Development of 5D-MRI for Robust Radiation Therapy Applications

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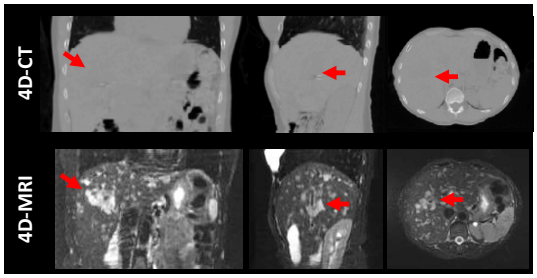
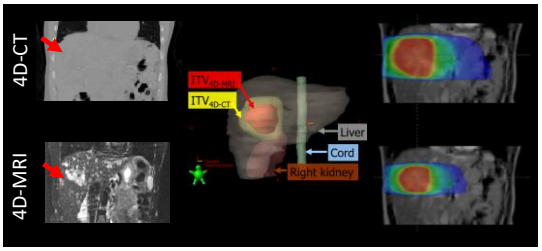
4D-MRI for Motion Management



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

4D-MRI for Motion Management



Treatment plan based on 4D-MRI spared more healthy liver tissue as compared to that based on 4D-CT. Mean dose to liver is 34.2 Gy in 4D-CT plan and 20.7 Gy in 4D-MRI plan.

4D-MRI Strategies

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

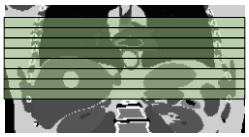
Based on 2D Acquisition

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

Based on 3D Acquisition

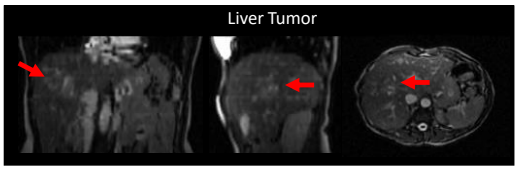
- fast 3D MR sequence + breathing signal
- more challenging, MR sequence development
- hardware and software demanding

4D-MRI Using Cine 2D Acquisition with Image Sorting

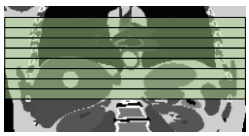


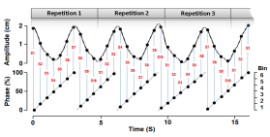
True fast imaging with steady-state free precession (TrueFISP, FIESTA)

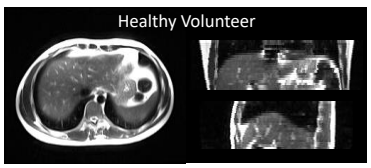
- T2/T1-w
- 3-10 frames/sec
- Phase sorting



4D-MRI Using Sequential 2D Acquisition with Image Sorting



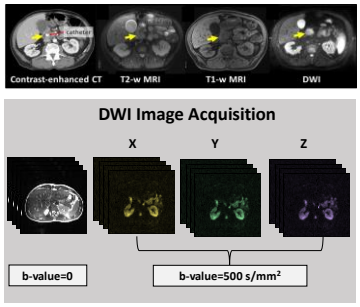


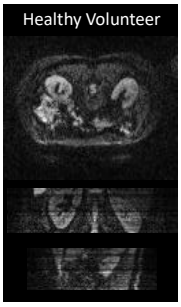


Single-Shot Fast Spin-Echo (SSFSE, HASTE)

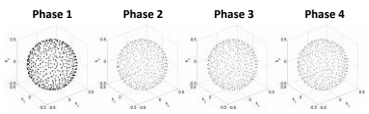
- T2-w,
- ~ 2 frames/s

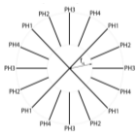
Diffusion-weighted 4D-MRI (4D-DWI)

