Rosette Trajectories

BIM 241 Final Project
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Janani
Linh
Rosette Trajectories Enable Ungated, Motion-Robust, Simultaneous Cardiac and Liver $T_2^*$ Iron Assessment

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Introduction

- This paper is about improving quantitative T2* MRI assessment of iron overload.
- Iron overload results from the body accumulating excess amounts of iron in the tissue, which can cause organ failure and death.
- T2* is a clinically useful biomarker for iron quantification because of iron’s paramagnetic properties that cause inhomogeneity and increase the local T2* measurement.
- MRI is a great non-invasive technique for assessing organs, such as the heart, kidneys, spleen, liver, and pancreas.
Challenges with MRI:

- T2* calculations are easily affected by motion artifacts
  - Thus, limiting for pediatric patients or patients with motor control disorders
  - Sedation may be required, adding risk and expense
- T2* calculations of the heart or areas near the lungs are greatly affected
  - Thus, limiting for pediatric patients or patients with motion control disorders
  - Gating and breath holds are required
- Gating MRI Scans take longer to complete
- T2* measurements of the heart and liver are the strongest prognostic markers of mortality
Rosette Trajectories

- There are more robust methods for capturing images with motion than Cartesian, such as radial and spiral k-space sampling methods. These types of methods include rosette trajectories.

- Rosettes are flower-like k-space trajectories that utilize frequent sampling of the center of k-space to reduce noise and produce diffuse aliasing artifacts.

- Thus, this group decided to try Rosette trajectories to improve these T2* iron assessments that are affected by motion.
Materials and Methods

- Performed on a GE Signa 450W MRI system with a 20-channel coil
- Phantom Imaging: Cartesian and Rosette Multi Echo images acquired for 6 phantoms containing ferumoxytol
- Patient Population: 8 healthy volunteers and 18 patients undergoing T2* iron assessment
- Reproducibility experiments: breath-hold scans
- Motion sensitivity: free breathing + failed breath-hold T2* scans
Imaging Parameters

- To reduce eddy current and gradient timing-related artifacts:
  - Max slew rate = 75 mT/m/s
  - Gradient amplitude = 40 mT/m
- Total of 800 repetitions
- Total readout time per shot = 16 ms
- $q=2.2$, Rotation Angle = 137.5°
- Rosette – 5 echoes; Cartesian – 8 echoes

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TABLE 1. Imaging Parameters Used in Cartesian and Rosette Multi-echo, Gradient Echo Pulse Sequences

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cartesian</th>
<th>Rosette</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gating</td>
<td>ECG/PPG gated</td>
<td>Ungated</td>
</tr>
<tr>
<td>Matrix size</td>
<td>256 × 256</td>
<td>512 × 512</td>
</tr>
<tr>
<td>FOV (cm)</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Resolution (mm)</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Flip angle (deg)</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Repetition time (msec)</td>
<td>15.7</td>
<td>18</td>
</tr>
<tr>
<td>Echo times (msec)</td>
<td>1.1, 2.4, 3.7, 5.0, 6.3, 7.6, 8.9, 10.2</td>
<td>0.8, 4.6, 7.6, 10.6, 13.6</td>
</tr>
<tr>
<td>Scan time (second)</td>
<td>15–20</td>
<td>15</td>
</tr>
</tbody>
</table>
Rosette Sequence
Results
Discussion

- Comparable T2* with:
  - HIGH image quality, spatial resolution, reproducibility
  - LOW motion artifacts and reduced spatial variability to clinical procedure
- No cardiac gating => no corruption by respiratory motion as in Cartesian
- Advantages over previous work:
  - No patient motion correction
  - Ungated
  - Same scan times as clinical standard
Limitations

- Limited number of subjects – increase in type 2 statistical errors
- Non-Cartesian sampling is more prone to gradient timing imperfections
- Incorporation of motion directly into the reconstruction model
- Magnitude-based T2* measurements are confounded by intravoxel fat
- Rosette T2* maps are more sensitive to off-resonance artifacts than the typical cartesian maps
Our Experiments and Results

1. Trade off Between Number of Rosette Petals and T2* Quantification (Linh)
2. SNR Comparisons of Rosette Heart Scan and LV Phantom Data (Valerie)
3. Effects of Off-Resonance Sources of Rosette Phantom Images (Janani)
The effects of changing number of petals

Objective:

- To improve motion artifacts, which usually corrupts the T2* estimates
- Evaluate the trade-off when changing the number of petals in rosette trajectories
Definition of number of petals

Class II rosettes are defined:

\[ \text{if } N \text{ is odd, } q = \left\{ \frac{N + 2}{N} + \frac{2(k - 1)}{N}, k \in Z^+ \right\} \]

\[ \text{if } N \text{ is even, } q = \left\{ \frac{N + 2}{N} + \frac{4(k - 1)}{N}, k \in Z^+ \right\} \]

\(N\) is the number of petals

\(q\) is a shape parameter = \(\omega_2/\omega_1\) (\(\omega_1 \gg \omega_2\)) [Noll, IEEE 1997]
Imaging Parameters

- Max slew rate = 80 mT/m/s
- Gradient amplitude = 40 mT/m
- Total of 80 repetitions
- Total readout time per shot = 16 ms
- Number of petals = 5, 7, 11, 13
Single Trajectory and 80 rotations

(q = 0.6) (5 petals)

80 Rotations
Gradient waveforms and Image reconstruction

Rosette Gradient waveforms for one trajectory

Time (ms)

$G_x$ [mT/m]

$G_y$ [mT/m]

(Spetals)
Performance of motion artifacts on dynamic LV

$q = 0.6$, 5 petals

$q = 0.43$, 7 petals

$q = 0.27$, 11 petals

$q = 0.23$, 13 petals
Calculate motion artifacts metric

Gradient entropy metric is to quantify MR motion corruption in the image space [Cheng et. al, MRM 2012]

Input:
- Image data
- The localization of the motion metric calculation in X, Y

Output:
- Gradient entropy metric
Performance of motion artifacts on phantom images for 80 rotations

Static LV

Dynamic LV

Pixels with improved motion = Dynamic motion < Static motion
Performance of motion artifacts with 800 rotations

<table>
<thead>
<tr>
<th></th>
<th>5 petals</th>
<th>7 petals</th>
<th>11 petals</th>
<th>13 petals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static LV</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Dynamic LV</strong></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Pixels with improved motion</strong></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>
## Overall Results

<table>
<thead>
<tr>
<th></th>
<th>5 petals</th>
<th>7 petals</th>
<th>11 petals</th>
<th>13 petals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient Amplitude (mT/m)</td>
<td>26.28</td>
<td>28.17</td>
<td>29.57</td>
<td>29.86</td>
</tr>
<tr>
<td>Computational Time (s)</td>
<td>1.64</td>
<td>1.68</td>
<td>1.98</td>
<td>2.53</td>
</tr>
<tr>
<td>Average T2*</td>
<td>2707</td>
<td>2166</td>
<td>3907</td>
<td>3987</td>
</tr>
</tbody>
</table>
Discussion

- The motion artifacts are reduced when increasing the number of petals
- The best performed model is with 5 or 11 petals for Rosette trajectories
- Average T2* is improved

Limitations:
- Takes more computational time with higher number of petals
- Other factors (e.g. number of rotations, shape of petals, rotational angles, etc.) might be taken into consideration for the investigation
SNR Comparison of Rosette and Cartesian Data

Objective:

- How do the Rosette trajectories affect the SNR of the image compared to the Cartesian method?
- How are anatomically relevant region signals affected by Rosette compared to Cartesian?
SNR Calculation:

\[ SNR = 20 \times \log_{10} \left( \frac{\text{signal}}{\text{noise}} \right) \]

Signal = mean( Entire_Image )

Noise of each ROI = std (ROI_Image)

Noise = mean( Noise_of_each_ROI )
SNR Comparison of Rosette and Cartesian Data

- ROIs are 32x32 pxls
- Cover relatively the same anatomy signal for each type of image
- Limitation: FOVs are NOT the same
- Calculate noise for each ROI and average for SNR calculation

SNR Comparison of Rosette and Cartesian Data

- Rosette Image ROIs
  - 256x256 pxls
  - 5 Echo Images
- Cartesian Image ROIs
  - 256x256 pxls
  - 8 Echo Images
**SNR of Cartesian Data**

<table>
<thead>
<tr>
<th>TE</th>
<th>SNR</th>
<th>TE</th>
<th>SNR</th>
<th>TE</th>
<th>SNR</th>
<th>TE</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1ms</td>
<td>8.69</td>
<td>2.4ms</td>
<td>7.62</td>
<td>3.7ms</td>
<td>7.78</td>
<td>5.0ms</td>
<td>8.11</td>
</tr>
<tr>
<td>6.3ms</td>
<td>7.38</td>
<td>7.6ms</td>
<td>7.88</td>
<td>8.9ms</td>
<td>7.38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Average Cartesian SNR**: 7.39

