Optimization of Radiotherapy for MRI

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Froedtert & Medical College of Wisconsin

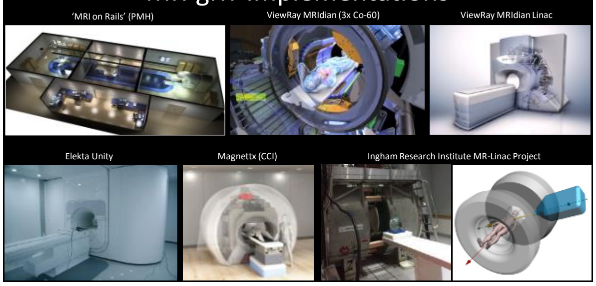
Learning Objectives

- 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

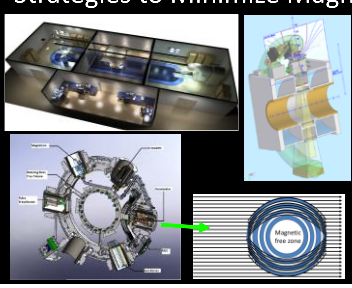
Challenges Facing MR-gRT

- 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

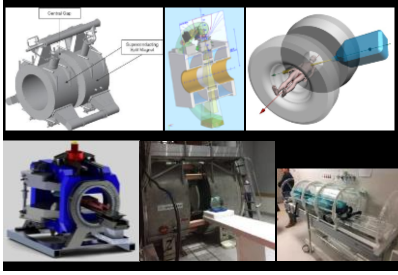


- Individual operation of MRI and Linac
- Utilize active shielding to reduce magnetic field over linac components
- Embed linac components in concentric ferromagnetic rings

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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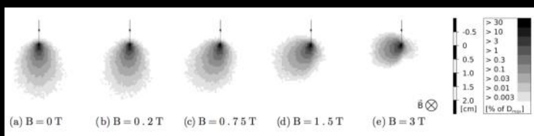
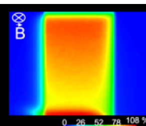
Dosimetry in Magnetic Fields

- Photon beam not affected by magnetic field
- Secondary electrons experience Lorentz force when magnetic and irradiation fields are orthogonal
- Effects:
  - Altered buildup distances
  - Titled dose kernels
  - Electron return effect

Tilted Dose Kernel

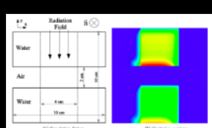


- If B_0 applied transverse to irradiation, Lorentz force induces helical secondary electron trajectories
- Results in asymmetric beam profiles, smeared penumbra, and (mention of) reduced LET

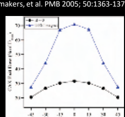


Raaijmakers AJE et al, PMB, 2008

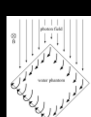
Electron Return Effect (ERE)



Raaijmakers, et al. PMB 2005; 50:1363-1376



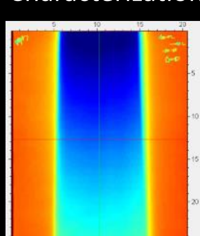
Keyvanloo, et al. Med Phys 2012;

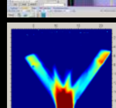


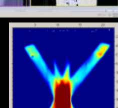
Raaijmakers AJE et al, PMB, 2007

- Helical electron trajectories result in “re-entrance effects” arise at tissue-air interfaces
- Increases exit, interface dose
- ERE Dependence:
  - Field strength (B0)
  - Irradiation field size
  - Entrance, exit surface orientations
  - Tissue mass density changes

Characterization of Lorentz Force Effects

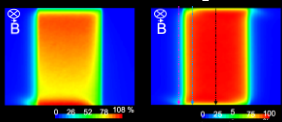




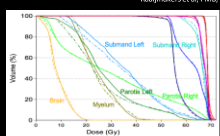


- Gafchromic film in unit density phantoms with air cavities

Strategies to Manage ERE



Raaijmakers et al, PMB, 2005



Raaijmakers et al, PMB, 2007

- 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

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 (GPUMCD, Hissoiny S, et al, PMB 2011)
  – 15 seconds to several minutes
- Deterministic:
  – Possible with newer hardware (Aubin J, et al Med Phys, 2015)

