Protocol development and MRI basics for the implementation of MRI in high dose rate brachytherapy
Ken-Pin Hwang
AAPM TG 303: MRI Implementation in HDR Brachytherapy
AAPM Annual Meeting, Washington, DC, July 12, 2022

Advantages of MRI in Cervical Cancer
T2-weighted imaging is optimal for differentiating tumor from normal tissue
- CT does not provide adequate contrast between tumor and normal tissue or organs-at-risk (OARs)
- Gynecologic tumors are often isointense relative to normal tissue
- Contrast-enhanced CT improves image quality, but tumor may still be isointense relative to healthy tissue
- Poor delineation of high-risk clinical target volume (HR-CTV) for radiotherapy
  - May reduce treatment efficacy

Differences from GEC-ESTRO
- Sagittal and coronal 2D T2 FSE made optional in favor of a 3D axial or oblique axial acquisition
- Optional DWI to aid in tumor delineation following EBRT-related treatment changes
- Optional FIESTA-C / CISS sequence for positive contrast in applicator channel
- Optional T1 in GEC-ESTRO not recommended for brachytherapy imaging

ABS-SAR Recommended MRI-guided Brachytherapy Protocols

<table>
<thead>
<tr>
<th>Series</th>
<th>Description</th>
<th>FOV (cm)</th>
<th>Slice Thickness (mm)</th>
<th>Gap (mm)</th>
<th>Matrix: Frequency Encoding</th>
<th>Matrix: Phase Encoding</th>
<th>Anatomic Coverage &amp; Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal or Sagittal-Oblique (T2-weighted)</td>
<td>3D T2 FSE or FRFSE</td>
<td>20–24</td>
<td>2–5</td>
<td>0</td>
<td>256</td>
<td>152–256</td>
<td>uterus, cervix, tumor, and applicator</td>
</tr>
<tr>
<td>Sagittal-Oblique (T2-weighted)</td>
<td>3D isotropic FRFSE</td>
<td>24–26</td>
<td>2–3</td>
<td>1–0</td>
<td>256–330</td>
<td>256–330</td>
<td>uterus, cervix, tumor, and applicator</td>
</tr>
</tbody>
</table>

T2w FRFSE MRI Applicator Appearance

Disclosures
Ken-Pin Hwang has received research support from GE Healthcare and Siemens Healthineers

Disclaimer:
We present specific examples of gynecologic imaging, but concepts are applicable to brachytherapy in general
Image Quality

Sequence parameters
- Sequence type
- FOV
- Matrix
- Bandwidth (F-W shift)
- Average (ROI)
- TR repetition time
- TE echo time
- Flip angle
- ETL

Image qualities
- Shift
- Resolution
- Speed
- Contrast
- Robustness against artifacts

Considerations for Brachytherapy
- Goal (IGEC-ESTRO, 2012)
  - Sufficient information about tumor/target extent, tumor/nontarget growth pattern and topography of pathoanatomical structures in three dimensions at the time of brachytherapy with the applicators in place

Challenges
- Application - metal reduce susceptibility effects
- Visualization of tumor anatomy - T2-weighted imaging
- Geometric accuracy
- Corrections, reduce shifts

Pros
- Robust against susceptibility
- Compatible with prep pulses (Fat Sat, Inversion)
- Time efficient k-space coverage
- Adjustable TE and TR for variety of contrasts
- Robust against susceptibility

Cons
- Violations:
  - Sufficient information about tumor/target extent, tumor/nontarget growth pattern and topography of pathoanatomical structures in three dimensions at the time of brachytherapy with the applicators in place
- Application - metal reduce susceptibility effects
- Visualization of tumor anatomy - T2-weighted imaging
- Geometric accuracy
- Corrections, reduce shifts

Matrix, FOV

Susceptibility

Susceptibility → \( \Delta f = \nu_B \Delta g \)
Typically expressed in \( \times 10^6 \) or ppm
Effects doubled at 3T!

Spin-echo RF pulse sequence: recovery of T2 relaxation effects

Why is this a problem?
Frequency encoding: Spatial gradients

Shift in frequency: violation of \( B_0 \) assumptions

Assumption:
- \( B_0 \) constant across FOV

Violations:
- \( \Delta B = \Delta f \) → distortion (\( \Delta g \)) in readout direction
- \( B_0 \) inhomogeneity → \( \Delta f = \nu_B \Delta B \)
- Spatial's mean magnetic field not perfectly uniform, \( \Delta B \) not constant across FOV

Susceptibility → \( \Delta f = \nu_B \Delta g \)
- Susceptibility of tissues, materials not uniform
- Composition and geometry of tissues, gases in patient

Chemical shift → \( \Delta f = \nu_B \Delta d \)
- Chemical composition not uniform
- \( \Delta g \) ppm -4 Hz at 1.5T, \(-220\) Hz at 3T
- Fat shift: 1-3ppm, 220 Hz at 1.5T, \(-440\) Hz at 3T

Gradient in Hz/mm will determine \( \Delta g \) for a given \( \Delta f \)
Shift in frequency: Mitigation

![Graph showing the relationship between gradient and FOV or pixel width.](image)

**Why it reduces chemical shift and distortion:**
Each millimeter spans a wider bandwidth, so shifts in frequency cause less shift in position.

