MRI Optimized for Radiation Therapy (MR-Guided RT)

Carri Glide-Hurst, Ph.D.
Director of Translational Research, Radiation Oncology, Henry Ford Health System
Associate Professor FTA, Wayne State University

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Disclosures

- Research funding provided by:
  - NIH R01CA204189
  - Philips Healthcare
  - HFHS Internal Mentored Grant
- Collaborations with Modus Medical Devices, MedSpira Medical, ViewRay
- I am the co-chair of TG-284 on MR-SIM QA

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Learning Objectives

- Describe how MRI hardware and software are being utilized for Radiation Therapy (what can be optimized)
- Specifications, clinical requirements, and common use cases of MRI guidance in a real-time radiation delivery system

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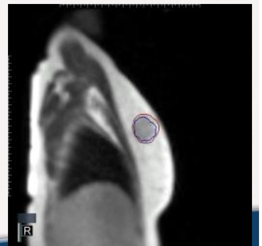
Why MR-Guided RT?

- Brings superior soft tissue contrast to treatment room for many indications
- High quality, volumetric information available at time of localization
- Enables non-ionizing, near real-time tracking, gating, & monitoring of patient during beam-on
- May facilitate dose escalation, online-IGART



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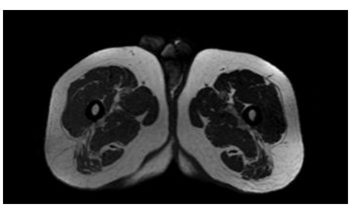
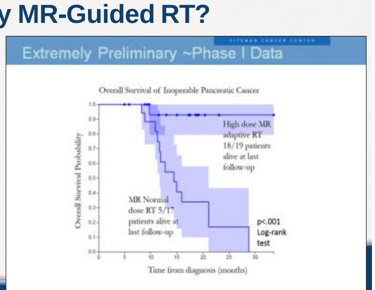
High Quality Planning/IGRT Dataset: First MRIdian Linac Prostate Patient



- FOV: 45 x 30 x 36 cm
- High resolution:
  - -1.5 x 1.5 x 1.5 mm^3
  - -178 sec (~3 min)

Why MR-Guided RT?

Investigation of relative pancreatic tumor to duodenal motion in MRI guided RT for potential online adaptive radiation therapy by UCLA, UW, VUMC and Wash U



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Slide credit: ViewRay

MRIdian Linac Coil/Immobilization Optimization

- Coils as close to patient as possible (increase SNR)
- Rethink immobilization (alpha cradles, breast boards)

Coil attenuation = 0.8%

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Challenges Facing MR in RT: Setup

- Wrapped around mask
- Adjacent to mask

- Wrapped in "U" shape

- Suspended on bridges, Further from spine coil

Paulson ES, et al, Med Phys 2015; 42:28-39

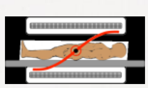
MRI Distortion Management

System Level:

-Non-linearity of the spatial encoding gradients (GNL)

-Typically <u>largest</u> source of distortion

-Inhomogeneities in B_0 field



Object/Patient Induced:

-Susceptibility, Chemical Shift

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Large FOV 3D Distortion Phantoms

3D Dis … hantom

Price, R., Knight, R., Hwang, K-P., Bayram, E., Nejad-Davarani, S., Glide-Hurst, C., JACMP, 2017

GNL Methods

- 3D gradient echo sequence with forward & reverse read gradient polarity
- Object dependent + B0 distortions only present in frequency-encode direction
- GNL present in all directions→ Taking average distortion between scans will isolate only GNL

<u>Note</u>: **3D vendor distortion corrections ENABLED**

- From average distortion map, extract landmarks, calculate centroids
- Difference between MR and CT control points determined
- Distortion maps generated via singular value decomposition (6th degree polynomial)

