MR-Guided Brachytherapy

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Outline

• Traditional 2D technique for brachytherapy treatment planning

• Transition to MR-guided brachytherapy
  – GEC ESTRO recommendations

• Clinical commissioning of MR-guided brachytherapy
What is Brachytherapy?

- Brachytherapy is a modality of radiation treatment in which sealed radioactive sources are placed in close proximity of a tumor ("brachy" – Greek for "short").
Commonly Treated Sites

- Breastological
- Cervical Cancer
- Prostate
Cervical Cancer

- Most common gynecologic cancer worldwide
- Incidence has decreased significantly with widespread use of Pap tests, and early studies suggested a further reduction with introduction of HPV vaccine

http://www.cdc.gov/media/releases/2013/p0619-hpv-vaccinations.html
Cervical Cancer

• The American Cancer Society estimates that in the US in 2015 there will be:
  – ~ 12,900 newly diagnosed cases of invasive cervical cancer
  – ~ 4,100 deaths from cervical cancer

• Brachytherapy has been an integral component of care for patients with cervical cancer for over 100 years

http://www.cancer.org/cancer/cervicalcancer/detailedguide/cervical-cancer-key-statistics
Traditional Applicator

- Intrauterine tandem + ovoids
• Orthogonal x-ray images of the patient with the applicator in place

A. Gerbaulet et al., The GEC ESTRO Handbook of Brachytherapy, Chapter 14, Copyright 2002.
Applicator Reconstruction

- In order to visualize and reconstruct the applicator, x-ray markers were placed into the applicator(s) prior to imaging.
Conventional Dose Specification

- Manchester System
  - Point A – 2 cm sup of cervical os and 2 cm lat of cervical canal
  - Point B - 3 cm lateral to point A if tandem is midline, otherwise 5 cm lateral of midline
Limitations to Point A

• It relates to position of sources, not patient anatomy.
• It is very sensitive to position of ovoids relative to tandem.
• Depending on cervical size, it may reside inside or outside the tumor.
  • Underdosing large tumors
  • Overdosing small tumors
In 2000, the Groupe Europeen de Curietherapie (GEC) ESTRO Gynaecology WG was formed.

Their main focus was to support volumetric brachytherapy planning for cervical cancer.

II. Concepts and terms – DVH parameters, anatomy, radiation physics, and radiobiology (2006)

III. Considerations and pitfalls in commissioning and applicator reconstruction (2010)

IV. Basic principles and parameters for MR imaging (2012)
GEC-ESTRO Working Group

- Develop a common language
- HR CTV, IR CTV, LR CTV
- Feasibility and reproducibility study
- Goal was not to immediately change clinical practice
- Transition to volume based planning should be gradual

GEC-ESTRO Working Group

- Develop consistent dose volume parameters for target and OARs.
- Provide recommendations for switching to volume based.
Dose Volume Parameters

• Target (GTV, HR CTV, IR CTV)
  – D100 (controversial), D90
  – V100, V150, V200

• OAR (bladder, rectum, sigmoid)
  – D_{0.1cc}, D_{1cc}, D_{2cc} (contour only outer walls)
  – If organ inner and outer walls are contoured, D_{5cc} and D_{10cc}

• Plus std dose reporting (e.g., Point A)

In 2003, the ABS Image-Guided brachytherapy WG developed guidelines for volumetric based planning for cervical cancer.

- Very similar to GEC-ESTRO (some differences in the contouring of OARs).

To prevent any confusion, in 2005 the ABS decided to adopt the GEC ESTRO recommendations.

Imaging Recommendation

- T2 weighted MR images for target and OAR delineation
- Compared to CT, MR provides:
  - Superior soft tissue resolution
  - Clear distinction of cervical tumor from the uterus, bladder, and rectum.
  - Clear distinction of cervix versus vagina.
- Advantage of volumetric planning - adapt and conform dose to individual patient’s anatomy
Imaging Comparison

AP Radiograph

CT

T2W 3D (SPACE)
MR Imaging

• However, applicator reconstruction is challenging
  – Scanning sequences need to be optimized
  – Commercial MR compatible markers are limited
  – In-house markers are prone to errors
  – Applicator introduce artifacts
    • Minimal with plastic, but pronounced with titanium
Why is this an issue?

