In room Magnetic Resonance Imaging guided Radiotherapy (MRIgRT)

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Hybrid MRI accelerator system

Requires system integration: accelerator and MRI system have to operate simultaneously and independently.

closed bore high field MRI gantry ring based 6 MV MLC accelerator

1.5 or 3 T MRI
6 MV accelerator
Soft tissue visualization: MRI of cervix carcinoma

GTV primary tumor  bladder  rectum

GTV pathological lymph nodes (left)

GTV pathological lymph nodes (right)

T2-weighted
Tumour regression and movement

MRI cervix, each week
Prostate movement due to different rectum filling

MRI compatible fiducial marker

Different rectum filling

T1 SE
Prostate intrafraction movement

Ghilezan et al. 2005, Beaumont, PMH, NCI
Prostate intrafraction movement

probability of displacement $> 3$ mm

minutes

mid-posterior
solid line: full rectum
dashed line: empty rectum

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Dynamic MRI lung

- Fast dynamic MRI
- Coronal view
- normal breathing
Dynamic MRI lung

- Fast dynamic MRI
- Sagittal view
- normal breathing
Repeated MRI cervix
Besides positioning information:

**Treatment response assessment**

- evaluation of tumour regression
- dynamic evaluation of tumour characteristics like hypoxia
Tumour regression and IMRT re-planning

IMRT dose based on pre-treatment MRI

IMRT dose based on MRI after half radiotherapy course
DCE MRI T1-weighted FFE:
Perfusion before radiotherapy

Functional example

Cranial

? Uterus
? GTV

colour scale:
0-12 ml/100g min
Dynamic treatment response assessment perfusion

Perfusion before RT

Perfusion 1 week after start RT

? Uterus

? GTV

? Same colour scale:

0-12 ml/100g min
In room MRI

- superb soft tissue visualisation high field MRI (1.5 T, 3 T)
- dynamic (on-line)
- tumour characteristics
- tumour response assessment
- registration with dose distribution
Integrating a MRI scanner with a radiotherapy accelerator

Radiotherapy accelerator  1.5 T or 3 T MRI system
Hybrid MRI-linear accelerator
Technical feasibility of a hybrid MRI-accelerator

Potential project killers:

- Magnetic coupling accelerator and MRI system
- Beam transmission through MRI system
- Dose deposition in 1.5 T magnetic field
Technical feasibility of a hybrid MRI-accelerator

Potential project killers:

- Magnetic coupling accelerator and MRI system
- Beam transmission through MRI system
- Dose deposition in 1.5 T magnetic field
Principle of active B field shielding

Primary field configuration

Coils

Patient

Table

cryostat
Principle of active B field shielding

Primary field configuration

$B_{p_{\text{in}}}$

$B_{p_{\text{out}}}$

Coils

cryostat
Principle of active B field shielding

Compensation field configuration

$B_{c_{\text{in}}}$

$B_{c_{\text{out}}}$

Compensation coils
**Principle of active B field shielding**

\[ B_0 = B_{p_{\text{in}}} - B_{c_{\text{in}}} \]

\[ B_{0_{\text{out}}} = B_{p_{\text{out}}} - B_{c_{\text{out}}} = 0 \]

0 T area

B0 field configuration
Location of accelerator

accelerator
Coil configuration hybrid system

window for beam
Field map 1.5 T RT magnet

location gun < 1 mT
Magnetic interference

- Active magnetic shielding
  - Low field toroid around MRI to position the linac
  - Low far field to allow installation in vicinity of other linacs
- No significant compromise performance
- Not much different in manufacture
- Design also feasible with 3 T
Technical feasibility of a MRI accelerator combination

Potential project killers:
- Magnetic coupling accelerator and MRI system
- Beam transmission through MRI system
- Dose deposition in 1.5 T magnetic field
Supporting structures MRI (Philips)
Gradient and rf coils

accelerator

Gradient coils
RF coils
Currently:
- Cryostat 5cm Al + 1 cm steel
- Gradient coils 8 cm epoxy + up-to 4 cm Cu
- rf coils few mm Cu

Gradient coils highly heterogeneous
Radiation windows

accelerator

Gradient coils
RF coils
Geant4 modelling of Elekta SLi25-15

Pdd for a 10x10 field

10 x 10 cm, 6 MV, pdd

Norm. Dose (%) vs. Depth (cm)

Measurement
Simulation

Geant4 freely available at CERN: geant4.web.cern.ch
Scatter induction in MRI accelerator geometry

8 concentric layers aluminium, steel, epoxy. Equivalent to 7.5 cm alu. Optimised eq. 4.2 cm alu.
Conclusions beam transmission

- Geant4 allows “virtual” prototyping
- Scatter less compared to the scatter induced by a conventional wedge
Technical feasibility of a MRI accelerator combination

Potential project killers:
• Magnetic coupling accelerator and MRI system
• Beam transmission through MRI system
• Dose deposition in 1.5 T magnetic field
Dosimetry test site: 1.1 T Bruker magnet
Electron beam in 1.1 T field, film measurements

20 MeV electron beam

No B field

1.1 T field
Photon beam in a 1.1 T field, film measurements

6 MV photon beam

No B field

1.1 T field

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**Pencil beam, beam's eye view**

No magnetic field  
1.5 T magnetic field

6 MV photon beam, scaled on 10% of dose maximum
• Penumbra increase 1mm
• Buildup decrease 4-5 mm
• Field shifted 0.7 mm
• Field width unaffected
Dose deposition at tissue-air interfaces: the Electron Return Effect (ERE)

Electrons escape the phantom

Electrons return to the phantom

\[ B = 0 \]

\[ B \gg 0 \]

<table>
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<tr>
<th>E (MeV)</th>
<th>r (mm)</th>
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<tr>
<td>0.5</td>
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<tr>
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<td>10.0</td>
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<td>6.0</td>
<td>14.5</td>
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</tbody>
</table>
Dose deposition at tissue-air interfaces
Increased dose deposition at tissue-air interface: Electron Return Effect (ERE)
ERE compensation with opposite beams

Air Layer Opposite Field PDD

Relative Dose vs. Depth (cm)

- Center
- 12 mm
- 18 mm
ERE compensation with cylindrical cavity and opposite beams

Air Tube Opposite Field PDD

Depth (cm)

Relative Dose

- center
- 8 mm
- 12 mm
ERE compensation with four beams

Air Tube Four Field PDD

- Center
- 8 mm
- 12 mm

Depth (cm) vs. Relative Dose
First Geant4 dose depositions at tissue-air interfaces in CT based anatomy

tumour of the larynx, opposite fields 3x3 cm
Dose deposition at tissue-air interfaces

- ERE creates dose heterogeneity around air cavities in case of a single beam
- Dose distribution is anatomy specific
  - air cavities
  - orientation with respect to B field
- Effect can be countered by:
  - multiple beams
  - IMRT
  - can be used as a feature in multiple small field irradiation of laryngeal tumours
General conclusions MRIgRT

- (on line) Imaging superb
- no significant technological problems
- some scatter (must be optimised further)
- New effects like the Electron return effect (ERE) must be dealt with
MRIgRT problems presently being investigated at the UMC Utrecht

- Absolute dosimetry
- Geometrical accuracy MRI
- Calibration of absolute positioning (MRI versus accelerator)
- RF interference
- Coil design
- On line image registration
- On line treatment planning

Related:
- treatment response assessment
  - functional imaging (MRS, perfusion, hypoxia)
  - tumour regression