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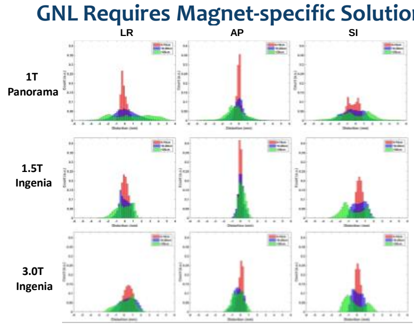
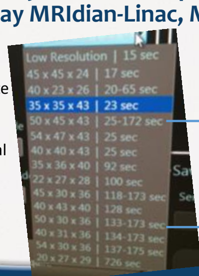
GNL Requires Magnet-specific Solutions



Clinically Available Sequences: ViewRay MRIdian-Linac, MR-Co^{60}

- Siemens 0.35T TrueFISP (Fast Imaging Steady-state Precession)
- T2/T1 ratio image contrast, fluids high signal
- Fast acquisition, less sensitive to motion



1.5^2 X 1.5 mm = 172 sec (~ 3 min)
1.5^2 X 3 mm = 25 sec

1.5^2 X 1.5 mm = 172 sec (~ 3 min)

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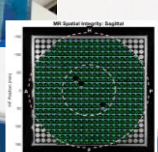
Spatial Integrity: ViewRay Phantom



- Oriented coronal & axial
- Sagittal at 0, ± 7, and ± 12.5 cm off-axis
- Images registered to CT reference
- ✓ Spatial integrity <2 mm over 35 cm diameter sphere volume FOV for 90% of the points
- ✓ <1 mm over 20 cm diameter sphere volume FOV for 100% of the points

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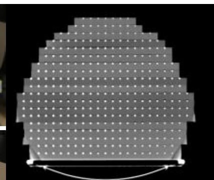
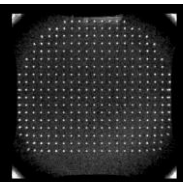
Total Distortion Assessment of Clinical MR-IGRT

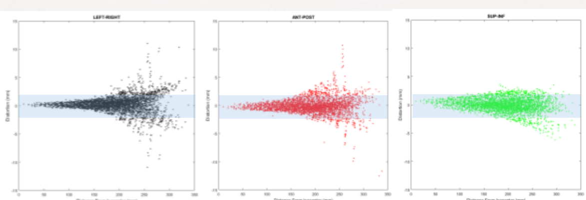


Axial CT Scan



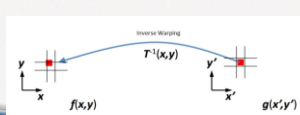
Axial MR Scan
TrueFISP, 1.5x1.5x3mm
54 LR, 46.5 AP, 43.2 HF (cm)

Spatial Integrity: TruFISP Sequence



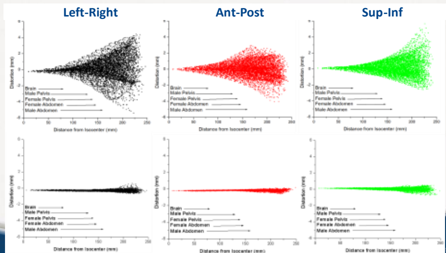
MR-IGRT Distortion Next Steps

- Develop/implement reverse gradient sequence to isolate GNL
- If needed, can develop distortion correction & verification schema
  - Inverse warping
  - Trilinear interpolation of intensity based on surrounding voxels
  - Jacobian



*http://people.ece.cornell.edu/land/courses/ece5760/FinalProjects/s2014/jsw267/html/

1.0T Gradient Nonlinearity Correction



Price, R.G., Kadbi, M., Kim, J., Balter, J., Chetty, I.J. and Glide-Hurst, C.K., 2015. Technical Note: Characterization and correction of gradient nonlinearity induced distortion on a 1.0 T open bore MR-SIM. Medical physics, 42(10), pp.5955-5960.