**Average Liver ROI SNR**: 13.41

**Average RV ROI SNR**: 13.56

**Average LV ROI SNR**: 11.14

**Average Lung ROI SNR**: 10.12
SNR of Rosette Data

TE = 0.8ms
SNR = 13.9

TE = 4.6ms
SNR = 13.86

TE = 7.6ms
SNR = 11.60

TE = 10.6ms
SNR = 10.93

Average Rosette SNR = 12.01
Average Liver ROI SNR = 14.10
Average RV ROI SNR = 18.39

Average LV ROI SNR = 15.02
Average Lung ROI SNR = 4.28
SNR Comparison Discussion

● Average Cartesian SNR = 7.39       Average Rosette SNR = 12.01
● Thus, Rosette trajectories may improve SNR
● First Echoes had the strongest SNRs for both methods
● All SNR ROIs improved (increased) with Rosette, except for Lungs
● Limitations:
  ○ SNR of Cartesian is likely affected by the FOV being larger than the Rosette
  ○ ROI size, although the same size, the anatomy area covered was larger for Cartesian than Rosette
SNR of Phantom Data Reconstruction with Rosette

**Objective:**

- How do Rosette trajectories affect a dynamic images compared to static ones?
- How does the changing the number of k-space samples affect the SNR of the reconstructed phantom image?
SNR of Phantom Data Reconstruction with Rosette

- Static and Dynamic LV Phantom
  - 12 Echos
  - $\text{lumend} = 180$;
  - $\text{walld} = 250$;

- Captured Image Signal with added complex Noise and without Noise w/ rosette_test.m:

  Random Noise = $10^{-6*\text{randn(k-trajectory value)}}$

  The real and complex parts are added to the k-trajectory values.

Then, calculate the SNR with the mean signal of the image w/o noise
Noise Calculation for Phantom

Signal = mean( Pure_Signal_Image)  
Noise = mean( Only_Noise_Image )
Some Other Cool Images of Noise
SNR of Rosette Phantom Data

Static Image

Average SNR = 8.33

Dynamic Image

Average SNR = 46.83
SNR of Rosette Phantom Data with $\frac{1}{2}$ Sampling

Static Image

Average SNR = 8.68

Dynamic Image

Average SNR = 62.20
Some More Cool Images of Noise!
SNR of Rosette Phantom Discussion

- Dynamic SNR > Static SNR, including reducing the number of samples
- Reducing the k-space samples improved SNR slightly for static (0.35 dB), and greatly for dynamic (15.37 dB)
- But, reducing the k-space introduced aliasing when halved
- Thus, Rosette seems to perform better with dynamic scans
- However, SNR may not be the best image quality quantification, since the sampling can mistakenly show image improvement. Other image quality factors should be taken into consideration.
Inclusion of Off-Resonance Sources

**Objectives:**

- To include contributions of off-resonance sources and examine the reconstructed Rosette phantom after changes in frequency range
- Evaluate the obtained images using image quality metrics
Off-Resonance Effects

Off-Resonance Effects arise due to:

• Main Field (Bo) Inhomogeneities: near-uniformity maintained using static shim coils

• Susceptibility-Induced Field Variations: differences in susceptibility in the body range from $10^{-5}$ to $10^{-6}$

• Chemical Shifts: magnetic field to the nucleus is reduced by a small factor because of electronic shielding
Off-Resonance Effects

The receive signal at baseband:

\[ s(t) = \int_{x,y} m(x, y) \, e^{-2\pi i (k_x + k_y)} \, dx \, dy \]

The receive signal at baseband with off-resonance sources:

\[ s(t) = \int_{x,y} m(x, y) \, e^{-2\pi i (k_x + k_y)} \, e^{-2\pi i \Delta f t} \, dx \, dy \]
Shifted phase effects on image quality
Shifted phase effects on image quality
Shifted phase effects on image quality
Shifted phase effects on image quality
Image Quality Evaluation

Deep residual network for off-resonance artifact correction with application to pediatric body MRA with 3D cones

David Y Zeng ¹, Jamil Shaikh ², Signy Holmes ², Ryan L Brunsing ², John M Pauly ¹, Dwight G Nishimura ¹, Shreyas S Vasanawala ², Joseph Y Cheng ²
# Image Quality Evaluation

