Protocol development and MRI basics for the implementation of MRI in high dose rate brachytherapy

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AAPM TG 303: MRI Implementation in HDR Brachytherapy
AAPM Annual Meeting, Washington, DC, July 12, 2022

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center
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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

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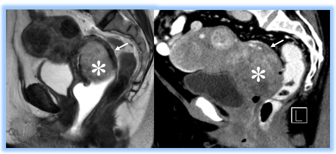
Advantages of MRI in Cervical Cancer

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



Sagittal T2-weighted (T2w) MRI (left) and portal venous CT (right) in a 58-year-old female with prolapsed endometrial tumor and multiple uterine leiomyomas. The cervix (white arrows) cannot be readily differentiated from tumor (*) on CT but has characteristic low signal-intensity on T2w MRI and is easily visible relative to the hyperintense tumor.

Venkatesan AM (2019) RadioGraphics. https://doi.org/10.1148/rg.2019180121.
Salib MY (2018) RadioGraphics. https://doi.org/10.1148/rg.2020200013

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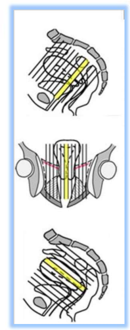
GEC-ESTRO MRI Protocols

GEC-ESTRO Recommended sequences:

- 2D T2 FSE, Oblique Axial
- 2D T2 FSE, Oblique Sagittal (or straight)
- 2D T2 FSE, Oblique Coronal

GEC-ESTRO Optional sequences

- 3D T2 FSE isotropic (coronal or axial)
- 2D Axial T2 FSE above uterine corpus or below applicator
- 3D T1 FSE, FLASH, or GRE (desired orientation)



Dimopoulos JCA (2012) Radiother Oncol. https://doi.org/10.1016/j.radonc.2011.12.024

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ABS-SAR Recommended MRI-guided Brachytherapy Protocols

Series Description	Dim	Pulse Sequence	FOV (cm)	Slice Thickness (mm)	Slice Gap (mm)	Matrix: Frequency Encoding	Matrix: Phase Encoding	Anatomic Coverage & Notes
Sagittal or Sagittal Oblique T2-weighted	2D	FSE or FRFSE	20 – 24	2 – 5	0	256	192 – 256	Uterus, cervix, tumor, and applicator
Axial or Axial Oblique T2-weighted	3D	Isotropic FRFSE	24 – 26	2 – 5	-1 – 0	256 – 320	256 – 320	Uterus, cervix, tumor, and applicator

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

Jacobsen MC (2022) Brachytherapy. https://www.sciencedirect.com/science/article/pii/S1538472122000733

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T2w FRFSE MRI Applicator Appearance

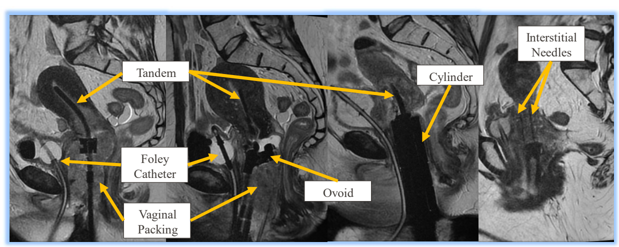

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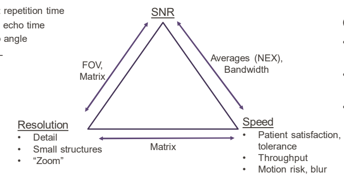
Image Quality

Sequence parameters
- Sequence type

- FOV
- Matrix
- Bandwidth (F-W shift)
- Averages (NEX)

- TR: repetition time
- TE: echo time
- Flip angle
- ETL

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



Considerations for Brachytherapy

Goal (GEC-ESTRO, 2012)
- Sufficient information about tumor/target extent, tumor/target growth pattern and topography of pathoanatomical structures <u>in three dimensions at the time of brachytherapy with the applicators in place</u>

Challenges
- Applicator:
  Metal - reduce susceptibility effects
- Visualization of tumor, anatomy:
  T2 weighted imaging
- Geometric accuracy:
  Corrections, reduce shifts

Dimopoulos JCA (2012) Radiother Oncol. https://doi.org/10.1016/j.radonc.2011.12.024

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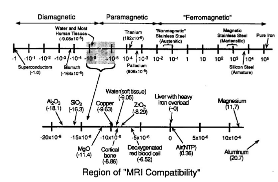
Susceptibility

Susceptibility $\rightarrow \Delta f = \gamma B_0 \cdot \Delta\chi$

Typically expressed in 10^{-6}, or ppm

Effects doubled at 3T!

