**Imaging Artifacts - CT, MRI, and Mammography**

**MR Artifacts: A Different Spin**

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**MRI Acquisition in a Nutshell**

- **Pulse Sequences determine k-space trajectory properties**

\[
S(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho(x, y) e^{-2\pi i (k_x x + k_y y)} \, dx \, dy
\]

- **Center (SNR; Contrast)**

- **Outer (Edges)**

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**Image Quality & k-space data**

- Full sampling
- Center (SNR; Contrast)
- Outer (Edges)

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**Artifacts arise from signal errors in k-space**

- **Line artifacts**
- **RF artifacts**
- **FOV/2 "ghosts"**
Common MRI artifacts

<table>
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<tr>
<th>Artifact source</th>
<th>Correction</th>
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<td>Resonant</td>
<td>Measure or estimate field map</td>
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<td>Main field inhomogeneity</td>
<td>Use field map to detour or remove artifacts</td>
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<td>Chemical shift</td>
<td>Use up-to-date hardware and calibration</td>
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<td>Magnetic susceptibility</td>
<td>Use error tolerant designs and approaches</td>
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<td>Gradient nonuniformities</td>
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<td>Time errors</td>
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<td>RF field nonuniformity</td>
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<td>Limited dynamic range</td>
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<td>Motion</td>
<td>Acquire data only during stationary intervals</td>
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<td>Distortion</td>
<td>Discard data not acquired during</td>
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<td>Displacement; contrast error</td>
<td>Estimate motion and compensate data acquired</td>
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<td>Correlated motion</td>
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Errors in $B_0$: Magnetic Susceptibility & Chemical Shift Artifacts

- T2 GRE
- T2 FSE
- Metal Artifact Reduction
- Chemical Shift
- SS EPI
- T2 FLAIR
- HASTE
- BSSFP
- MagnaFit

Errors in $G$: Distortions from gradient non-linearity

Assumption: $G$ is approximately linear across FOV

$\delta x = \frac{\Delta G}{G}$

Solutions:
- Use higher bandwidth
- Use smaller voxel
- Use 3D imaging
- Use metal imaging
- Use non-linear correction
- Use restricted field of view
- Use CT fusion

Excitation ($B_1^+$) Homogeneity: Standing wave (dielectric) artifacts

- 1.0 T: $\lambda_{B1} = 79 \text{ cm}$
- 1.5 T: $\lambda_{B1} = 52 \text{ cm}$
- 3.0 T: $\lambda_{B1} = 26 \text{ cm}$
- 7.0 T: $\lambda_{B1} = 11 \text{ cm}$

Distortions from magnetic field errors

Assumption: $B_0$ is approximately constant across FOV

$\delta B = \frac{\Delta B}{B}$

Solutions:
- Use higher bandwidth
- Use smaller voxel
- Use 3D imaging
- Use metal imaging

Errors in $B_0$: Magnetic Susceptibility & Chemical Shift Artifacts

- T2 FSE
- T2 FLAIR
- Metal Artifact Reduction
- SS EPI
- T2 FLAIR
- HASTE
- BSSFP

Errors in $G$: Distortions from gradient non-linearity

Assumption: $G$ is approximately linear across FOV

$\delta G = \frac{\Delta G}{G}$

Solutions:
- Use higher bandwidth
- Use smaller voxel
- Use restricted field of view
- Use CT fusion
Excitation (B1+) Homogeneity: Standing wave (dielectric) artifacts

**B1+**

- 1.0 Tesla: \( k_{B1+} = 79 \text{ cm} \)
- 1.5 Tesla: \( k_{B1+} = 52 \text{ cm} \)
- 3.0 Tesla: \( k_{B1+} = 26 \text{ cm} \)
- 7.0 Tesla: \( k_{B1+} = 11 \text{ cm} \)

1.5T and 3T:

- Standing wave artifacts:
  - Dielectric interface between air and tissue
  - Fat and muscle layers


Phased array issue (B1-):

**Peripheral Signal Artifacts**

- FOV - Excited signal outside encoded volume (shim, non-linear gradients, etc.) picked up by active coil elements.

