution 4D-MRI



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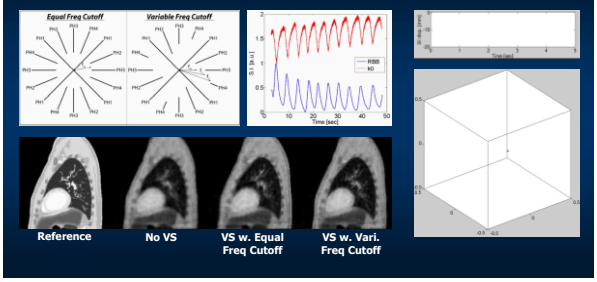
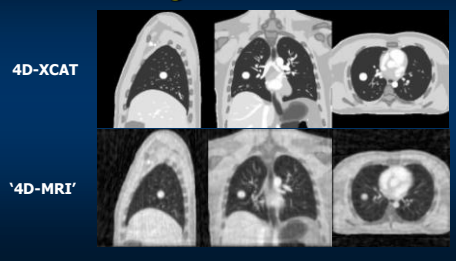
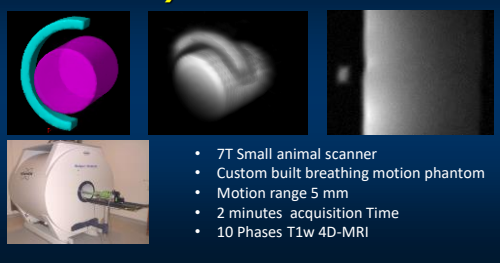
Fast 4D-MRI with View Sharing



Fast 4D-MRI with View Sharing Digital Phantom

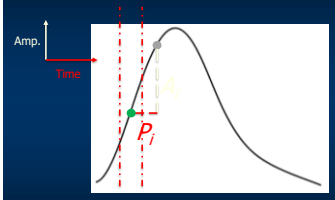


Fast 4D-MRI with View Sharing Physical Phantom



- 7T Small animal scanner
- Custom built breathing motion phantom
- Motion range 5 mm
- 2 minutes acquisition Time
- 10 Phases T1w 4D-MRI

Fast Robust 4D-MRI through Spatiotemperal Constrained Sorting and Compressed Sensing Reconstruction



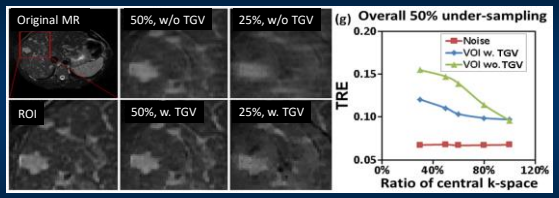
For each k-data point (k_{xyz}, t):

A_i : Amplitude difference to phase bin center

P_i : Phase (percentage) difference to phase bin center

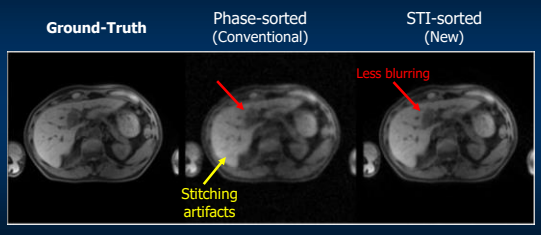
$$STI_i(k_{xyz},t) = \sqrt{\left(\frac{A_i(k_{xyz},t)}{A_t(k_{xyz})}\right)^2 + \left(\frac{P_i(k_{xyz},t)}{P_t}\right)^2}, \quad i = 1,2,..10$$

Fast Robust 4D-MRI through Spatiotemperal Constrained Sorting and Compressed Sensing Reconstruction