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Magnetic Field Homogeneity

- Magnetic field variation over diameter spherical volume (DSV)
- Affected by:
  - Internal effects (inaccuracies in coil windings or passive shim coils)
  - External effects (perturbations induced by ferromagnetic structures near magnet)
- Inhomogeneities can impact uniformity and contribute to distortion
- Shielding linac from magnetic field and room influences may influence homogeneity
  - Evaluate at multiple gantry angles

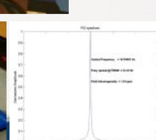
Magnetic Field Homogeneity: MRIdian Linac

<u>Acceptance Testing</u>

- Large FOV (45 cm) with field camera during functional testing
  - ✓Within 25 ppm specification

<u>Commissioning</u>

- 24 cm sphere imaged at magnet isocenter
- Evaluated at multiple gantry angles
- Spectral peak (FWHM)



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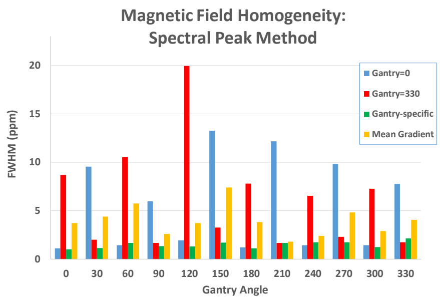
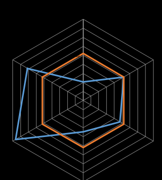
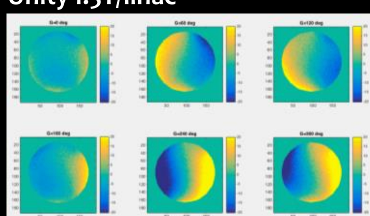


- Optimal solution: gantry-specific tuning
- Currently implemented: Mean gradient

Phase Mapping: Magnetic Field vs Gantry Unity 1.5T/linac

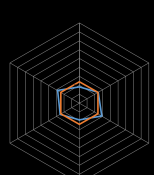


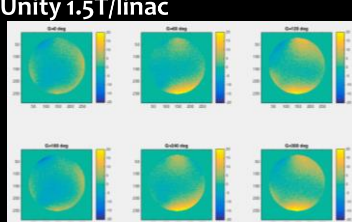


- Passive shimmed at gantry = 0 deg: 4.1 Hz RMS
- Average of all angles: 10 Hz RMS

Paulson et al, AAPM 2017

Magnetic Field vs Gantry Rotation (+Shimming) Unity 1.5T/linac



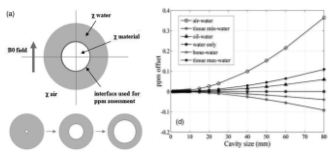


- Average of all angles: 4.8 Hz RMS
- Conclusion: Perform shimming at each gantry angle prior to beam-on

Paulson et al, AAPM 2017

Object-induced distortion

- Local magnetic field perturbations generated at interfaces with different magnetic susceptibility values (i.e. tissue/air, tissue/bone)
- Can be quantified, distortions calculated, and corrected for sequences used



T. Stanescu, K. Wachowicz, and D. A. Jaffray. "Characterization of tissue magnetic susceptibility-induced distortions for MRIgRT" *Med Phys* 39, 7185 (2012)

Image Processing Methods

- Phase maps reconstructed by complex division of data from two in-phase echoes of dual-echo GRE, unwrapped in Prelude/FSL
- B_0 field maps from phase difference between echoes
- Converted to displacement maps using:

$$\Delta x = \frac{\Delta B_0}{G_x} = \frac{\Delta f_0}{BW_f}\Delta V_x = \frac{\Delta \phi}{2\pi \Delta TE * BW_f}\Delta V_x$$

Δx = x-displacement frequency-encoding direction, G_x = readout gradient, BW_f = measured pixel bandwidth (Hz/pixel) in frequency-encoding direction, ΔV_x = pixel size in the frequency encoding direction

