MRI-guided Radiation Therapy
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Assistant Professor, Radiation Oncology, University of Toronto
Affiliated Faculty, Guided Therapeutics, Techna Institute, UHN

Introduction

MRI-guided radiotherapy

MRI
- best for RTP target delineation, tissue characterization
- excellent soft tissue contrast compared to x-ray imaging (CT/CBCT)
- fast imaging techniques
- multiplanar acquisition

Applications:
- liver, pancreas, kidney, prostate, paraspinal, etc.
- SBRT, dose escalation, target control
- adaptive RT planning (ART)

In-room MRI for setup verification | quantify organ motion

Liver CBCT MRI

Liver CBCT MRI
MR-Linac system integration for MRgRT

MR imaging
Treatment delivery
MR Linac system integration for MRgRT

MR-guided RT systems

1. Radiofrequency (RF) interference b/w linac & MR
2. Magnetic field mutual interaction: MR magnet & Linac
3. Dose deposition effects in MR’s magnetic field
4. Skin dose effects in MR’s magnetic field

MR-linac systems

1. Radiofrequency (RF) interference
   - MR needs to be isolated | Collects weak signal from patient
   - Linac is a significant source of RF

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Linac is a significant source of RF
RF shield
MR
Linac
MR-linac systems

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   - Linac is a significant source of RF

2. Magnetic field mutual interaction: MR magnet → Linac
   - B0 fringe field of MR scanner reaching the Linac structure
   - Linac performance affected | Beam output = f(fringe B-field)
MR-linac systems

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magnetic field (on all the time)
MR-inac systems

2. Magnetic field mutual interaction: MR magnet \(\rightarrow\) Linac
- \(B_0\) fringe field of MR scanner reaching the Linac structure
- Linac performance affected \(\implies\) Beam output = f(fringe B-field)

- Linac is a large metallic structure, ferromagnetic components
  - MR imaging field homogeneity affected

MR-inac systems

2. Magnetic field mutual interaction: MR magnet \(\leftarrow\) Linac
- Linac is a large metallic structure, ferromagnetic components
  - MR imaging field homogeneity affected
MR-linac systems

- Dosimetry in MR's magnetic field
  - e trajectories perturbed by the presence of \( B_0 \) \( \rightarrow \) Lorentz force
  - effect \( = f(\text{KE}, B_0, \text{interface}) \)

\[ B_0 \rightarrow F_L \]

Skin dose effects in MR's magnetic field

- \( x \)-ray beam - scattered/contaminant electrons - Linac head, air
- trajectories affected by MR's magnetic field \( \rightarrow \) increased patient dose
**MRIgRT systems**

/ challenge 1  RF interference
- Relocate linac main RF sources in adjacent rooms
- Enclose linac head or MRI in a Faraday cage

/ challenge 2  Magnetic field mutual interaction: MR magnet & Linac
- Passive & active magnetic shielding
- Physical separation

/ challenge 3  Dosimetry in MR's magnetic field
- Effects when magnetic field
- Monte Carlo dose computations

/ challenge 4  Skin dose effects in MR's magnetic field
- System configuration
- Treatment planning strategies

CCI, Edmonton
PMCC, Toronto

ViewRay, WashU
UMC, Utrecht
Univ. of Sydney
CCI, Edmonton, Canada

Functioning Whole-body Linac-MR Installed in 2013

www.linac-mr.ca

Courtesy of G. Fallone

Room size:
5.9 x 6.0 x 3.6 (m)

System specs:
- MR scanner: 0.6T | Paramed - MgB2 (He free technology)
- Linac: 600C
- System installed in pre-existing RT vault through the maze
- 60 cm patient gap → intention to investigate MR with 80 cm gap
- Gantry rotation: 1 rpm
- Magnet ramp up/down: 20 min (for servicing)
- Linac head on rails for servicing

Adapted from G. Fallone
Current Whole Body Installed

- Biplanar magnet assembly
- Treatment assembly
- Superconducting coil
- Gantry support link

Courtesy of G. Fallone

SUMMARY SURFACE DOSE

<table>
<thead>
<tr>
<th>Entry</th>
<th>Parallel</th>
<th>Perpendicular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease by &lt; 1/2</td>
<td>INsignificant increase</td>
<td></td>
</tr>
<tr>
<td>Increase by &gt; 1/2</td>
<td>SAME as Bo=0</td>
<td></td>
</tr>
</tbody>
</table>


Courtesy of G. Fallone

Ion chamber response

PR06C

Perpendicular

Parallel

INsignificant increase

SAME as Bo=0


Courtesy of G. Fallone
Concurrent Auto intra-fractional contouring, tracking & irradiation

Stationary CTV

Moving CTV

Large PTV

Current RT

CTV moves over

Radiation Field

Tracking CTV

without Prediction

Tracking CTV with Prediction= EXACT

ViewRay system implementation, Washington Univ, St. Louis

Viewray system

- MR scanner: 0.35 T, split-ring bore
- 3 x Co-60 teletherapy heads & MLCs
- DR: 550 cGy/min
- Rotating gantry assembly
- Room: 5.8 x 7.5 x 2.9 (m)
- Installation through maze | He vent
- FDA Clearance

www.viewray.com
Viewray system
- First patients treated - Jan. 2014
- Siteman Cancer Center & Wash U
- Ongoing: breast, bladder, lung, pancreas, stomach, palliative

PMCC, Toronto, Canada

PMCC MRgRT Project
- Varian TrueBeam 6X Linac room
- Brachy suite
- Control room
- Varian modified couch
- MR 1.5 T MR-Brain room
MRgRT Facility