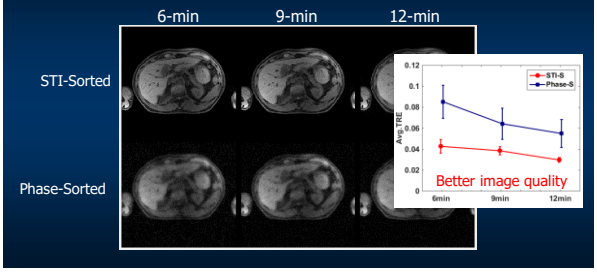


- Total generalized variation (TGV) reconstruction algorithm to maximally recover the missing information, to determine optimal k-space under-sampling pattern for various MR sequences

Fast Robust 4D-MRI through Spatiotemperal Constrained Sorting and Compressed Sensing Reconstruction

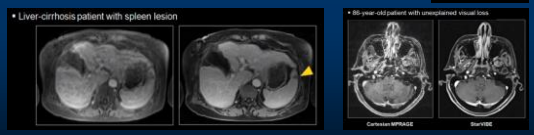


Fast Robust 4D-MRI through Spatiotemperal Constrained Sorting and Compressed Sensing Reconstruction



FREEZEit MRI

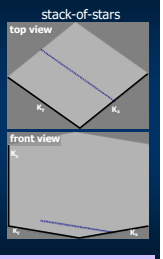
- TWIST-VIBE/StarVIBE/GRASP, Fat-suppressed T1-w 3D GRE
- Radial version of VIBE, Stacks of star k-space sampling
- Compressed sensing & parallel imaging
- High robustness to motion artifacts
- Thorax, abdomen, pelvis, DCE, 4D, cardiac



Siemens, NYU Langone Medical Center

3D VIBE GRE Pulse Sequence

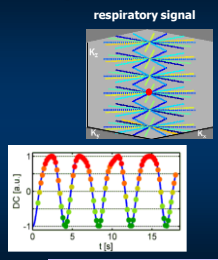
- A 3D stack-of-stars gradient echo sequence (3D VIBE GRE) with golden angle sampling of the radial views
- kx-ky: radial read out; kz: Cartesian encoding
- Golden-angle trajectory
  - $\phi_n = n \times 111.25\ (180/1.618)$
  - radial spokes never repeat
  - fill the largest gap by previous spokes
  - relative uniform k-space coverage
  - uncorrelated in temporal dimension



Slides courtesy: Li Pan, Siemens Healthineers
James Balter, University of Michigan

3D VIBE GRE Pulse Sequence

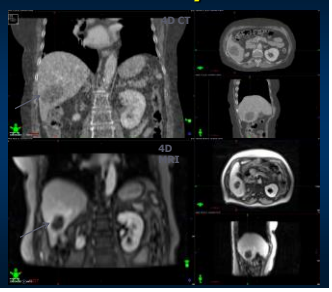
- A self-gating respiratory signal is derived from the k-space centers (kx = ky = 0, kz ~= 0), similar to the signal of a respiratory bellow
- Retrospectively binning of the radial spokes into multiple breathing states
- Uniform binning - evenly splits the data into a user-defined number of bins with equal number of radial spokes in each bin
- Ungated and binned images were reconstructed online



Slides courtesy: Li Pan, Siemens Healthineers
James Balter, University of Michigan

3D VIBE GRE: Patient Example

- Patient with Intrahepatic tumor
- 4D MRI provides much better soft tissue contrast and delineation of intrahepatic tumor compared to 4D CT



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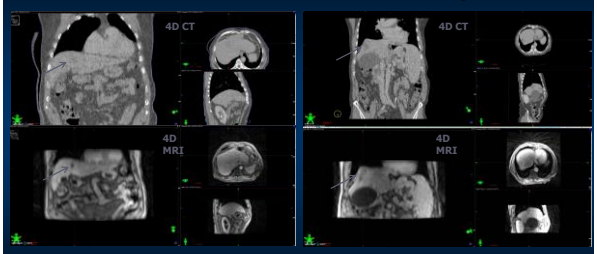

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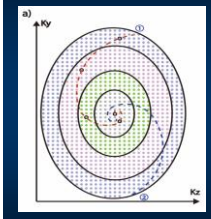
James Balter, University of Michigan

