What is the Real Benefit of MRI-based Simulation and Planning?

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Disclosures

- None
Outline

- Current role of MR and its benefits in RT planning process
- CT-MR co-registration errors and clinical impact
- MR simulation
- Dose calculation in treatment planning
- MR-guided treatment delivery and verification
- Other considerations
  - Geometric distortions, MR scan acquisition time, costs
Role of MR in current radiation therapy

- MR has superior soft tissue contrast compared to CT
  - Tumor staging, response monitoring, detecting recurrence
  - Target and critical structure delineation for RT planning
Soft tissue contrast on MR vs. CT: Impact on tumor contours

- CT tumor contours overestimate the tumor

- **Cervical cancer:**
  - GTV cannot be seen on CT
  - Target volume on CT, 20%\(^1\) larger

- **Prostate cancer:**
  - Prostate: CT overestimates prostate volume by 27-35%\(^2-4\)
  - MR better for localizing prostatic apex,\(^3\) prostate-rectal and bladder-prostate interface, seminal vesicles, lymph nodes

- **Rectal cancer:**
  - Average tumor volumes 18 cc greater on CT\(^6\)
  - Average tumor dimensions greater by 0.5 to 3 cm on CT

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\(^1\)Wachter et al., Radiother Oncol (2003); \(^2\)Hentschel et al., Strahlenther Onkol (2011); \(^3\)Roach et al., IJROBP (1996); \(^4\)Rasch et al., IJROBP (1999); \(^5\)Milosevic et al. Radiother Oncol (1998); \(^6\)O’Neill et al., BJR (2009)
Contours on MR vs. CT: Dosimetric and clinical impact

- Smaller target volumes: reduced dose to OARs, potential for dose escalation
  - Prostate: lower dose to rectum and penile bulb allowing for dose escalations of 2-7 Gy$^{1-3}$
  - Reduced dose to rectal wall, reduces risk for late toxicities$^2$

- Accurate delineation of critical structures
  - Dose escalation while sparing normal tissue
  - Ex: urethral sparing in prostate SBRT

- Improved local control and overall survival
  - local control of $\geq 85\%^4$ with low treatment related morbidity for locally advanced, extensive cervical cancer

$^1$Steenbakkers et al., IJROBP (2003); $^2$Rasch et al., IJROBP (1999); $^3$Perna et al., Radiother Oncol (2009);
$^4$Pötter et al., , Radiother Oncol (2007)
Multi parametric MR imaging to guide RT planning

- Useful for boosting sub-lesions, or delivering high doses to a localized tumor region while sparing normal tissue
- Treatment delivery techniques (i.e. Brachytherapy, CyberKnife, VMAT) capable of achieving such complicated dose distributions

Images: Schmuecking et al., IJROBP (2009) and Haack et al., Acta Oncologica (2010)
CT-MR registration errors

<table>
<thead>
<tr>
<th>Year</th>
<th>Method</th>
<th>Anatomical Site</th>
<th>Reported co-registration error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kagawa et al., 1997</td>
<td>3 anatomical landmarks</td>
<td>Prostate</td>
<td>0.9 (±0.6)</td>
</tr>
<tr>
<td>Sannazzari et al., 2002</td>
<td>9-15 anatomical landmarks</td>
<td>Prostate</td>
<td>1.5</td>
</tr>
<tr>
<td>Krempien et al., 2003</td>
<td>Mutual information</td>
<td>H&amp;N, GYN</td>
<td>1.8 (±0.9)</td>
</tr>
<tr>
<td>Brock et al., 2010</td>
<td>Various deformable</td>
<td>Various</td>
<td>0.4 – 6.2</td>
</tr>
</tbody>
</table>

- Dependent on anatomical site and co-registration algorithm
- Rigid co-registrations are more accurate, yet may generate 1-2 mm uncertainties
  - Can be challenging for GU cancers (organ motion and deformation due to i.e. bladder and rectal filling, gas in bowel)

Table: Devic, Med Phys (2012)
Large uncertainties in deformable image co-registration algorithms

- Liver 4D CT: 0.8 – 5.9 mm
- Liver MR-CT: 1.1 – 5mm
- Prostate repeat MRI: 0.4-6.2 mm

Higher errors for multimodal registrations and anatomy with less contrast variation (i.e. prostate)

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### CT-MR registration errors

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Potential contributors to MR-CT registration errors

- Tumor/organ deformation due to physiological fillings (rectum, bladder)
- Differences in patient set up position from MR and CT acquisition
  - Immobilization devices not used for MR acquisition
  - Flat table top for CT vs. curved for diagnostic MR

Images: Harvey et al., BJR (2012)
MR simulators for radiation therapy

Common features:

- Larger bore size
- Flat table insert with indexing
- External laser positioning system
- MR compatible immobilization devices
- RF coils that accommodate immobilization devices
- Geometric distortion correction software
Clinical impact of registration errors:

- Compromises accuracy gained in target delineation on MRI
- Sophisticated treatment delivery technologies (i.e. CyberKnife, VMAT) capable of generating steep dose gradients
  - partial tumor miss (locally recurrent disease)
  - unintended overdosing of critical structures
- Uncertainties are larger than certain target volume margins, especially for SBRT
- Not quantified and clinically accounted for, in the RT planning process
Rationale for MR only RT planning

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Can we eliminate these uncertainties from treatment planning?
Why cannot we use MR for dose calculation?