• Due to steep brachy dose gradients, reconstruction errors can produce significant deviations in doses to targets and OARs

• Thus it is important to properly commission applicators and your process

T.P. Hellebust et al., Radiotherapy and Oncology, 96, 153-160 (2010).
Applicator Selection - Plastic

http://static.elekta.com/Brachytherapy_Applicators/01Gynecology/index.html#p=8

www.varian.com/us/oncology/brachytherapy/resources/
Applicator Selection - Metal

Verify tested at your field strength

https://www.varian.com/oncology/products/treatment-delivery/brachytherapy-afterloaders-applicators/catalogues
Commissioning

- Staff training, including MR safety
- Optimize scan sequence
  - MR expertise important (radiologists, MR physicists)
- Determine how to reconstruct applicator
- Evaluate uncertainties (in phantom and \textit{in vivo})
- Develop workflow – identify all necessary equipment and resources
- Develop documentation
### Imaging Sequences

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Number</th>
<th>Mandatory (M)/optional (O)</th>
<th>Sequence</th>
<th>Plane orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT MRI scan</td>
<td>8</td>
<td>M</td>
<td>T2 FSE</td>
<td>Para-axial (according to cervix uteri)</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>M</td>
<td>T2 FSE</td>
<td>Para-sagittal (according to cervix uteri)</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>M</td>
<td>T2 FSE</td>
<td>Para-coronal (according to cervix uteri)</td>
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<tr>
<td></td>
<td>11</td>
<td>O</td>
<td>T2 FSE</td>
<td>Axial</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>O</td>
<td>3D T2 FSE isotropic</td>
<td>Coronal or axial with reconstructions</td>
</tr>
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<td></td>
<td>13</td>
<td>O</td>
<td>T1 FSE, FLASH, T1 GRE 3D</td>
<td>As appropriate</td>
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Limited to magnetic field strengths ranging from 0.2 – 1.5 T

Image distortions and artifacts expected to be greater with higher $\vec{B}$
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Imaging Sequences

• Kim et al. evaluated applicator artifacts/distortion using a 3T MR for T&O and T&R

• Advantage 3T vs 1.5T
  – ~double the SNR
  – Image contrast in uterine cervix and uterus higher
  – Faster acquisition

### Imaging Sequences

#### Phantom
- Artifacts off tip of tandem (T1W): 1.5 +/- 0.5 mm

#### In vivo
- Artifacts off tip of tandem (T1W): 2.6 +/- 1.3 mm
- Artifacts off tip of tandem (T2W): 6.9 +/- 3.4 mm

**T1W MR favorable sequence for applicator reconstruction**

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*Kim et al., Int J Radiation Oncology, 80 (3), 947-55 (2011)*

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<table>
<thead>
<tr>
<th>MR sequence type</th>
<th>Voxel size (mm³)</th>
<th>Slice thickness (mm)</th>
<th>Bandwidth (Hz)</th>
<th>TR (ms)</th>
<th>TE (ms)</th>
<th>Scanning time (min)</th>
<th>Scan direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1-weighted GRE</td>
<td>1.2 x 0.9 x 1.0</td>
<td>1.0</td>
<td>600</td>
<td>3.33</td>
<td>0.95</td>
<td>&lt;10</td>
<td>Axial</td>
</tr>
<tr>
<td>T2-weighted TSE</td>
<td>1.0 x 1.0 x 3.0</td>
<td>3.0</td>
<td>651</td>
<td>2,000</td>
<td>122</td>
<td>&lt;5</td>
<td></td>
</tr>
</tbody>
</table>
Applicator Reconstruction

- Digitization of tip and inner lumen of applicator in software (TPS)
  - Markers (plastic only)
  - Direct digitization
  - Fusing multiple image sets
  - Library plans/models
  - Commercial vs in-house
MR Compatible Markers

Schindel et al., Int J Radiation Oncology, 86 (2), 387-93 (2013).
Observation

• Marker based or direct digitization possible.