- Using T2 acquisition parameters for each timepoint

Processing Pipeline: Weili Zheng, PhD

Patient-Specific Distortion Changes (PTV)

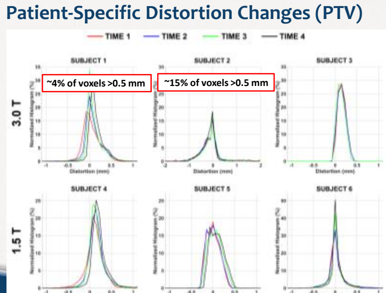


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Figure Credit: Siamak Nejad-Davarani, PhD

Distortion changes within the target volume!

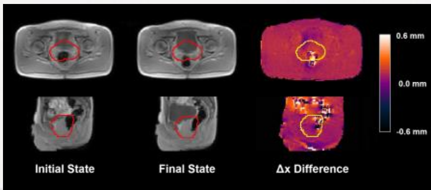

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Figure Credit: Siamak Nejad-Davarani, PhD

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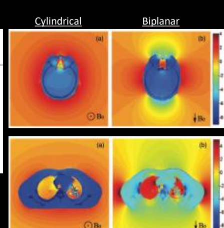
Local Susceptibility-Induced Perturbations

Anatomical site	Structure	Max distortion (ppm)	Mean distortion (ppm)	Range of distortion (ppm)
Brain	Body	5.48	0.43	9.36
	Bone	3.36	0.25	6.37
	Air cavities	5.66	0.92	9.96
Lung	Body	2.99	0.41	5.37
	Bone	4.96	0.64	7.71
	Lung	5.56	0.71	8.85
Prostate (no air pockets)	Body	3.98	0.54	6.42
	Bone	2.48	0.41	3.03
Pelvis (air pockets)	Body	3.91	0.46	5.91
	Bone	2.54	0.47	4.02
	Air pockets	4.85	0.68	7.27



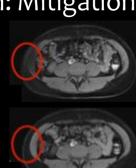
- Largest effects around air-tissue interfaces (largest $\Delta\chi$)
- Effects tend to be higher for biplanar geometries

Stanescu et al, Med Phys, 2012
Slide Credit: Eric Paulson, PhD, MCW

Alternative to Correction: Mitigation

- ΔB = 2 ppm (spectral fat saturation fails)
- Max gradient amplitude: 30 mT/m

- Spin Warp Sequence Parameters:
  - rBW = 2xWFS (440 Hz @ 1.5T, 890 Hz @ 3.0T)
  - FOV = 256 mm
  - Matrix = 256x256



1.5T
- Δx = 0.3 mm
- Gr = 10.3 mT/m

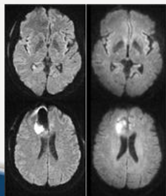
3T
- Δx = 0.3 mm
- Gr = 20.9 mT/m

- > 1mm shift requires > 6.8 ppm
- May need to increase acquisition time to recover SNR (-30%)
- Alternative is set rBW based on max expected $\Delta\chi$ per region

Slide Credit: Eric Paulson, PhD, MCW

Caveat: Some Sequences More Susceptible to Distortion

- Echo-planar imaging (diffusion, perfusion) sensitive to off-resonance effects → severe geometric distortions



(Left) Single shot diagnostic DWI (b = 1000 s/mm)

(Right) RadOnc DWI (multi-shot spiral) → reduced local susceptibility & signal pileup

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Paulson et al., Med Phys (2016)

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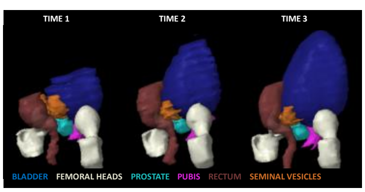
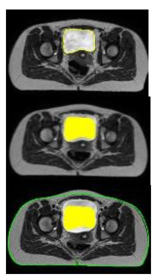
Temporal Patient-specific Changes