SUSCEPTIBILITY SPECTRUM



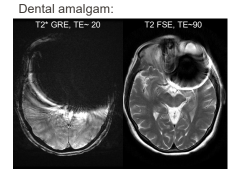
Schenck JF, Med Phys, 1996

Tissues and materials have varying magnetic susceptibility

Particularly near interfaces, these differences can cause shifts in local magnetic field

Two major effects:
- <u>Shift in frequency</u>: distorts assumed relationship between frequency and position created by system gradients
- <u>Spread of frequencies</u> within a voxel: local gradient, dephasing of spins causes rapid T2* signal decay

Dental amalgam:



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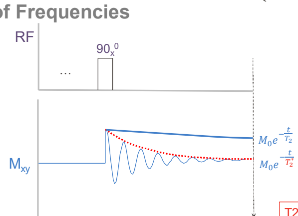
Spread of Frequencies

$$s(t=\mathrm{TE}) \sim \underbrace{\mathrm{PD}}_{\text{proton density}}\ \underbrace{(1-\cancel{e^{-\mathrm{TR}/\mathrm{T1}}})}_{\text{Longitudinal contribution } (M_z)}\ \underbrace{e^{-\mathrm{TE}/\mathrm{T2}}}_{\text{Transverse contribution } (M_{xy})}$$



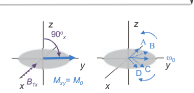
T2-weighted Imaging:
- Long rep. time TR (>2000 msec)
- "Long" echo time TE (80-120 msec)

After 90x rf pulse, M_{xy} decays with T_2^*(≈10 msec), not T_2 (≈60-100 msec)

<u>T2*</u> primarily determined by spread of frequencies (slight gradient) within a voxel, including those caused by susceptibility differences

<u>T2</u> primarily determined by spin-spin interactions

Rotating frame:
isochromat spreading due to ±dB in voxel



Jung BA, Weigel M. Spin echo magnetic resonance imaging. J Magn Reson Imaging. 2013 Apr;37(4):805-17.

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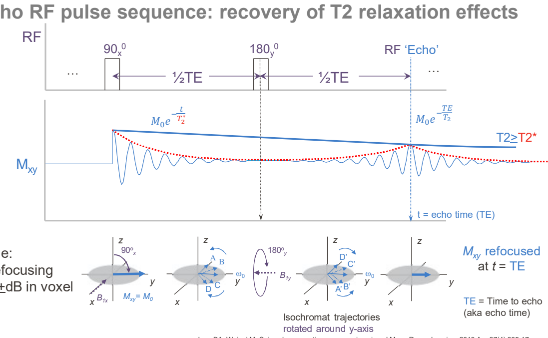
Spin-Echo RF pulse sequence: recovery of T2 relaxation effects



Rotating frame:
isochromat refocusing due to same ±dB in voxel

Jung BA, Weigel M. Spin echo magnetic resonance imaging. J Magn Reson Imaging. 2013 Apr;37(4):805-17.

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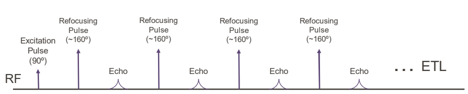
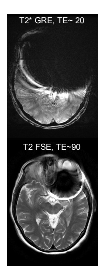
The Clinical Workhorse
FSE / TSE (Fast Spin Echo / Turbo Spin Echo)





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

<u>Cons</u>
- Sensitive to motion / flow artifacts
- High flip angles – SAR, dielectric
- Contrast doesn't exactly match spin echo
- Inter-slice effects
  - Crosstalk
  - Magnetization Transfer

Long ETL (12-24) for T2-weighted imaging

Long TR (>2000ms), TE ~ T2 (80-120ms)

$$s(t=\mathrm{TE}) \sim \underbrace{\mathrm{PD}}_{\text{proton density}}\ \underbrace{(1-\cancel{e^{-\mathrm{TR}/\mathrm{T1}}})}_{\text{Longitudinal contribution } (M_z)}\ \underbrace{e^{-\mathrm{TE}/\mathrm{T2}}}_{\text{Transverse contribution } (M_{xy})}$$

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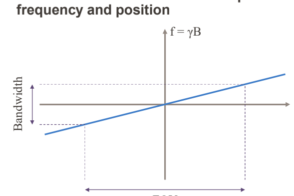
Shift in frequency: violation of B_0 assumptions

Why is this a problem?
Frequency encoding: Spatial gradients create assumed linear relationship between frequency and position



$$Gradient\ \left(\frac{Hz}{mm}\right) = \frac{Total\ BW}{FOV} = \frac{BW/pixel}{Pixel\ width}$$

Matrix, FOV

Assumption:
B_0 is constant across FOV

Violations:
$\Delta B \Rightarrow \Delta f \Rightarrow$ distortion (Δx) in ***<u>readout</u>*** direction

B_0 inhomogeneity $\rightarrow \Delta f = \gamma \Delta B$
- Scanner's main magnetic field is not perfectly uniform, especially away from isocenter

Susceptibility $\rightarrow \Delta f = \gamma B_0 \cdot \Delta\chi$
- Susceptibility of tissues, materials not uniform
- Composition and geometry of tissues, gases in patient

Chemical shift $\rightarrow \Delta f = \gamma B_0 \cdot \Delta\delta$
- Chemical composition not uniform
- 1 ppm ~64 Hz at 1.5T, ~128 Hz at 3T
- Fat shift ≈3.5ppm, ≈ 220 Hz at 1.5T, ≈ 440 Hz at 3T

Gradient in Hz/mm will determine Δx for a given Δf

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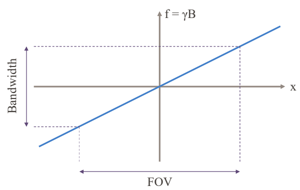
Shift in frequency: Mitigation

What can we do?

