MRI Guided Radiotherapy: Integration of a Philips MRI scanner with an Elekta Linac

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Disclosures

• Related grant funding from Elekta
• Other (not related) funding from NCI, CPRIT, Varian

• The MRI-LINAC is a work-in-progress
• Equipment described is experimental only
• (and we don’t have one yet….)

• Lots of thanks to Bas Raaymakers (Utrecht) for slides
• Some slides are from Elekta
MRI-linac concept

- Introduction / general concepts
- Delivered dose
- Dose measurements
- Imaging
- Tracking
- Current status
MRI-linac: General concept
What clinical benefits could MR bring to IGRT?

- Difficult-to-image targets and critical structures become ‘easy’
- Improved ability to adapt treatment
- Ability to see the tumor not just the organ - GTV boost

- Imaging simultaneous with irradiation
- Gating and tracking without surrogates

- Freedom to image at any time

- Tumor treatment response assessment (inter-& intra-fractions)

Based on a slide from Elekta
The rectum, anatomy on MRI, from inside to outside:

- Lumen
- Three rectal wall layers:
  - Mucosal layer
  - Submucosal Layer
  - Muscle layer
- Mesorectal fat
- Mesorectal fascle

T2 weighted imaging

Courtesy of Martijn Intven
Breathing related motion

- Kidney tumour, irregular breathing
- bSSFP sequence (high SNR per unit time)
- Short $T_R$
- Parallel imaging, 2Hz

Stam & Crijns et al. PMB 2012
Integrating a 1.5 T MRI functionality with an Elekta radiotherapy accelerator
Concept of MRI accelerator

- Simultaneous MRI and irradiation
- Technical issues
  - Magnetic interference
  - Beam absorption
  - RF interference

Raaymakers et al. PMB 2009
15cm central region free from coils
8cm Al eq
Active magnetic shielding (pair of shield coils with opposite polarity)

Raaymakers et al. PMB 2009
1.5 T MRI accelerator: Simultaneous beam on and MRI

1.5 T diagnostic MRI quality

No impact of beam on MRI
Upgrading the prototype

Cooling equipment

Power supplies & electronics

MLC & accelerator waveguide

RF waveguides

Slipring

modulator
Effect of magnetic field on delivered dose
Point spread kernels as function of magnetic field

(a) $B = 0 \, T$    (b) $B = 0.2 \, T$    (c) $B = 0.75 \, T$    (d) $B = 1.5 \, T$    (e) $B = 3 \, T$
Dose deposition in a magnetic field
The Electron Return Effect (ERE)

$B = 0$

$B = 1.5 \, T$

Raaijmakers et al. PMB 2008
ERE (Electron Return Effect)
Dose increase at all tissue-air boundaries

From Raaijmakers et al. PMB 2005
If field covers whole phantom.....

Inhomogeneous Phantom

6 MV spectrum 5 x 5 cm²

Depth dose curve for single field

Impact of surface orientation

Raaijmakers 2007
Impact of surface orientation

Varying exit angle

Raaijmakers 2007
AP lung field
Mitigating the electron return effect:
Opposing beams
Opposed fields with angled surface

Raaijmakers 2007
Patient phantom - EGSnrc simulation

Modified from Kirkby et al, Med Phys, 2008
DVH for optimized dose distribution oropharynx
Comparison between B = 0 T and B = 1.5 T
What about the effect of RF coils?

Hoogcarospel et al., PMB 2013
Are there any radiobiological consequences?

- This is an open question….
- There are a few manuscripts, but mixed results…..
- So clinical experiments are underway……
Summary of Dose Perturbation Effects

• Reduction of buildup distance
• Laterally-shifted, asymmetric penumbra
• Electron return effect (distal and lateral)
• All of these can give hot and cold spots in the dose distributions
• Treatment planning: In some instances these effects can be mitigated by opposed, multiple, or inverse-planned fields
• Radiobiology questions remain (for now…..)