**Tradeoff:** Increasing bandwidth reduces sampling time. This makes sampling faster but reduces SNR.
- BW: 2 = displacement / 4, SNR = 2

**How high is “enough”**?
- Rule of thumb: Expect double fat-water shift.
  - ~440 Hz at 1.5T, ~880 Hz at 3T

**Also preferable to map frequencies, but such techniques are not turnkey**

**Ideally increase bandwidth to achieve desired tolerance**

**However, may be limited by SNR and/or scan time**

**There are other sources of errors!**

---

**3D Pulse Sequences (vs stack of 2D slices)**

**Examples of 3D FSE/TSE sequences include:**
- CUBE (GE), SPACE (Siemens), VISTA (Philips), or 3D MVOX (Canon)

**Advantages**
- Phase encoding takes place in slice direction as well as phase encoding direction
  - No frequency shift distortion in PE or slice directions!
  - Allows for thinner slices, even isotropic acquisitions
  - Ideal for reformatting from single sequence, but in native plane they are generally lower resolution than 2D
  - Reconstruction determines reconstructed slice thickness – less “stair step” artifact than interpolation after recon
  - Enables gradient nonlinearity corrections in all three dimensions (3D GNL correction)

**Disadvantages**
- Time required to encode increased slices typically results in lower native plane resolution
- Contrast altered compared to 2D sequences – less of a concern for applicator reconstruction

---

**Summary**

MRI is preferred imaging modality for guidance of HDR brachytherapy
- General consensus around the use of T2-weighted FSE/TSE sequences

**Susceptibility differences from applicators present challenge in designing protocols**
- Spin-echo sequences refocus T2* decay and are necessary for T2-weighted imaging
- Gradients map frequency to position and are controlled by bandwidth and FOV

---

**Slices selection and phase encoding**

**What about slice selection?**
Similar relationship between BW and position, but can’t detect or measure

**Can’t control pulse bandwidth (and often don’t know unless you ask vendor), but can use thinner slices**
- Sharper resolution but also lower SNR
- Thinner slices (~3mm) also better for reconstruction

**What about the phase encoding direction?**
Phase encoding direction is immune to frequency shifts!

**Why?**
- Every phase encoded line is acquired at the same time from excitation. At echo time TE, spin phase is constant from line to line.

---

**Distortions from gradient non-linearity**

**Assumption:** G approximately linear across FOV

**Reality:** Distortion in every encoding direction

**Mitigation:**
- Reliant on vendor supplied corrections (image warping), activated in sequence settings (2D vs 3D correction)

**Expect residual errors away from isocenter:**

---

**Thanks!**

Contact:
- Ken-Pin Hwang
  - khwang@mdanderson.org
  - [kwhang@mdanderson.org](mailto:kwhang@mdanderson.org)

---

**References**

- AAPM Task Group 303
- Contemporary image-guided cervical cancer brachytherapy: Consensus imaging recommendations from the Society of Abdominal Radiology and the American Brachytherapy Society
  - [PDF](#)
  - [PDF](#)

- Use of MR for image-guided Cervix Brachytherapy
  - SWAAPM Annual Meeting, April 2022

- MRI Principles & Quality Characteristics
  - AAPM Diagnostic Review Course, July 2022

- Chris Walker, Ping Hou

---

**Image credits:**
- 'spin-echo' pulse sequence diagram
  - [Image](#)

- [Image](#)

---

**3D Pulse Sequences (vs stack of 2D slices)**

- CUBE (GE), SPACE (Siemens), VISTA (Philips), or 3D MVOX (Canon)

**Advantages**
- Phase encoding takes place in slice direction as well as phase encoding direction
  - No frequency shift distortion in PE or slice directions!
  - Allows for thinner slices, even isotropic acquisitions
  - Ideal for reformatting from single sequence, but in native plane they are generally lower resolution than 2D
  - Reconstruction determines reconstructed slice thickness – less “stair step” artifact than interpolation after recon
  - Enables gradient nonlinearity corrections in all three dimensions (3D GNL correction)

**Disadvantages**
- Time required to encode increased slices typically results in lower native plane resolution
- Contrast altered compared to 2D sequences – less of a concern for applicator reconstruction

---

**Summary**

MRI is preferred imaging modality for guidance of HDR brachytherapy
- General consensus around the use of T2-weighted FSE/TSE sequences

**Susceptibility differences from applicators present challenge in designing protocols**
- Spin-echo sequences refocus T2* decay and are necessary for T2-weighted imaging
- Gradients map frequency to position and are controlled by bandwidth and FOV

---

**Slices selection and phase encoding**

**What about slice selection?**
Similar relationship between BW and position, but can’t detect or measure

**Can’t control pulse bandwidth (and often don’t know unless you ask vendor), but can use thinner slices**
- Sharper resolution but also lower SNR
- Thinner slices (~3mm) also better for reconstruction

**What about the phase encoding direction?**
Phase encoding direction is immune to frequency shifts!

**Why?**
- Every phase encoded line is acquired at the same time from excitation. At echo time TE, spin phase is constant from line to line.

