Optimization of Radiotherapy for MRI

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Learning Objectives

- Gain insight into strategies used to overcome the design challenges facing MR-gRT
- Understand how dosimetry changes in the presence of magnetic fields
- Understand how QA procedures and equipment need to be modified for use in MR-gRT
- Appreciate how clinical radiotherapy workflows may change with MR-gRT

Challenges Facing MR-gRT

- Decoupling the magnetic field from RT components:
  - Minimizing magnetic interference
- Decoupling the RT components from MRI acquisition:
  - Minimizing radiofrequency interference
- Beam transmission through the MRI
- Influence of Lorentz force on secondary electrons
MR-gRT Implementations

Strategies to Minimize Magnetic Interference

- Individual operation of MRI and Linac
- Utilize active shielding to reduce magnetic field over linac components
- Embed linac components in concentric ferromagnetic rings

Strategies to Minimize RF Interference

- Individual operation of MRI and Linac
- Use radionuclides rather than linac as photon source
- Surround linac with materials to shield RF:
  - Integrate cryostat into Faraday cage
  - Layers of carbon fiber and copper to reflect and absorb RF
Strategies for Beam Transmission

• Perpendicular to B0:
  - Between split magnet cores
  - Through cryostat between magnet winding bands
  - Between magnet poles

• Parallel to B0:
  - Through holes in magnet poles, rotating magnet around patient or patient in magnet

Choice will affect attenuation and dosimetry

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Dosimetry in Magnetic Fields

• Photon beam not affected by magnetic field
• Secondary electrons experience Lorentz force when magnetic and irradiation fields are orthogonal

• Effects:
  – Altered buildup distances
  – Tilted dose kernels
  – Electron return effect
Tilted Dose Kernel

- If $B_0$ applied transverse to irradiation, Lorentz force induces helical secondary electron trajectories
- Results in asymmetric beam profiles, smeared penumbra, and (mention of) reduced LET

Electron Return Effect (ERE)

- Helical electron trajectories result in "re-entrance effects" arise at tissue-air interfaces
- Increases exit, interface dose
- ERE Dependence:
  - Field strength ($B_0$)
  - Irradiation field size
  - Entrance, exit surface orientations
  - Tissue mass density changes

Characterization of Lorentz Force Effects

- Gafchromic film in unit density phantoms with air cavities
Strategies to Manage ERE

- Opposed beams
- Including magnetic field in IMRT optimization
- Use gating or re-optimization for non-stationary air cavities
- Orient irradiation parallel to B0:  
  - Inline MR-gRT implementations

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Dose Calculation Algorithms

- MR-gRT requires optimization in magnetic fields:  
  - Surface orientation dependency on ERE  
  - Magnetic field strength and direction  
  - Cryostat
- Monte Carlo:  
  - Implementation dependent (GPU-MCD, Hissoiny S, et al, PMB 2011)  
  - 15 seconds to several minutes
- Deterministic:  

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Dose Response in Magnetic Fields

- Dose response of air filled ion chambers affected by size, geometry, orientation in magnetic field, and irradiation orientation
- Linearity and reproducibility not affected by magnetic field

Reference Dosimetry Formalism for MR-gRT

- Must perform in liquid water due to air gap effects
- Careful choice of beam quality specifier and chamber orientation
- Additional correction factors required

Relative Dosimetry for MR-gRT

- Moving chamber during irradiation not affected by magnetic field
- Use of ion chamber as reference for linac output variations does not require correction
- Rotate chamber for in-plane profile measurements
Routine QA Procedure Modifications

- Magnetic field effects require redesign of some existing linac QA tests

- Approaches:
  - Apply correction factors to existing procedures
  - Develop new procedures

- Incorporate high density materials (Copper):
  - Shorter path length of electrons
    - Reduces size of dose kernel
  - Minimizes magnetic field effects
  - Dose is deposited more locally

Adapted Routine QA Procedures

Radiation Isocenter Accuracy

Beam Profile Measurements

New QA Devices for MR-gRT

- Ferromagnetic components removed. Power supply outside field
Profiles, Plan QA

Date: 16/03/2017

ArcCHECK QA of Dose Distribution

Hospital Name:

QA File Parameter

ArcCHECK

Plan

ArcCHECK-Plan

Patient Name: MRLINAC, CIRS

Patient ID: MRLINAC06

Plan Date: 3/16/2017

SSD

Distance (mm)

Threshold (%)

Meas Uncertainty

CAX Offset X=1 Y=-1

Summary (Gamma Analysis)

Total Points

Passed

Failed

% Passed

*DTA/Gamma is using 2D Mode

: 3.0

: 3.0

: 5

: 272

: 261

: 11

: 96

Dose Values in cGy

CAX

Norm

Sel

Max

ArcCHECK

85.35

10.93

85.35

Plan

21.79

125.01

15.01

126.49

ArcCHECK

-39.66

-4.08

-41.14

-Plan

% Diff

-31.73

-3.27

-32.91

DTA(mm)

NA

0.00

NA

0,-0.5

Coords

(y,x) cm

0,0

1,-21.5

Notes

Reviewed By :

Set1

Set2

X(mm)

300

250

200

150

100

50

0

-50

-100

-150

-200

-250

-300

%

100

80

60

40

20

0

Unmet Need: Water Tanks for MR-gRT

- No commercially available scanning systems for MR-gRT
- Physical dimensions may restrict phantom size and range of SSDs
- Unable to measure PDD at multiple gantry angles
- Increases commissioning time and uncertainty in measurements