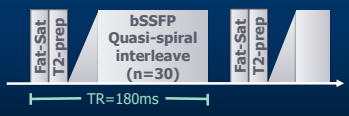
ROCK 4D-MRI: Methods



ROCK sampling pattern

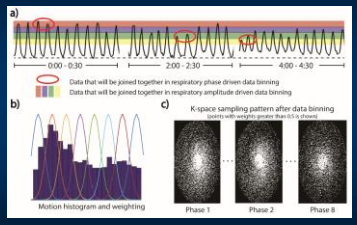
Respiratory motion-resolved, self-gated 4D-MRI using rotating Cartesian k-space (ROCK)

4D-MRI sequence using ROCK sampling pattern



Courtesy of P. Hu, PhD, UCLA

ROCK 4D-MRI: Methods

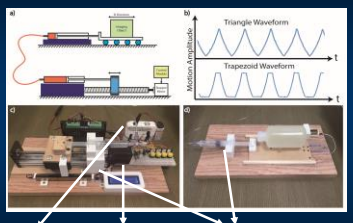


Data binning based on Respiratory Amplitude

- 8 respiratory bins
- Soft-gating approach

Courtesy of P. Hu, PhD, UCLA

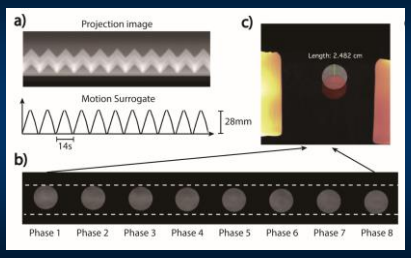
ROCK 4D-MRI: Phantom



Arduino Step Motor 3D printed parts

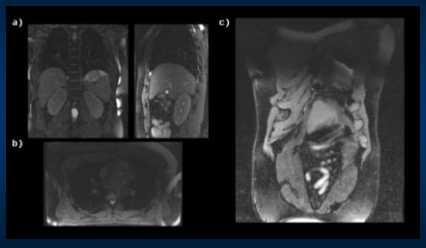
Courtesy of P. Hu, PhD, UCLA

ROCK 4D-MRI: Methods



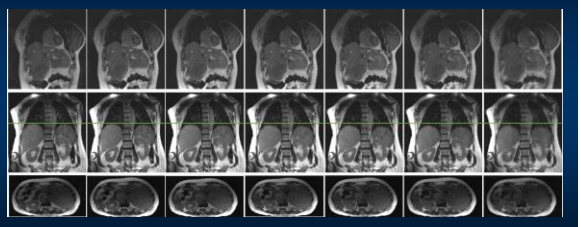
Courtesy of P. Hu, PhD, UCLA

ROCK 4D-MRI: 1.5T Siemens



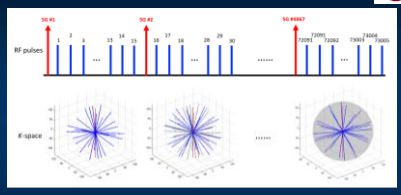
Courtesy of P. Hu, PhD, UCLA

ROCK 4D-MRI: 0.35T ViewRay



Courtesy of P. Hu, PhD, UCLA

4D-MRI for Vessel Highlight

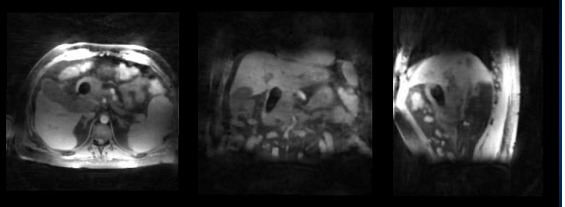


Courtesy of Wensha Yang, PhD

Deng Z et. al Magn Reson Med. 2015 May 14. PMID: 25981762

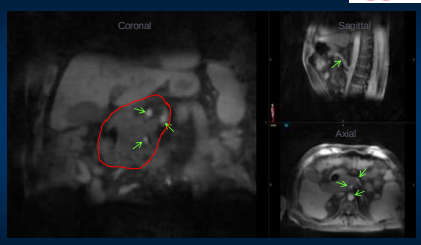
- Current sequence uses a Koosh-ball like sampling trajectory.
- Self-gating lines were inserted to guide data binning and reconstruction.
- A large axial slab (~40cm in SI direction) is excited.