**Solutions:**

- Turn off unnecessary elements
- Swap phase and frequency encode directions
- Spatial saturation

**Short/Inside bone systems more prone to this artifact**

Phased array issue (B1-):

**Parallel Imaging Artifacts**

- Sensitive to coil setup, element density and independence (p-factor)
- Primary artifacts with incorrect encoding and noise enhancement
- Artifacts increase with acceleration factor (R) which is more undersampling

- Solutions: SENSE/ASSET, GRAPPA/ARC

- Techniques: SENSE/ASSET, GRAPPA/ARC

- Artifacts increase with acceleration factor (R) which is more undersampling

Fat Suppression and Saturation

- T2W+FS
- T2W-STIR
- T1W PRE
- T1W "DIXON"

Dixon Fat-Water Imaging Artifacts

- Thrombus mimicking artifacts (3D Dixon MRA)

4D Dixon for Dynamic 3D Acquisitions

- Artifactual tradeoffs
  - Larger R: slower sampling temporal averaging
  - Smaller R: more dynamic, faster resolution

Artifact tradeoffs:

- **Dixon**: Smaller A → slower sampling temporal averaging
  Smaller A → faster dynamic spatial resolution
  Gibbs ringing

Echo-Planar Imaging (EPI)

- Echo Planar Imaging is a fast imaging technique that utilizes an echo-train readout for subsecond image acquisition

  - The sequence k-space trajectory and sequencing determine a lot of its imaging properties (and artifacts)
  - The sequence is a workhorse for a variety of advanced imaging used clinically
    - Diffusion Weighted Imaging (DWI) and Diffusion Tensor Imaging (DTI)
    - Blood Oxygen Level Dependent (BOLD) contrast (e.g., fMRI)
    - Dynamic Susceptibility Contrast (DSC) imaging
    - MR Elastography (MRE)
    - Chemical Exchange Saturation Transfer (CEST)

Spin-Echo Echo-Planar Imaging (SE-EPI) for DWI

- Strong diffusion gradients → long TE
- High readout bandwidth to reduce ESP
- Ramp Sampling to reduce ESP
- Effective ESP

Common ss-EPI DWI artifacts

- Artifacts in phase encoding direction due to long ETL readout
  - Susceptibility
  - Eddy current
  - Chemical shift
  - T2* filtering
  - N2/Ghosting

- Artifacts in DWI & ADC map contrast
  - T2* "shine through" motion

\[ M_{1\text{eff}} = \frac{1}{\delta \gamma \gamma_{1\text{p}}} + \frac{1}{\delta \gamma \gamma_{1\text{q}}} + \frac{1}{\delta \gamma \gamma_{1\text{t}}} \]

\[ M_{2\text{eff}} = \frac{1}{\delta \gamma \gamma_{2\text{p}}} + \frac{1}{\delta \gamma \gamma_{2\text{q}}} + \frac{1}{\delta \gamma \gamma_{2\text{t}}} \]
Multi shot DWI & ADC Mapping Issues: T2 Shine Through & Motion

- T2* Filtering Effects
  - Signal decays in phase encoding direction
  - Amount of decay is based on ETL, ESP and tissue T2* value
  - K-space is apodized by this exponential filter in the phase encoding direction (blurring)
  - Note effect isn’t always straightforward when asymmetric k-space acquisition used

- DWI & ADC Mapping Issues: T2 Shine Through & Motion
  - DWI is strongly T2 weighted due to long TE
  - Sometimes cannot if signal reduced in long T2 structures from DWI alone becomes smaller than that for k-space collected (T2 shine through)
  - ADC mapping removes the shine through effect for properly assessing if restricted diffusion is present
  - Motion can cause pseudo-rapid echo effects on DWI or misregistration on ADC maps resulting in quantitative errors and visible shine through

Eddy Current Effects

- Generate spatially varying off-resonance manifest as distortions along PE
- Shear (gradient in y direction) function of eddy current amount, (sheared)
- Scale (gradient in x direction, distortion function of y)
- Note there is also a loss of intensity (gradient in x direction, perturbation of spins, dephasing) (not shown)
- Combat with eddy current compensation, sequence pre-scan, twice refocused spin-echo and real time field adjustment

Single shot EPI: N/2 "ghosts" in PE

- Full k-space
- Half k-space
- Error signals are observed at half the size in FOV

Off-resonance errors: Susceptibility & Chemical Shift

- Eddy currents still induce errors different for y next to x polarity
- Baseline shift (B0 field along z direction, shear (gradient in z direction, distortion function of x)
- Large diffusion gradients induce eddy currents on conducting surfaces
- Combat with eddy current compensation, sequence pre-scan, twice refocused spin-echo and real time field adjustment
Other non-Cartesian trajectories

- Radial - Motion insensitive acquisition being used for 4D view sharing applications, free breathing abdominal imaging, ultra-short TE, etc.


*Summary*

- Knowledge of system components and image synthesis is essential to understanding and minimizing or remediating artifacts in MRI.

- Violations to key assumptions assumed in our image reconstruction process propagate into the image as artifacts.

- Despite this, management of image quality issues, including artifacts, should focus on identifying the step(s) in the imaging chain in which specific teams can intervene to control.

Thank you for your time!

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