PDD/Profile Analysis

- Large Field Profile

Courtesy of Carri Glide-Hurst
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Online MR-gRT Treatment Cycle

Fractional Dose Modulation

• With MR-gRT, fractionation schemes may be less important
• Increase fractional dose on days with more favorable anatomy
• Use real-time imaging to confirm OAR positions are stable throughout treatment
• Accumulate BED and terminate treatment when targeted BED achieved
• May result in accelerated treatments
Biological Adaptive

- Identify poorly responding regions using quantitative MRI
- Incorporate using adaptive dose-painting
- Degree of dose escalation depends on location, size, and shape of subvolume

Dalah E, et al, IJROBP 2014; 90:S253

Courtesy Yue Cao (U Michigan)

Hypoperfused subvolume preRT

Hypoperfused subvolume wk 2

Standard Plan

70 Gy to PTV

Adaptive Boost Plan

80 Gy (87 Gy equivalent) to the persisted Hypoperfused subvolume

4D Adaptive

- Continuously adapt plan based on each anatomy update from MRI
- Adaptive Sequencer:
  - Segment-by-segment optimization based on ideal fluence with direct update to MLCs

Kontaxis et al, PMB 2015; 60:7485-7497

Summary

- MR-gRT extends the advantages of MRI into the RT treatment room, facilitating high precision, dose escalated radiotherapy
- Different MR-gRT implementations uniquely address the design challenges of integrating MRI and RT devices
- The presence of the magnetic field can affect dosimetry but it is largely possible to manage these effects
- As technology improves, MR-gRT has the potential of shifting the RT paradigm from a sequential approach to a continuous online adaptive approach in which morphology, biology, and motion changes can be handled on the fly
Potential Future MR-gRT Paradigm

Why MRI in Radiation Oncology?

- Pillars of success in RT:
  - Accurate delineation of disease extent
  - Optimal alignment of the treatment beam to the target
- MR Simulation:
  - Consistent, true CTV
  - More accurate CTV
- MR-guided RT:
  - Reduce inter-, intra-fractional uncertainties
  - Biologically adaptive, dose-escalated RT
Adaptive MR-gRT

- Daily (real time) translation, rotation, deformation of targets and/or OAR
- Target volumes change due to treatment response

Common concerns:
- Recontouring time
- Reoptimization time
- How to QA?

Concerns unique to MRI:
- Lack of electron density information
- Magnetic field effects

Strategies for Online Adaptive MR-gRT

- Virtual Couch Shift:
  - Handles translations and rotations with aperture shifts
  - ~2cm limits due to FFF beam on MR/Linac, S/L leaf orientation

- Pre-Shifted Plan (PSP) Library:
  - Warm start optimization based on original dose
  - Handles FFF beam effects

- Segment Aperture Morphing (SAM):
  - Fast
  - Handles deformations

Ahunbay et al, Med Phys 2016; 43:4575-4584

Online MR-gRT Treatment Cycle

“See”

“Plan”

“Treat”

Possible Pancreas MR-gRT Strategy

- **Pre-Beam**: 4D MRI
- **Beam-On**: Real-Time Imaging
- **Beam-On**: Dynamically update motion models, adapt plan, update delivery
- **Post-Beam**: Accumulate RT Dose

- Radiation Delivery

Possible Prostate MR-gRT Strategy

- **Pre-Beam**: 3D T2
- **Beam-On**: Dynamically update motion models, adapt plan, update delivery
- **Post-Beam**: Accumulate RT Dose

- Radiation Delivery

- Slower motion (filling, drifting)
- Consider sequential 3D imaging for monitoring, dose accumulation

Possible Brain MR-gRT Strategy

- **Pre-Beam**: 3D FLAIR
- **Beam-On**: Quantitative Imaging
- **Post-Beam**: Accumulate Dose, Adapt RT Plan

- Radiation Delivery

- Static tissues may not need real-time monitoring
- Spend time acquiring images for response assessment, risk-adaptation
MR-MV Isocenter Alignment

Transmission through RF Coils

- **Attenuation:**
  - Problem in PET/MR
  - Not issue with MR-Linac due to higher energy photons
  - Attenuating components moved to edges of coils

- **SNR Degradation:**
  - Pulsed radiation induced currents (implementation dependent?)

- **Benefits:**
  - Reduced ERE from attenuation of returning electrons in RF coil

Surface Dose Dependence

- Compton scatter from RT hardware and transmission through cryostat
- Transverse magnetic field sweeps away contaminating electrons
- Small reduction in surface dose for perpendicular orientation
- Increase in surface dose for parallel (inline) configuration
In Vivo Dosimetry

- **MOSFETs:**
  - Response increased 5% during MRI-gRT at 0.35T (Knutson et al, Med Phys, 2014)
  - Recommend using handheld readers

- **TLDs/OSDs:**
  - Response not affected at 0.35T (Goddi et al, Med Phys, 2013)

- **Treatment plans:**
  - MR-compatible ArcCheck (0.35T through 1.5T)
  - Feasible to use polymer gels (Zhang et al, Med Phys, 2014)

- **Daily:**
  - Ensure RF coils in same position (may be modeled in TPS)

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New Software Needed

- Isocenter radius 1.5 mm
- Could be due to RF handling of asymmetric beam profiles