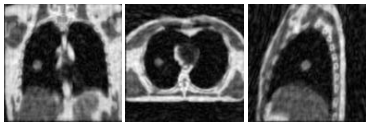


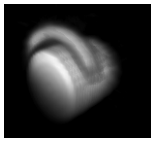


4D-MRI using 3D Acquisition with k-space Sorting





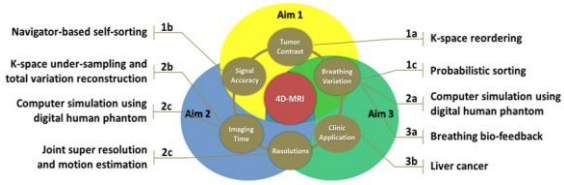




Subashi and Cai, 2017 AAPM

Current Challenges of 4D-MRI Development

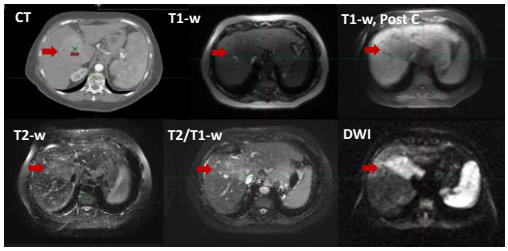
- suboptimal or inconsistent tumor contrast
- long image acquisition times
- insufficient temporal and spatial resolution
- inaccurate breathing signals
- poor handling of breathing variation
- lack of patient validation and applications



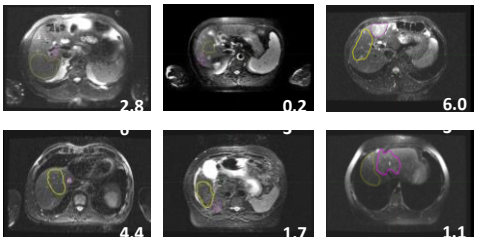
Current Challenges of 4D-MRI Development

- Despite many recent advances in 4D-MRI, current 4D-MRI technology has **inadequate image quality for precision radiotherapy applications** due to at least one of the following deficiencies: low temporal/spatial resolutions, **suboptimal/inconsistent contrast**, lack of anatomical details, and motion artifacts caused by breathing variations.
- These deficiencies have hampered 4D-MRI from becoming a clinical standard for radiotherapy of abdominal cancers, as well as from advancing precision radiotherapy through advanced applications .

Tumor Contrast: Inter-sequence Variation



Tumor Contrast: Inter-patient Variation

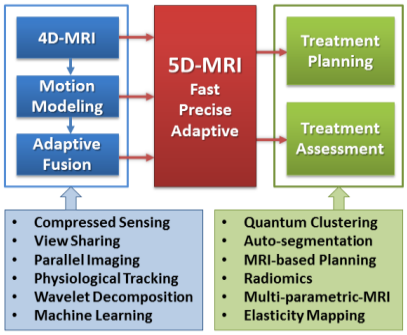


- Large inter-patient (range: 51.1-88.1%) variabilities in tumor contrast in MR images of liver cancer patients.

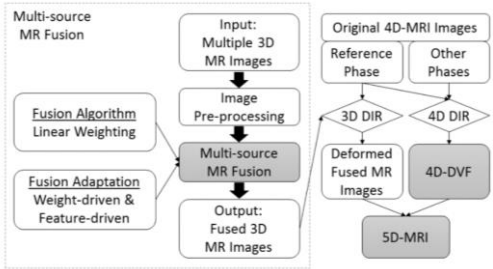
5D-MRI

- Take a systematic approach to comprehensively address the deficiencies of 4D-MRI by developing a *novel super-resolution 5D-MRI technology*.
- 5D-MRI is an extension of 4D-MRI, embedding all the characterizations of 4D-MRI with an additional dimension of "image contrast".
- The basic idea of 5D-MRI is to generate a series of synthetic 4D-MRI with versatile image contrast and improved image quality through a joint application of motion modeling and multi-parametric MRI fusion.

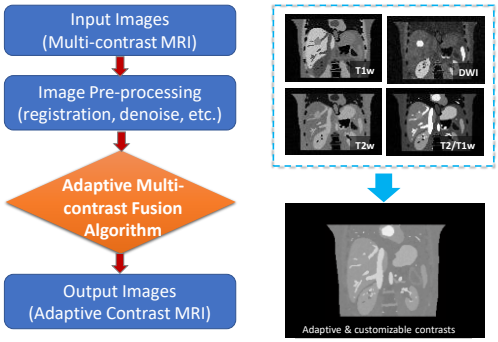
5D-MRI Overall Design



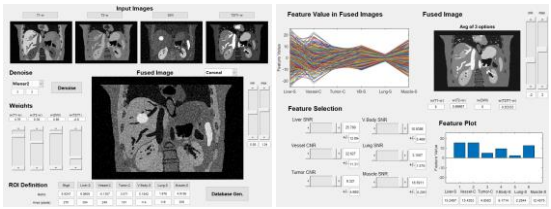
5D-MRI via Motion Modeling: Method and Workflow