- Lack of electron density information needed for dose calculation

CT

CT # to electron density conversion

Dose distribution on CT
Methods that allow for dose calculation on MR

(1) Homogeneous geometry

(2) Bulk density assignment

(3) Atlas based bone densities

(4) Atlas based density assignment

(5) Converting MR intensities to HUs
Methods that allow for dose calculation on MR

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Dose calculation on MR

(3) Atlas based bone densities

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(5) Converting MR intensities to HUs
(3). Atlas-based bone segmentation and density assignment

**Research version of Advantage Sim™ software (GE Healthcare)**

- Enhance cortical bone in MR to generate bone intensities similar to offline CT bone atlas
- Use bone atlas to segment and transfer heterogeneous bone densities to MR
- All soft tissue considered homogeneous

- Automated approach to generating pCTs
- Accuracy of bone segmentation needs further investigation and is pulse sequence dependent

G Novak et al, ASTRO 2011
(4). Atlas-based electron density mapping for all tissue

- Register input MRI to MRI atlas
  
  New input MRI
  
  Registration
  
  MRI atlas

- Apply same transformations, deformations to electron density atlas to generate pseudo CT
  
  CT
  
  MRI
  
  MR-CT registration
  
  Electron density atlas
  
  Pseudo CT

1Dowling et al., IJROBP 2012
Results

- Dose differences with reference CT ~ 1.5%

- Automated pseudo CT generation
- Includes bone and soft tissue heterogeneities

Limitations:
- Technique draws from average HUs – not patient specific
- Includes uncertainties caused by image co-registrations

1Dowling et al., IJROBP 2012
(5). Converting MR intensities to HUs

- T1/T2*-weighted MR intensity to HU conversion models for bone and soft tissue in the pelvis

ROI selection from different tissue on CT
To transfer to the co-registered MR

\[1\] Korhonen et al., Med Phys 2014
(5). Converting MR intensities to HUs

- T1/T2*-weighted MR intensity to HU conversion models for bone and soft tissue in the pelvis

HU Conversion Model for Soft Tissue

1Korhonen et al., Med Phys 2014
(5). Converting MR intensities to HUs

- 2D Gamma pass rates > 92% for 1%/1mm criteria
- Patient specific tissue heterogeneities
- **Limitation**: manual bone segmentation

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1 Korphonen et al., Med Phys 2014
Summarizing points: MR-based dose calculation

- Significant progress in developing methods for MR-based dose calculations
  - Patient specific MR intensity to HU conversion models are promising

- Can achieve dose differences < 1% compared to conventional CT

- Need accurate auto segmentation techniques or HU conversion models that do not require segmentation, for clinical implementation
MR-based treatment delivery

**ViewRay™**
- Co-60 based MRI-guided RT system

**U. Alberta, Canada**
- 0.2 T permanent MR
- 6 MV linac

**Australia MR-Linac program**
- 1T split bore
- Varian Linatron

**U.M.C. Utrecht, Netherlands**
- 1.5 T Phillips MRI
- 6 MV Elekta accelerator
What should the reference image series be for treatment verification?
- Pseudo CT or MR?

MR-based dose calculations → CT-based Linac treatment delivery (conventional linac, CyberKnife)

MR-based dose calculations → MR-guided treatment delivery (ViewRay, MR-Linac)
2D verification: DRR generation from MR

- DRRs directly generated from MRI have insufficient bony structure information for patient set up verification

Input MRI  
Projection through MR image set

G Novak et al, ASTRO 2011
2D verification: DRR generation from **pseudo-CT**

- DRRs directly generated from MRI have insufficient bony structure information for patient set up verification.
- Pseudo-CT based DRRs provide better information for patient positioning.

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**Input MRI**

**Projection through MR image set**

**Projection through Pseudo-CT**

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G Novak et al, ASTRO 2011
What should the **reference image series** be for treatment delivery?
- Pseudo CT or MR?

MR-based dose calculations → **CT-based Linac treatment delivery** (conventional linac)
MR for radiation therapy planning: Other considerations

- **Geometric distortions**
  - Due to nonlinearity of gradients and magnetic field inhomogeneities
  - Depends on,
    - scanner type
    - distance from scanner isocenter
    - quality of geometric correction software

- **Time for MRI scan acquisition**
  - Need high resolution scans for RT
  - Scan volume needs to be larger than for diagnostic MR scans
  - 1-2 min for CT vs. ~ 10 –15 mins for high resolution MR
  - Will need scan protocols specific to RTP

- **Significantly high capital and operational costs compared to CT**
Concluding remarks

What is the real benefit of MR simulation and treatment planning?
- Accuracy in target and critical structure delineation → dose escalation
- Multi parametric MR to guide radiation therapy
- Eliminating MR-CT registration errors from treatment planning

Is MR-based simulation feasible in the clinic?
- MR simulation is already in use in certain clinics.

What about MR-based treatment planning and verification?
- Accuracy in MR-based dose calculations are more than sufficient for clinical use, but requires automation
- MR-based images provide viable options for treatment verification
Acknowledgements

- Jean Pouliot
- Martina Descovich
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- Thank you to all of you for coming here today!