• However,
  – Longer acquisition time than CT
  – MR markers prone to errors
  – Additional uncertainties if multiple images are fused
Observation

- Susceptibility related artifacts result in large uncertainties in titanium applicator evaluation.
- Can be assessed by fusing CT and MR scans in phantom.

T.P. Hellebust, Radiotherapy and Oncology, 96, 153-160 (2010).
Observation

- Direct digitization is possible, but caution must be taken.
Commercial Models/Libraries

- Pre-defined source and applicator geometry files
- Often derived from computer-aided design (CAD) drawings
• Developed by user, typically on CT images
• Errors with models result in systematic errors in digitization
## Commercial Model Experience

### Plastic Vaginal Cylinder

#### In phantom

<table>
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<tr>
<th>Sequence</th>
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<th>Min (mm)</th>
<th>Max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1W 3D (MPRAGE)</td>
<td>0.5</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>T2W 3D (SPACE)</td>
<td>0.8</td>
<td>0.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

#### In vivo

<table>
<thead>
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<th>Min (mm)</th>
<th>Max (mm)</th>
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<tbody>
<tr>
<td>T1W 3D (MPRAGE)</td>
<td>1.2</td>
<td>0.5</td>
<td>1.9</td>
</tr>
<tr>
<td>T2W 3D (SPACE)</td>
<td>1.4</td>
<td>0.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Owrangi et al., JACMP, Accepted for publication.
In-house Model Experience
Titanium Ring & Tandem

T1W 3T (VIBE) scans were registered to CT

<table>
<thead>
<tr>
<th></th>
<th>Applicator</th>
<th>Aver (mm)</th>
<th>Min (mm)</th>
<th>Max (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In phantom</td>
<td>Tandem</td>
<td>0.9</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>In vivo</td>
<td>Tandem</td>
<td>2.6</td>
<td>0.4</td>
<td>8.0</td>
</tr>
<tr>
<td>In phantom</td>
<td>Ring</td>
<td>0.8</td>
<td>0.2</td>
<td>2.5</td>
</tr>
<tr>
<td>In vivo</td>
<td>Ring</td>
<td>1.7</td>
<td>0.2</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Larger observed errors may be due to:
- Systematic error in the model
- Complexity of the applicator
- Additional artifacts introduced by the titanium
Observations

- Uncertainties dependent
  - MR protocol
  - Magnetic field strength
  - Applicator
  - Whether a commercial model is available
  - Multiple imaging modalities
Workflow

• MR brachytherapy will require a change in clinical workflow of patients
  – Ensure you have MR compatible equipment, including anesthesia cart
  – Patient screened (day 1)
  – Imaging (CT and MR, or MR only)
  – Contouring of structures
  – Volume based planning
Conclusion

- Transition to volumetric based planning for cervical cancer is recommended by GEC ESTRO and ABR.
- Requires MR compatible equipment and extensive pre and post clinical commissioning
- Requires dedicated staff, and availability of radiology staff for consultation
Conclusion (Cont.)

- Since the introduction of MR-guided brachytherapy to clinical practice, significant improvements have been reported in clinical outcomes (e.g., reductions in normal tissue toxicity, and improvement in local control and overall survival).

Potter et al., Radiotherapy Oncology, 83(2), 148-55 (2007)
Jurgenliemk-Schulz et al., Radiotherapy Oncology, 93(2), 322-30 (2009)
Tanderup et al., Radiotherapy Oncology, 94(2), 173-80 (2010)
Potter et al., Radiotherapy Oncology, 100(1), 116-23 (2011)
THANK YOU!