MRI Optimized for Radiation Therapy (MR-Guided RT)

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- Collaborations with Modus Medical Devices, MedSpira Medical, ViewRay
- I am the co-chair of TG-284 on MR-SIM QA

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
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

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 mm³
  - 178 sec (~3 min)

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

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**

- **Brain, Head/Neck**
  - Wrapped around mask
  - Adjacent to mask

- **Prostate**
  - Wrapped in "U" shape

- **Abdomen, Pelvis, Chest**
  - Wrapped in "U" shape
  - Further from spine coil

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**MRI Distortion Management**

**System Level:**
- Non-linearity of the spatial encoding gradients (GNL)
  - Typically largest source of distortion
- Inhomogeneities in B₀ field

**Object/Patient Induced:**
- Susceptibility, Chemical Shift
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

**Note:** 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)
GNL Requires Magnet-specific Solutions

- 1T Panorama
- 1.5T Ingenia
- 3.0T Ingenia

Clinically Available Sequences: ViewRay MRidian-Linac, MR-Co60

- Siemens 0.3T TrueFISP (Fast Imaging Steady-state Precession)
- T2/T1 ratio image contrast, fluids high signal
- Fast acquisition, less sensitive to motion

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
Total Distortion Assessment of Clinical MR-IGRT

Axial CT Scan
Axial MR Scan
TrueFISP, 1.5x1.5x3mm
S4 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

1.0T Gradient Nonlinearity Correction

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

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

Commissioning
- 24 cm sphere imaged at magnet isocenter
- Evaluated at multiple gantry angles
- Spectral peak (FWHM)
Magnetic Field Homogeneity: Spectral Peak Method

- 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

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
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

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:
  \[
  \Delta x = \frac{\Delta B_0}{G_x} \cdot \Delta f \cdot \frac{\Delta V_x}{\Delta T_E \cdot BW_f}
  \]
  $\Delta x = x$-displacement; $B_0$ = frequency-encoding direction; $G_x$ = readout gradient; $BW_f$ = measured pixel bandwidth (Hz/pixel) in frequency-encoding direction; $\Delta V_x$ = pixel size in the frequency encoding direction
- Using T2 acquisition parameters for each timepoint

Patient-Specific Distortion Changes (PTV)

- ~15% of voxels >0.5 mm
- ~4% of voxels >0.5 mm

Figure Credit: Siamak Nejad-Davarani, PhD
Distortion changes within the target volume!

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

Local Susceptibility-Induced Perturbations

Alternative to Correction: Mitigation

- $\Delta B = 2$ ppm (spectral fat saturation fails)
- Max gradient amplitude: 30 mT/m
- Spin Warp Sequence Parameters:
  - $\Delta x = 0.3$ mm
  - $Gr = 10.3$ mT/m
  - FOV = 256 mm
  - Matrix = 256x256

- $\Delta B = 2$ ppm (spectral fat saturation fails)
- $Gr = 20.9$ 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 $\Delta x$ per region
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

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

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

4D-MRI vs 4D-CT in Cholangiocarcinoma
Recent Works in Progress

Low-Field 4D MRI for MRI-Guided Treatment Planning and Dose Delivery
H. Gao1, H. Ma2, H. Wang1, H. Jiang1, H. Fernandez-Seara1, V. Steiger1, B. Vajpeyi1, J. Demopolou1, S. Metz1, O. Green2, Q. (Washington University in St. Louis, MO) (The University of Texas MD Anderson Cancer Center, Houston, TX) (University of Hawaii Hospital, Honolulu, HI) (University of Hawaii at Manoa, Honolulu, HI). (V. Vajpeyi, Oakwood Village, OH); (L. Steiger, Mountain View, CA); (O. Virginia Commonwealth University, Richmond, VA)

Presentations:
MD-16AM-G007-17-2 (Monday, July 24, 2012, 9:50 AM-10:00 AM Room: Joint Imaging Therapy of Poster Theater)

Initial Investigation of Four-Dimensional (4D) Dose Calculation Based On 4D-MRI
D. Xu1, D. He2, Z. Zhou2, J. F. Lee2, Y. Yang2, F. Liu2, J. Hu2, A. Kailan2, O. Liu2, M. Cox2 (UCLA School Medicine, Los Angeles, CA)

Presentations:
TI-C5-G108-K6 (Tuesday, August 2, 2011, 9:50 AM-10:00 AM Room: Joint Imaging Therapy of Poster Lounge A)

Thank You!

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

(Henry Ford)