Multi-parametric MRI Fusion



Multi-MRI Fusion Method



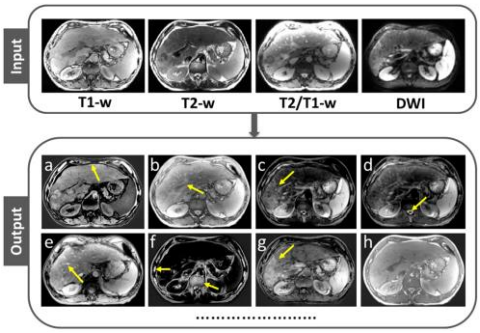
- Contrast adaption: input-driven, output-driven, AI-driven
- Fusion algorithm: linear-weighted fusion,
- Processing: prior generation of contrast library

Multi-MRI Fusion: Method

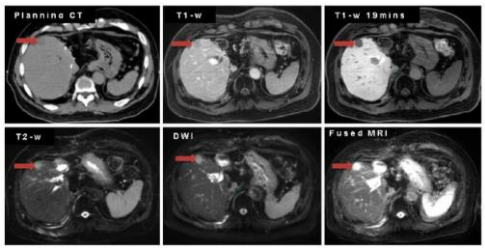
Fusion#	Weightings w(T1w)	w(T2w)	w(DWI)	w(T2/T1w)	Features Liver SNR	Vessel CNR	Tumor CNR	V.Body SNR	Lung SNR	Muscle SNR
235	-0.5	1	-0.5	1	3.35	12.18	1.02	2.57	0.14	4.47
236	-0.5	1	0	-1	-6.91	-1.60	3.15	2.12	-0.33	0.20
.	-0.5	1	0	-0.5	-3.40	3.76	4.48	3.92	0.17	2.68
.	-0.5	1	0	0	0.81	9.45	5.61	5.62	0.72	5.24
.	-0.5	1	0	0.5	4.77	14.13	6.24	6.80	1.19	7.27
240	-0.5	1	0	1	7.77	17.19	6.39	7.37	1.51	8.53
241	-0.5	1	0.5	-1	-2.62	-1.35	5.95	4.28	0.76	1.74
242	-0.5	1	0.5	-0.5	0.07	2.31	6.98	5.60	1.17	3.51
.	-0.5	1	0.5	0	2.97	6.17	7.84	6.83	1.56	5.29
.	-0.5	1	0.5	0.5	5.77	9.80	8.39	7.78	1.90	6.87
.	-0.5	1	0.5	1	8.16	12.83	8.60	8.40	2.15	8.09
246	-0.5	1	1	-1	-0.23	-0.99	6.08	4.44	1.10	2.10

Multi-MRI Fusion: Digital Phantom

Multi-MRI Fusion: Liver Tumor

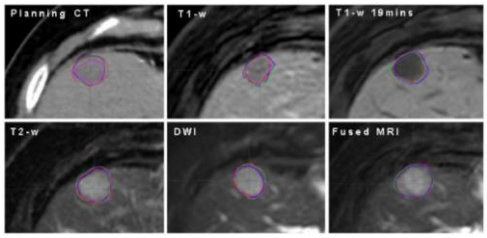


Multi-MRI Fusion: Liver Tumor



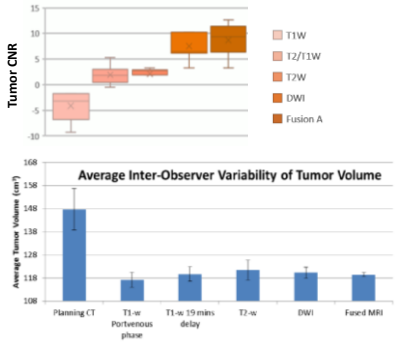
A representative patient that illustrates the tumor-to-tissue CNR for original MR sets. (T1-w, T1w 19mins, T2-w, DWI and Fused MRI were 1.57, 3.24, 2.23, 4.01, and 6.20 respectively)

Multi-MRI Fusion: Liver Tumor

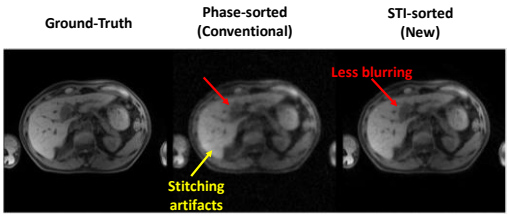


Liver tumor delineation in a representative patient that illustrates the inter observer variation in planning CT, original MR sets and fused MRI set.