- Patients are dynamic during long MR acquisitions
  - Changing anatomy (e.g., bladder/rectal filling)
  - Respiratory state





Impact of rectal status on real-time tracking of 1st MR-linac prostate patient during beam-on

- FOV: 35 x 35 cm
- Resolution: 3.5 x 3.5 x 7 mm, 4 fps
- Target = prostate (red)
- Boundary = 5 mm (blue)
- 6XFFF, Step & Shoot IMRT, ~500 MU
- Beam on / Tx time = 2.5 / 5.4 mins
- 1:13-1:27: Transient gas→hold

Other Motion Management Considerations: 4DMRI

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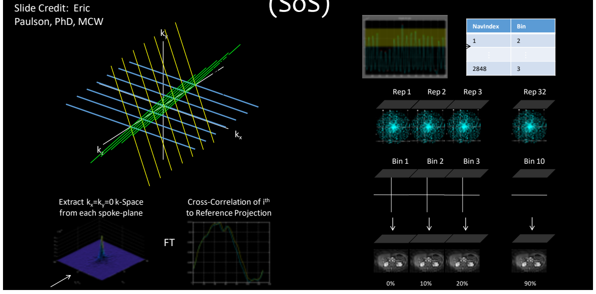
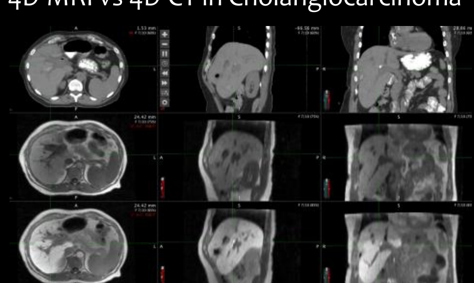
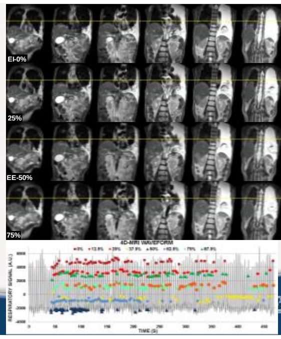
Self-Navigated 4DMRI, Radial Stack of Stars (SoS)

Slide Credit: Eric Paulson, PhD, MCW



4D-MRI vs 4D-CT in Cholangiocarcinoma





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Recent Works in Progress

Low-Field 4D MRI for MRI-Guided Treatment Planning and Dose Delivery

H Gach[1*], T Mazur[1], H Wang[1], H Song[2], M Fernandez-Seara[3], V Stenger[4], B Vajko[5], J Dempsey[6], Y Motai[7], S Mutic[1], O Green[1], (1) Washington University in St. Louis, St. Louis, MO,(2) The University of Texas MD Anderson Cancer Center, Houston, TX, (3) University of Navarra Hospital, Pamplona,(4) University of Hawaii at Manoa, Honolulu, HI, (5) ViewRay, Oakwood Village, OH, (6) ViewRay, Mountain View, CA,(7) Virginia Commonwealth University, Richmond, VA

Presentations

MO-RAM-GePD-JT-3 (Monday, July 31, 2017) 9:30 AM - 10:00 AM Room: Joint Imaging-Therapy ePoster Theater

Initial Investigation of Four-Dimensional (4D) Dose Calculation Based On 4D-MRI

D Du*, F Han, Z Zhou, J Lamb, J Neylon, Y Yang, P Hu, P Lee, A Raldow, D Low, M Cao, UCLA School of Medicine, Los Angeles, CA

Presentations

TU-C3-GePD-J(A)-5 (Tuesday, August 1, 2017) 10:30 AM - 11:00 AM Room: Joint Imaging-Therapy ePoster Lounge - A

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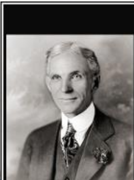
Thank You!



If everyone is moving forward together, then success takes care of itself.

(Henry Ford)

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