Unit 1
Brachytherapy Suite
Brachytherapy Console
MR Suite
MR Console
Linac Suite
Linac Console
Screening room

MR Suite
MR Console
MRgRT Facility
Brachytherapy Suite
Brachytherapy Console

MR Suite
MR Console
MRgRT Facility
Linac Suite
Linac Console

MRgRT Facility

Zone I
- Freely accessible

Zone II
- Access to other zones
- Screening area

Zone III
- Magnetic field present
- Access restricted
- Supervised by MR staff
- Control for ferromagnetic objects

Zone IV
- Magnet room
- Very strong fields


System performance & Safety:
- System simulation CAD & FEM
- Experimental validation (B-field, forces)
- Couch performance
- Couch safety testing for B-field forces
- Beam testing after MR in the RT room
- MR shimming at 2 imaging positions
- End-to-end performance
### Application Sites for MR-guided External Beam

<table>
<thead>
<tr>
<th>Site</th>
<th>Support</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBRT Liver</td>
<td>++++</td>
<td>IG</td>
</tr>
<tr>
<td>SBRT Paraspinal Mets</td>
<td>++++</td>
<td>IG</td>
</tr>
<tr>
<td>RT for Cancer of the Cervix</td>
<td>++++</td>
<td>IG/A/R</td>
</tr>
<tr>
<td>RT for Partial Breast Irradiation</td>
<td>+++</td>
<td>IG/A</td>
</tr>
<tr>
<td>RT for Head and Neck (Oro)</td>
<td>++</td>
<td>IG/A</td>
</tr>
<tr>
<td>RT Prostate</td>
<td>*</td>
<td>IG/B</td>
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IG – Online Image Guidance; A – Adaptive; R – Response Assessment; B – Boost

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**UMC, Utrecht, Netherland**

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**Imaging Division**
MRL, therapy & oncology

MR-guided Radiotherapy

Jan Lagendijk, Bas Raaymakers, Marco van Vulpen

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**Courtesy of J. Lagendijk**
Vision

- Develop Centre of Image Guided Oncological Interventions
- Improving local cancer therapy and making this therapy non-invasive

System specs - Stereotactic MRI accelerator (MRL):
- MR scanner: 1.5T (Philips)
- Linac: 6X (Elekta)
- Gantry assembly: rotation in both directions - 10 rpm (slip ring) | 0.1° accuracy
- MLC field size 24 x 56 cm² – 7 mm leaves at iso
- 1 mm spherical volume as target at iso
- Simultaneous irradiation and MR imaging

Adapted from J. Lagendijk
Building and installing the MRI linac at the UMCU

Radiotherapy UMC Utrecht goes MRI

- Tumour characterization
- MRI simulation: delineation
- MRI guidance
  - MRI treatment guidance external beam
  - MRI guided brachytherapy
  - MRI guided HIFU
  - MRI guided protons
  - MRI guided radioembolization
- MRI treatment response assessment
The Australian MRI-Linac Program

**EQUIPMENT STATUS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Bunker</td>
<td>Crookes construction: ~14x12x5 m³, completed</td>
</tr>
<tr>
<td>Magnet</td>
<td>Agilent: 1T split bore, actively shielded with low field in linac region, delivery ~11/14,</td>
</tr>
<tr>
<td>Linac and MLC</td>
<td>Varian Linatron and Millennium MLC, delivered, installation ongoing</td>
</tr>
<tr>
<td>Spectrometer</td>
<td>Siemens, delivery ~12/14</td>
</tr>
<tr>
<td>Gradient coil system</td>
<td>Tesla, delivery ~11/14</td>
</tr>
<tr>
<td>RF system</td>
<td>Magnetics, delivery ~11/14</td>
</tr>
</tbody>
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**Research program overview**

- University of Sydney: Real-time imaging and treated adaptation
- University of Queensland: Image guided treatment
- University of New South Wales: Integrated system measurements
- University of Western Sydney: MR-linac program development
KEY SCIENTIFIC ACHIEVEMENTS

<table>
<thead>
<tr>
<th>Message</th>
<th>Source</th>
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<tbody>
<tr>
<td>The electron gun can be modified to operate in magnetic fields</td>
<td>Constantin Med Phys 2011, 2014</td>
</tr>
<tr>
<td>Real-time image guidance via template matching is feasible</td>
<td>Bjerre Phys Med Biol 2013</td>
</tr>
<tr>
<td>The MLC will not inhibit MRI image quality; if sufficiently separated</td>
<td>Kolling Med Phys 2013</td>
</tr>
<tr>
<td>Real-time MLC tracking is used for patient treatments</td>
<td>Keall Med Phys 2014</td>
</tr>
<tr>
<td>Skin dose is really high inline; but can be reduced</td>
<td>Oborn, Med Phys 2014</td>
</tr>
</tbody>
</table>
Acknowledgements

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A. Rink, K. Chan, K. Wang, F. Panici, W. Xia

IMRIS
J. Sarata, J. Winters, M. Dahan, D. Graves, L. Petropoulos, B. Guyot

Varian
M. Sweitzer, K. Kennedy, B. Saunders, B. Tonks, M. Harris,
J. Harrold, J. Marle, B. Barnard, P. Toi, K. Shet

Slides
J. Lagendijk, G. Fallone, P. Keal

MR Guided Radiation Therapy

Technology Review & Innovation – T. Stanescu

Commissioning & QA/QC - J. Balter

RT Planning - T. Nyholm

RT Guidance - J. Lagendijk