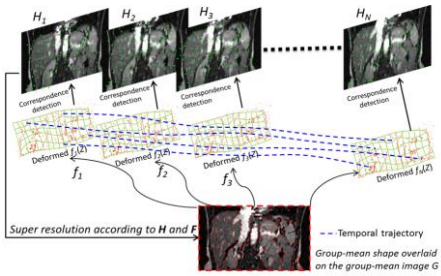
Multi-MRI Fusion: Improvement



Motion Robust 4D-MRI via Spatiotemperal Constrained Sorting and Compressed Sensing

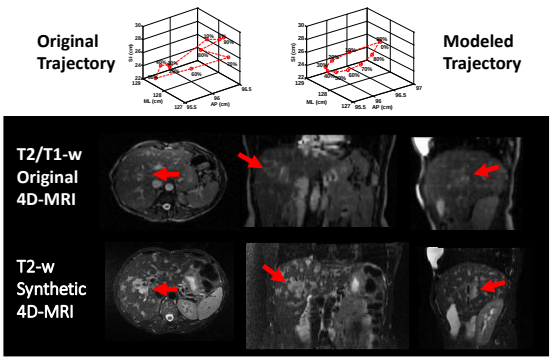


5D-MRI via Motion Modeling: Super Resolution

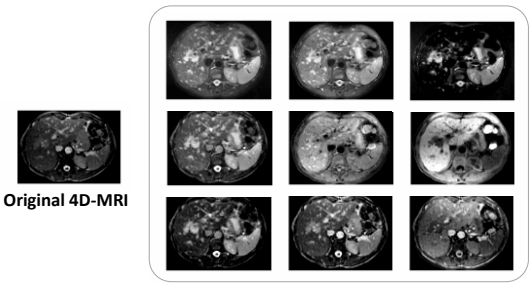


Collaboration with Dr. DG Shen, UNC Chapel Hill

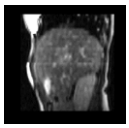
5D-MRI via Motion Modeling



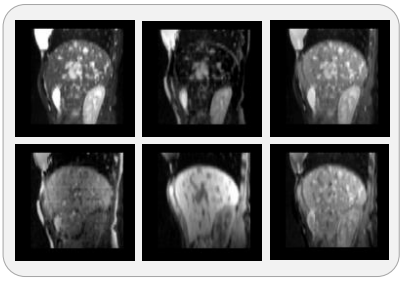
5D-MRI via Motion Modeling: Patient Example



5D-MRI via Motion Modeling: Patient Example

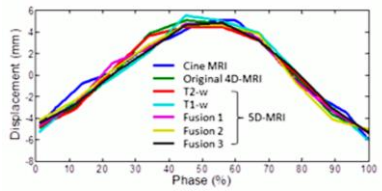


Original 4D-MRI



Synthetic Multi-contrast 4D-MRI: 5D-MRI

5D-MRI: Patient Example



	Original 4D-MRI (T2/T1-w)	5D-MRI				
		T2-w	T1-w	Fusion 1	Fusion 2	Fusion 3
D (mm)	0.592	0.523	0.561	0.403	0.428	0.402
CC	0.981	0.980	0.987	0.989	0.987	0.987

Summary

- Despite many recent advances in 4D-MRI, current 4D-MRI technology has **inadequate image quality for precision radiotherapy applications.**
- 5D-MRI is an extension of 4D-MRI, embedding all the characterizations of 4D-MRI with an additional dimension of "**image contrast**".
- Being able to provide versatile image contrast allows 5D-MRI for a wider clinical application, providing better and more consistent image quality, than 4D-MRI.

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