4D-MRI for Vessel Highlight



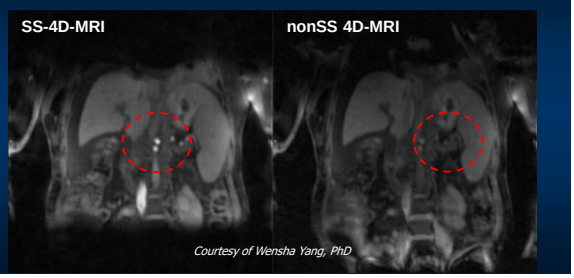
Courtesy of Wensha Yang, PhD

4D-MRI for Vessel Highlight

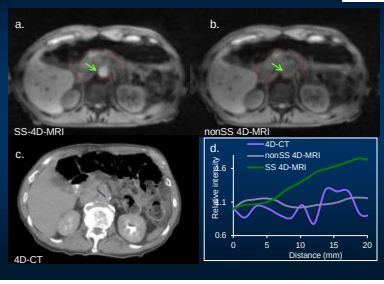


Courtesy of Wensha Yang, PhD

4D-MRI for Vessel Highlight



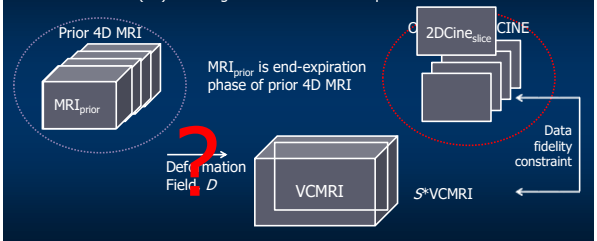
4D-MRI for Vessel Highlight



Courtesy of Wensha Yang, PhD

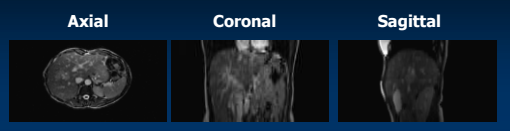
Volumetric Cine (VC) MRI

Volumetric cine (VC) MR images are estimated from prior 4D MRI and 2D cine MRI



Harris et al, Int. Journal Rad Onc Bio Phy, 2016

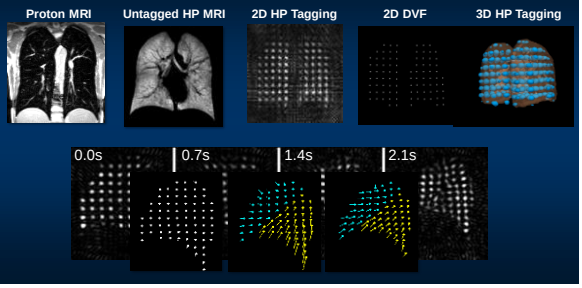
VC-MRI: Patient



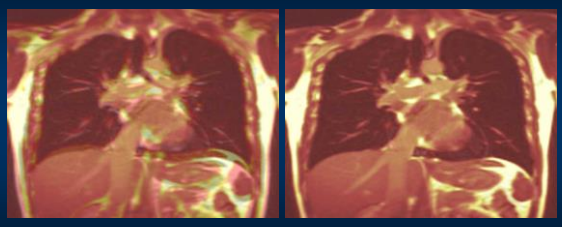
- VC-MRI generated based on patient motion modeling, and sparsely sampled 2D MR cine images.
- Real time volumetric MRI imaging
- Temporal resolution: up to 30 frames/s.
- Spatial resolution: 1.875 x1.875 x5mm