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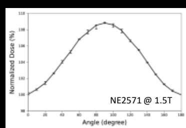
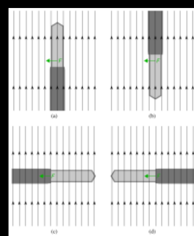
Dose Response in Magnetic Fields

- Dose response of air filled ion chambers affected by size, geometry, orientation in magnetic field, and irradiation orientation



Smit et al, PMB, 2016

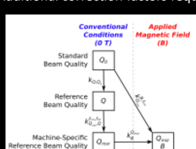
- Linearity and reproducibility not affected by magnetic field



O'Brien et al, Med Phys, 2016

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



$$D_{w,Q_{msr}}^{B,f_{msr}} = M_{Q_{msr}}^{B,f_{msr}} N_{D,w,Q_0} k_{Q_{msr}}^{B,f_{msr}},$$

$$k_{Q_{msr}}^{B,f_{msr}} = k_{Q,Q_0} k_{Q_{msr},Q}^{f_{msr},f_{ref}} k_B^{Q_{msr}},$$

$$k_B^{Q_{msr}} = \frac{D_{w,Q_{msr}}^{B,f_{msr}} / M_{Q_{msr}}^{B,f_{msr}}}{D_{w,Q_{msr}}^{f_{msr}} / M_{Q_{msr}}^{f_{msr}}}.$$

Detector	$k_{B_{\parallel}}^{Q_{msr}}$	$k_{B_{\perp}}^{Q_{msr}}$	$k_{B_{\perp}}^{Q_{msr}}$	Uncertainty (%)
PTW 30013	0.994	0.961	0.976	0.15
PTW 30012[a]	0.992	0.958	0.970	0.25
PTW 30011[a]	1.000	0.958	0.968	0.25
PTW 30010[a]	0.996	0.961	0.975	0.25
NE2571[a]	1.003	0.962	0.973	0.20
NE2571	1.001	0.962	0.973	0.15
Exradin A19	1.005	0.962	0.956	0.25

O'Brien et al, Med Phys, 2016

Relative Dosimetry for MR-gRT

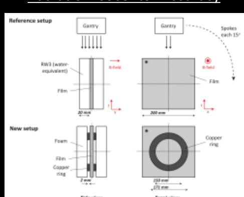
- Moving chamber during irradiation not affected by magnetic field
- Use of ion chamber as reference for linac output variations does not require correction
- Rotate chamber for in-plane profile measurements

Routine QA Procedure Modifications

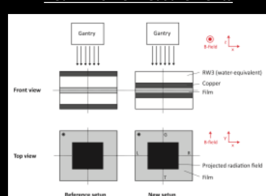
- Magnetic field effects require redesign of some existing linac QA tests
- Approaches:
  - Apply correction factors to existing procedures
  - Develop new procedures
- Incorporate high density materials (Copper):
  - Shorter path length of electrons
    - Reduces size of dose kernel
  - Minimizes magnetic field effects
  - Dose is deposited more locally

Adapted Routine QA Procedures

Radiation Isocenter Accuracy



Beam Profile Measurements

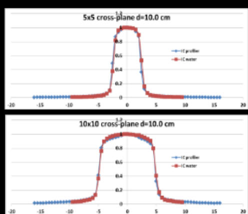


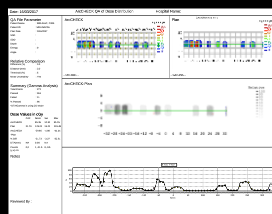
Van Zijp HM et al, PMB, 2016

New QA Devices for MR-gRT

- Ferromagnetic components removed; Power supply outside field

Profiles, Plan QA





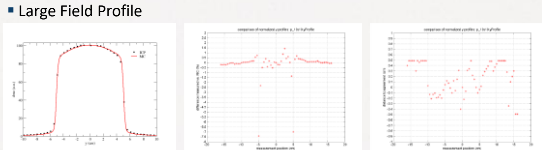
Paulson et al, AAPM 2017

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



all for you

Henry Ford Health System Henry Ford Cancer Institute

Courtesy of Carri Glide-Hurst

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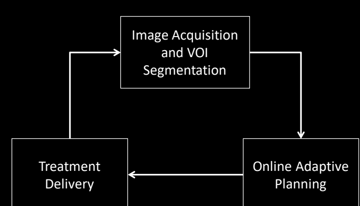
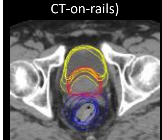
Online MR-gRT Treatment Cycle