Increase gradient by increasing bandwidth or decreasing FOV or pixel width



$$Gradient\ \left(\frac{Hz}{mm}\right) = \frac{Total\ BW}{FOV} = \frac{BW/pixel}{Pixel\ width}$$

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 · ½, 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!

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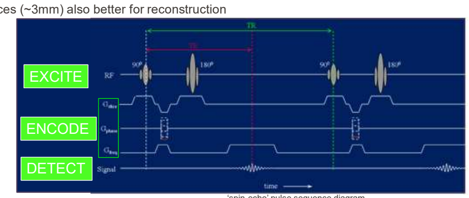
Slice selection and phase encoding

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
- Thin slices (~3mm) also better for reconstruction

What about the phase encoding direction?
PE 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.



'spin-echo' pulse sequence diagram

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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!
  - <10 min is feasible with parallel imaging, compressed sensing, and/or partial Fourier techniques
- 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

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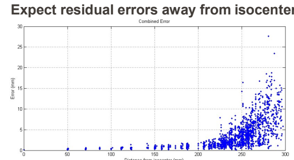
Distortions from gradient non-linearity

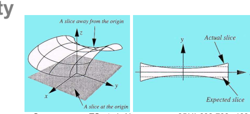
Assumption:
G approximately linear across FOV

Reality:
Distortion in every encoding direction

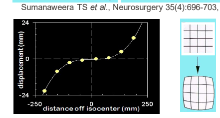
Mitigation:
Reliant on vendor supplied corrections (image warping), activated in sequence settings (2D vs 3D correction)

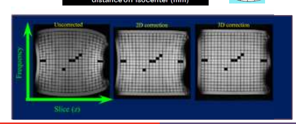
Expect residual errors away from isocenter:





Sumanaweera TS *et al.*, Neurosurgery 35(4):696-703, 1994.





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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

Susceptibility causes T2* signal decay and frequency shifts
- 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

Frequency shift distortion
- Readout direction: reduced by increasing bandwidth or decreasing FOV
- Slice selection: reduced by using thinner slices
- Phase encoding direction is immune to frequency shift distortion

3D sequences achieve thinner slices and are more robust against distortion

Gradient nonlinearity is always in effect in all directions but mitigated by vendor supplied corrections

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Thanks!

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Contemporary image-guided cervical cancer brachytherapy: Consensus imaging recommendations from the Society of Abdominal Radiology and the American Brachytherapy Society
(2022) Brachytherapy.
https://www.sciencedirect.com/science/article/pii/S1538472122000733

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

R. Jason Stafford
MRI Principles & Quality Characteristics
AAPM Diagnostic Review Course, July 2022

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MD ANDERSON CANCER CENTER

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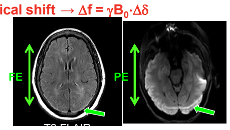
B_0 assumption violations

B_0 homogeneity → $\Delta f = \gamma \Delta B$

Susceptibility → $\Delta f = \gamma B_0 \cdot \Delta\chi$
- tissue
- metal

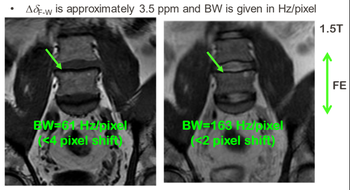
Chemical shift → $\Delta f = \gamma B_0 \cdot \Delta\delta$



- Fat protons have a different chemical environment.
- The local magnetic field is shifted due to this environment
- Like other ΔB 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:

$$\delta x = \frac{\Delta f}{BW} \cdot FOV_x \implies \boxed{\frac{\delta x}{\Delta x} = \frac{\Delta f}{BW/pixel}}$$

- $\Delta\delta_{F\text{-}W}$ is approximately 3.5 ppm and BW is given in Hz/pixel



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Upcoming ABS-SAR **Optional* MRI-guided Brachytherapy Sequences

Series Description	Dim	Pulse Sequence	FOV (cm)	Slice Thickness (mm)	Slice Gap (mm)	Matrix: Frequency Encoding	Matrix: Phase Encoding	Anatomic Coverage & Notes
Axial or Axial Oblique T2-weighted	2D	FSE or FRFSE	24 – 26	2 – 5	0	256 – 320	256 – 320	Uterus, cervix, tumor, and applicator
Coronal or Coronal Oblique T2-weighted	2D	FSE or FRFSE	24 – 26	2 – 5	0	256	192 – 256	Uterus, cervix, tumor, and applicator
Axial or Axial Oblique DWI	2D	EPI	28 – 35	4 – 5	0	80 – 128	80 – 128	Perineum to top of L5; b = 0 – 150 & 800 - 1000
Sagittal T2/T1-weighted	3D	CISS FIESTA-C	20 – 24	2 – 3	-1 – 0	192	192	Whole applicator; used for imaging positive contrast markers

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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, iZOOM)
- 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

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