---

**Distortions from gradient non-linearity**

**Assumption:** G approximately linear across FOV

**Reality:** Distortion in every encoding direction

**Mitigation:**
- Reliant on vendor supplied corrections (image warping), activated in sequence settings (2D vs 3D correction)

**Expect residual errors away from isocenter:**

---

**Thanks!**

Contact:
- Ken-Pin Hwang
  - khwang@mdanderson.org
  - [kwhang@mdanderson.org](mailto:kwhang@mdanderson.org)

---

**References**

- AAPM Task Group 303
- Contemporary image-guided cervical cancer brachytherapy: Consensus imaging recommendations from the Society of Abdominal Radiology and the American Brachytherapy Society
  - [PDF](#)
  - [PDF](#)

- Use of MR for image-guided Cervix Brachytherapy
  - SWAAPM Annual Meeting, April 2022

- MRI Principles & Quality Characteristics
  - AAPM Diagnostic Review Course, July 2022

- Chris Walker, Ping Hou

---

**Image credits:**
- 'spin-echo' pulse sequence diagram
  - [Image](#)

- [Image](#)
B₀ assumption violations

- Fat protons have a different chemical environment.
- The local magnetic field is shifted due to this environment.
- Like other B₀ violation assumptions, this chemical shift leads to a shift in the local resonance frequency and therefore distortion.
- Magnitude of in-plane shift of fat and water pixels.

\[ \Delta f = B₀ \cdot \Delta x \]

Susceptibility → \( D_f = g \cdot B₀ \cdot D_c \) • tissue • metal

Chemical shift → \( D_f = g \cdot B₀ \cdot D_d \)

Fat protons have a different chemical environment. The local magnetic field is shifted due to this environment. Like other B₀ violations assumptions, this chemical shift leads to a shift in the local resonance frequency and therefore distortion. Magnitude of in-plane shift of fat and water pixels.

\[ \Delta x = \frac{\Delta f}{B와 FOV_0} = \frac{\delta x}{\delta f} = \text{BW/pixels} \]

Additional Protocol Options

- No Phase Wrap, Phase Oversampling, Fold-over Suppression, Phase-wrap Suppression
- Oversampling in the phase encode direction to reduce aliasing/wrap-around artifacts
- Highly recommended!

Small FOV techniques (i.e. FOCUS, ZOOMit, UZOOM):
- Techniques that only excite a smaller inner FOV to avoid aliasing artifacts
- Frequently used for DWI imaging in prostate and gynecologic imaging
- Reduces geometric distortion on echo planar imaging sequences

Acceleration techniques:
- Parallel Imaging
- Compressed Sensing
- Partial Fourier

Reconstruction options:
- Deep learning reconstructions are becoming increasingly available
- Increase SNR while maintaining scan time or spatial resolution

Upcoming ABS-SAR “Optional” MRI-guided Brachytherapy Sequences

<table>
<thead>
<tr>
<th>Description</th>
<th>coil</th>
<th>Pulse Sequence</th>
<th>FOV [cm]</th>
<th>Slice Thickness [mm]</th>
<th>Slice Gap [mm]</th>
<th>Matrix: Frequency Encoding</th>
<th>Matrix: Phase Encoding</th>
<th>Analytic Coverage &amp; Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial or Axial Oblique T2-weighted</td>
<td>3D</td>
<td>FFE or FRFSE</td>
<td>24 – 26</td>
<td>2 – 5</td>
<td>0</td>
<td>256 – 320</td>
<td>256 – 320</td>
<td>Uterus, cervix, tumor, and applicator</td>
</tr>
<tr>
<td>Coronal or Coronal Oblique T2-weighted</td>
<td>2D</td>
<td>FFE or FRFSE</td>
<td>24 – 26</td>
<td>2 – 5</td>
<td>0</td>
<td>256</td>
<td>192 – 256</td>
<td>Uterus, cervix, tumor, and applicator</td>
</tr>
<tr>
<td>Sagittal T2-weighted</td>
<td>3D</td>
<td>SS</td>
<td>20 – 24</td>
<td>2 – 3</td>
<td>-1 – 0</td>
<td>192</td>
<td>192</td>
<td>Whole applicator; used for imaging positive contrast markers</td>
</tr>
</tbody>
</table>