Bol GH, PhD Thesis, UMC Utrecht, 2015

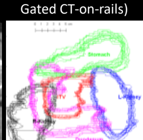
Fractional Dose Modulation

Prostate
(5 fractions,
CT-on-rails)



Ates O, et al, ASTRO 2016

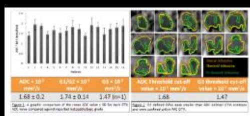
Pancreas
(28 fractions,
Gated CT-on-rails)



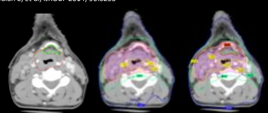
Liu F, et al, IJROBP 2012; 83:e423-9

- 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



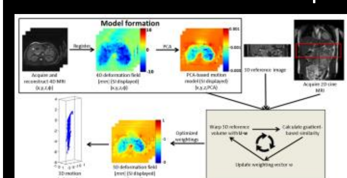
Dalah E, et al, IJROBP 2014; 90:S253



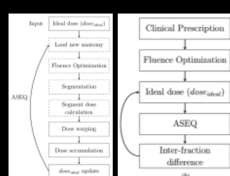
Courtesy Yue Cao (U Michigan)

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

4D Adaptive



Stemkens B, et al, PMB 2016; 61:5335-5355



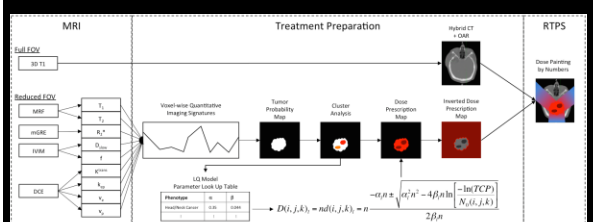
Kontaxis et al, PMB 2015; 60:7485-7497

- 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

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

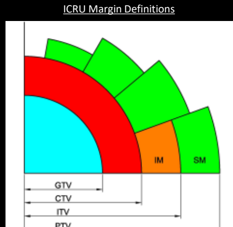
Potential Future MR-gRT Paradigm



Adapted from U.A. van der Heide, PhD

Why MRI in Radiation Oncology?

ICRU Margin Definitions

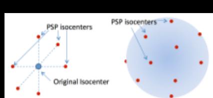


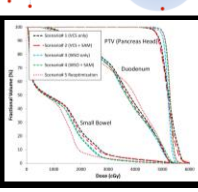
- Pillars of success in RT:
  - Accurate delineation of disease extent
  - Optimal alignment of the treatment beam to the target
- MR Simulation:
  - Consistent, true GTV
  - More accurate CTV
- MR-guided RT:
  - Reduce inter-, intra-fractional uncertainties
  - Biologically adaptive, dose-escalated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



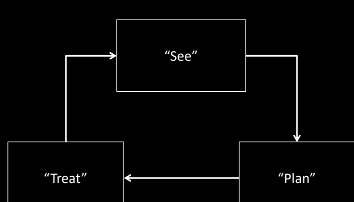


- Virtual Couch Shift:
  - Handles translations and rotations with aperture shifts
  - ~2cm limit due to FFF beam on MR-Linac, S-I leaf orientation
- Pre-Shifted Plan (PSP) Library:
  - Warm start optimization based on original dose
  - Handles FFF beam effects
- Segment Aperture Morphing (SAM):
  - Fast
  - Handles deformations

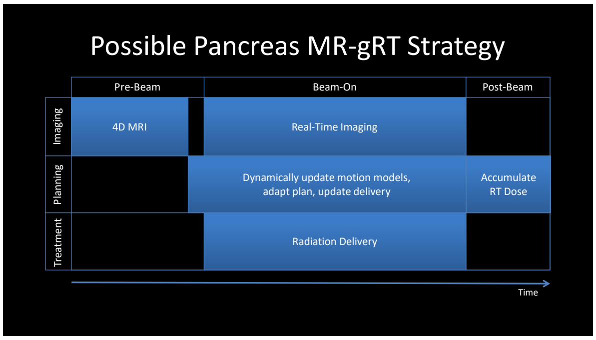
Operation		Corrections		
On planning CT	On daily CT	Translation	FFF effect	Target deformation
VCS		×		
VCS	SAM	×		×
WSO		×	×	
WSO	SAM	×	×	×
	Reoptimization	×	×	×