Effect of magnetic field on dose measurements
Effect of magnetic field on dose measurements

Meijsing et al, 2009
\( \vec{B} = 1 \text{ T} \)

Meijsing et al, 2009
What about TG51 measurements?

\[ M = M_{\text{raw}} \times P_{TP} \times P_{\text{ion}} \times P_{\text{pol}} \times P_{\text{elec}} \]

\[ D_w^Q = M k_O N_{D,w}^{60\text{Co}} \]

- Linearity, repeatability, influence of orientation
- Influence of B on \( P_{\text{ion}}, P_{\text{pol}} \)
- Impact of B on \( M_{\text{raw}} \) -> correction factor

\[ P_{1.5T} = \frac{M_{0T}}{M_{1.5T}} \]

Smit et al 2013
Ion chamber orientation

Linearity/reproducibility
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Without magnetic field</th>
<th>With magnetic field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Maximum deviation</td>
</tr>
<tr>
<td>Linearity</td>
<td>100.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>$P_{\text{ion}}$</td>
<td>1.000</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$P_{\text{pol}}$</td>
<td>1.000</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$P_{1.5\ T}$</td>
<td>0.953</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Relative Dosimetry, IC profiler versus film

Courtesy Kimmy Smit and Bas Raaymakers
Summary of dose delivery and measurement

- Effect of magnetic field on delivered dose can be significant
- In many situations this can be mitigated with appropriate planning approach
- Reference dosimetry is possible with additional correction factor, $P_{1.5}$
- More data for more detectors is needed
- Relative dosimetry seems feasible
Imaging
First generation high field MR Linac
Example volunteer image courtesy of Philips

High resolution (0.7mm x 0.7mm x 1mm), 3D acquisition with exquisite image quality in all planes

High frame-rate, multi-planar acquisition for motion monitoring

MR-Linac is currently a research programme. It is not available for sale and its future availability cannot be guaranteed. Confidential and privileged information. Not for distribution.
Can we do MV portal imaging?

• Yes – the detector does work.

• But….
  – Image quality is poorer (CNR approx ¼ that for conventional linac)
  – Increased SID (258cm)
  – Transmission through the MRI

• Fine for dynamic QA of field edges, perhaps for verification of MRI geometric corrections

Raaymakers 2011
Tracking
Gated and tracked radiation delivery on moving target (=lego cart)

- Phantom rides up and down the MRI table
- Beam gated or tracked
- 1D MRI navigator for fast target tracking
- Dose recorded by film on target

From Crijns et al. PMB 2011
Measured and MRI based reconstructed dose profiles for gated delivery

Tracking consistency: ~0.5mm for phantom, 1.5mm for patient

From Crijns et al. PMB 2011
Tracking experiment – results
Current Status
Elekta MR Linac Consortium established

The MR Linac Consortium aims to:

• Demonstrate improved patient outcomes for existing radiation therapy indications
• Extend radiation therapy with new treatment techniques and be able to treat more indications

Each consortium member will have a MR Linac for:

• Identifying clinical benefits and techniques
• Resolving clinical and technical challenges to implement these techniques
• Conducting clinical research to demonstrate the clinical value of the techniques

Current members:
– UMC Utrecht, MD Anderson, AvL/NKI,
– Sunnybrook, Medical College of Wisconsin

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UMCU announces start of installation of first high field MR Linac

- On 5 April 2014 UMCU announced the start of the installation of the next generation system
  - The system’s ring gantry on which Linac parts are mounted – was lowered by crane through a modular roof into one of UMC Utrecht’s radiotherapy treatment rooms

- Building and Testing will take place throughout 2014
MD Anderson
• Ashley Rubinstein
• Geoff Ibbott, Ph.D.
• Zhifei Wen, Ph.D.
• Jihong Wang, Ph.D.
• Jim Bankson, Ph.D.
• David Fried
• Xenia Fave
• Scott Ingram
• Josh Niedzielski
• Rachel Mccarroll
• Mindy Hsieh
• Adam Yock, Ph.D.
• Joey Cheung, Ph.D.
• Lifei Zhang, Ph.D.
• Jinzhong Yang, Ph.D.

MRI-Linac consortium members
• Bas Raaijmakers and team (Utrecht)
• Elekta/Philips MRI-linac team