Harris et al, Int. Journal Rad Onc Bio Phy, 2016

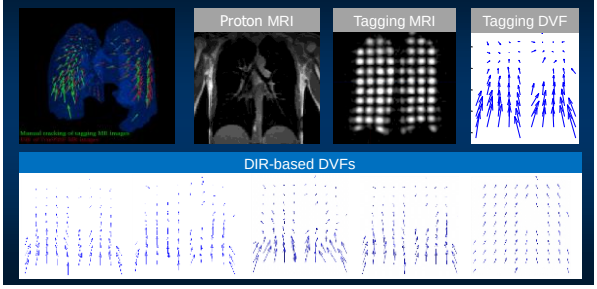
Hyperpolarized Gas Tagging MRI



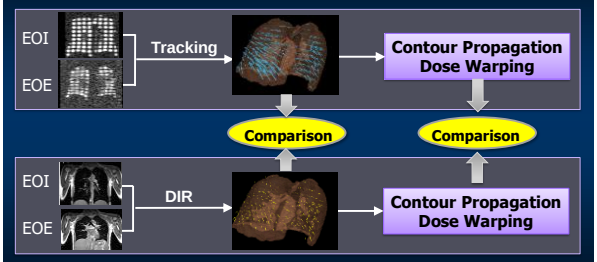
DIR of Proton MRI



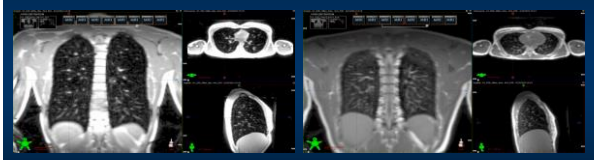
DVF Comparison: Tagging vs DIR



Tagging MRI for DVF Assessment

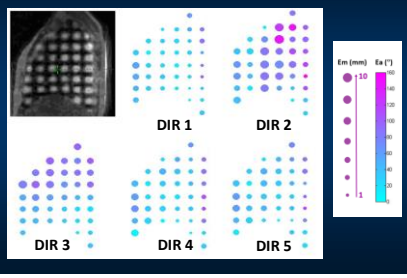


Hybrid Proton MRI and HP 3He Tagging MRI Acquisition



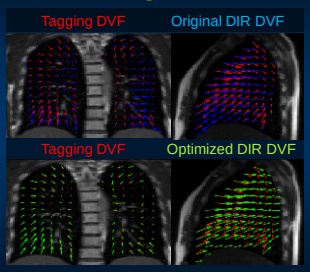
End of Inhalation End of Exhalation

Spatial Distribution of DVF Error



Physiological-based DVF Optimization

Original DVF
↓
1st Optimization based on Tagging DVF
↓
2nd Optimization based on Tagging Ventilation
↓
Optimized DVF



Summary

- MRI provides unique advantages over CT for motion management of abdominal cancers in RT.
- Current challenges in 4D-MRI include motion artifacts, limited spatial resolution, lack of internal features, etc.
- Fast MR imaging together with sophisticated sorting and reconstructions techniques hold great promises in improving 4D-MRI image quality.

Acknowledgements

Duke Radiation Oncology

Fang-Fang Yin, PhD
Mark Oldham, PhD
Jim Chang, PhD
Lei Ren, PhD
Brian Czito, MD
Manisha Palta, MD
Chris Kelsey, MD
Rachel Blitzblau, MD

Duke Radiology

Nan-kuei Chen, PhD
Paul Segars, PhD
Mustafa Bashir, MD
Michael Zalutsky, PhD

MDACC

Jihong Wang, PhD

UCLA

Yingli Yang, PhD

Siemens

Xiaodong Zhong, PhD
Brian Dale, PhD

UNC-CH Radiology

Dinggang Shen, PhD
Guorong Wu, PhD

Duke Department of Radiation Oncology