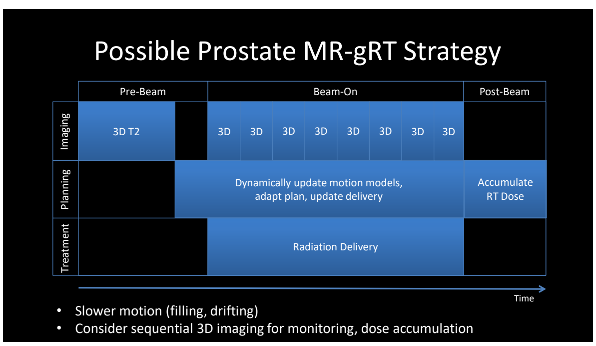
Ahunbay et al, Med Phys 2016; 43:4575-4584

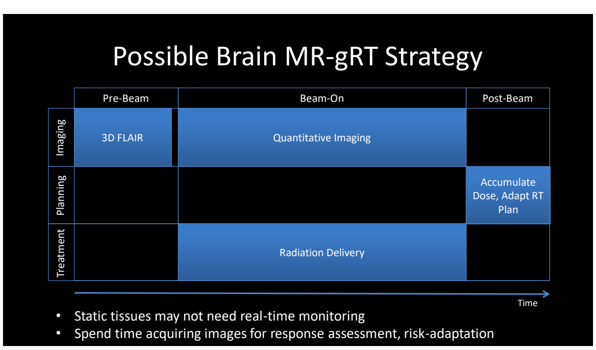
Online MR-gRT Treatment Cycle



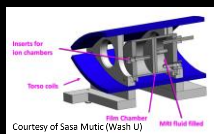
Bol GH, PhD Thesis, UMC Utrecht, 2015


Possible Pancreas MR-gRT Strategy
Pre-Beam
Beam-On
Post-Beam
Imaging
Planning
Treatment
4D MRI
Real-Time Imaging
Dynamically update motion models, adapt plan, update delivery
Accumulate RT Dose
Radiation Delivery
Time

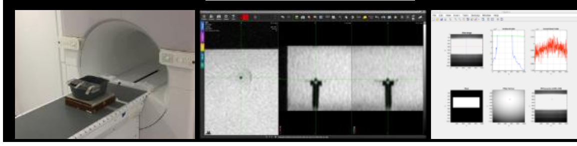

Possible Prostate MR-gRT Strategy
Pre-Beam
Beam-On
Post-Beam
Imaging
Planning
Treatment
3D T2
3D
3D
3D
3D
3D
3D
3D
3D
Dynamically update motion models, adapt plan, update delivery
Accumulate RT Dose
Radiation Delivery
Time
• Slower motion (filling, drifting)
• Consider sequential 3D imaging for monitoring, dose accumulation


Possible Brain MR-gRT Strategy
Pre-Beam
Beam-On
Post-Beam
Imaging
Planning
Treatment
3D FLAIR
Quantitative Imaging
Accumulate Dose, Adapt RT Plan
Radiation Delivery
Time
• Static tissues may not need real-time monitoring
• Spend time acquiring images for response assessment, risk-adaptation

MR-MV Isocenter Alignment



Courtesy of Sasa Mutic (Wash U)



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

Hoogcarspel SJ et al, PMB, 2013

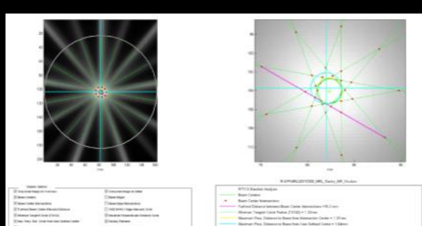
Surface Dose Dependence

- 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

- in-vivo dosimetry:
  - MOSFETs:
    - Response increased 5% during MRI-gRT at 0.35T (Knutson et al, Med Phys 2014)
    - Recommend using handheld readers
  - TLDs/OSLs:
    - Response not affected at 0.35T (Goddu et al, Med Phys, 2012)
- Treatment plans:
  - MRI-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)

New Software Needed



- Isocenter radius 1.3 mm
- Could be due to RIT handling of asymmetric beam profiles