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Off-resonance Frequency Range (Hz)</th>
<th>NRMSE</th>
<th>PSNR</th>
<th>SSIM</th>
<th>R Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-256 to 256</td>
<td>0.19</td>
<td>55.45</td>
<td>0.23</td>
<td>0.73</td>
</tr>
<tr>
<td>2.</td>
<td>-128 to 128</td>
<td>0.17</td>
<td>56.21</td>
<td>0.20</td>
<td>0.78</td>
</tr>
<tr>
<td>3.</td>
<td>-16 to 16</td>
<td>0.12</td>
<td>56.75</td>
<td>0.19</td>
<td>0.80</td>
</tr>
<tr>
<td>4.</td>
<td>-1 to 1</td>
<td>0.089</td>
<td>62.33</td>
<td>0.25</td>
<td>0.95</td>
</tr>
</tbody>
</table>
SSIM Maps

SSIM Map for Peak Freq=16Hz

SSIM Map for Peak Freq=1Hz
Frequency Spectrum

Frequency Spectrum, On Res, 128Hz

Frequency Spectrum, Off Res, 128Hz
Effect of Changed Parameters on SNR

Objective:

- To change the number of petals and add off-resonance sources in different ranges of frequency and calculate the SNR
Changing No. of Petals and adding Off-Resonance Sources

Peak Frequency = 128Hz
## SNR Calculations for Off-Res Sources and Different No. of Petals

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Resonance Condition</th>
<th>Number of Petals</th>
<th>Peak Frequency (off-res)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>On-Resonance</td>
<td>5</td>
<td>-</td>
<td>80.94</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>5</td>
<td>16Hz</td>
<td>80.30</td>
</tr>
<tr>
<td>2.</td>
<td>On-Resonance</td>
<td>7</td>
<td>-</td>
<td>101.96</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>7</td>
<td>16Hz</td>
<td>100.69</td>
</tr>
<tr>
<td>3.</td>
<td>On-Resonance</td>
<td>11</td>
<td>-</td>
<td>129.23</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>11</td>
<td>16Hz</td>
<td>118.31</td>
</tr>
<tr>
<td>4.</td>
<td>On-Resonance</td>
<td>13</td>
<td>-</td>
<td>76.24</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>13</td>
<td>16Hz</td>
<td>70.63</td>
</tr>
</tbody>
</table>
## SNR Calculations for Off-Res Sources and Different No. of Petals

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Resonance Condition</th>
<th>Number of Petals</th>
<th>Peak Frequency (off-res)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>On-Resonance</td>
<td>5</td>
<td>-</td>
<td>80.94</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>5</td>
<td>512Hz</td>
<td>97.20</td>
</tr>
<tr>
<td>2.</td>
<td>On-Resonance</td>
<td>7</td>
<td>-</td>
<td>101.96</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>7</td>
<td>512Hz</td>
<td>127.20</td>
</tr>
<tr>
<td>3.</td>
<td>On-Resonance</td>
<td>11</td>
<td>-</td>
<td>129.23</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>11</td>
<td>512Hz</td>
<td>134.33</td>
</tr>
<tr>
<td>4.</td>
<td>On-Resonance</td>
<td>13</td>
<td>-</td>
<td>76.24</td>
</tr>
<tr>
<td></td>
<td>Off-Resonance</td>
<td>13</td>
<td>512Hz</td>
<td>86.06</td>
</tr>
</tbody>
</table>
Discussion

- As the peak value of $f$ reduces, the image approaches the on-resonance/original image

- Image Metrics:
  
  \[ F_{\text{max}} \propto NRMSE \]
  
  \[ F_{\text{max}} \propto \frac{1}{PSNR} \propto \frac{1}{R^2} \]

- The SNR increases up to 11 petals and then decreases
Conclusion

- Increasing the number of petals leads to a decrease in motion artifacts, with optimal performance at 5/11 petals – limitation: exclusion of petal shape, num. of rotations etc. in the analysis.

- For patient data, the first echo had the highest SNR and Rosette outperformed Cartesian. For phantom data, the dynamic SNR was larger than static SNR – limitation: differences in FOV.

- A decrease in frequency range => reconstructed image is nearer to on-resonance. With off-resonance sources, the SNR increases up to 11 and decreases – limitation: limited analysis with dynamic phantom only.