Rosette Trajectories

BIM 241 Final Project

Team Members:
Valerie Porter
Janani
Linh

Project Paper

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Rosette Trajectories Enable Ungated, Motion-Robust, Simultaneous Cardiac and Liver T_2* Iron Assessment

Adam M Bush [1], Christopher M Sandino [2], Shreya Ramachandran [3], Frank Ong [1], Nicholas Dwork [4], Evan J Zucker [1], Ali B Syed [1], John M Pauly [2], Marcus T Alley [1], Shreyas S Vasanawala [1]

Affiliations + expand

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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

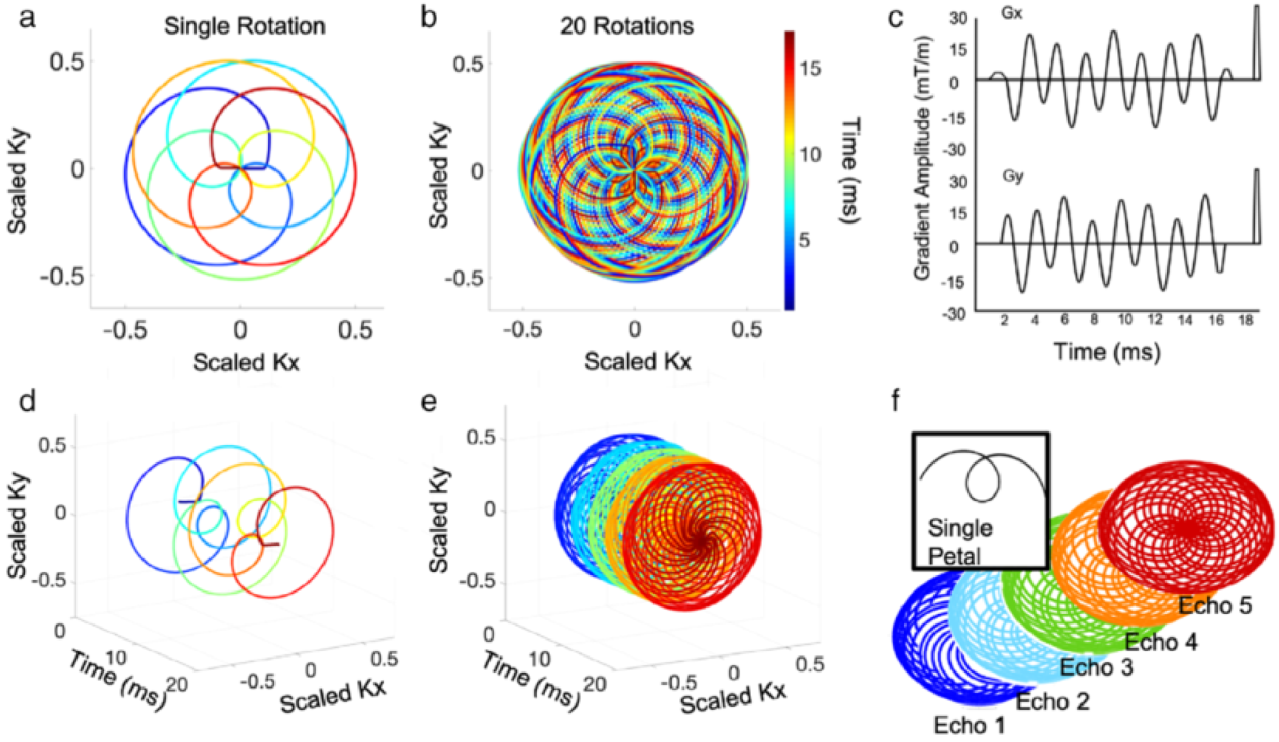
Imaging Parameters

- 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

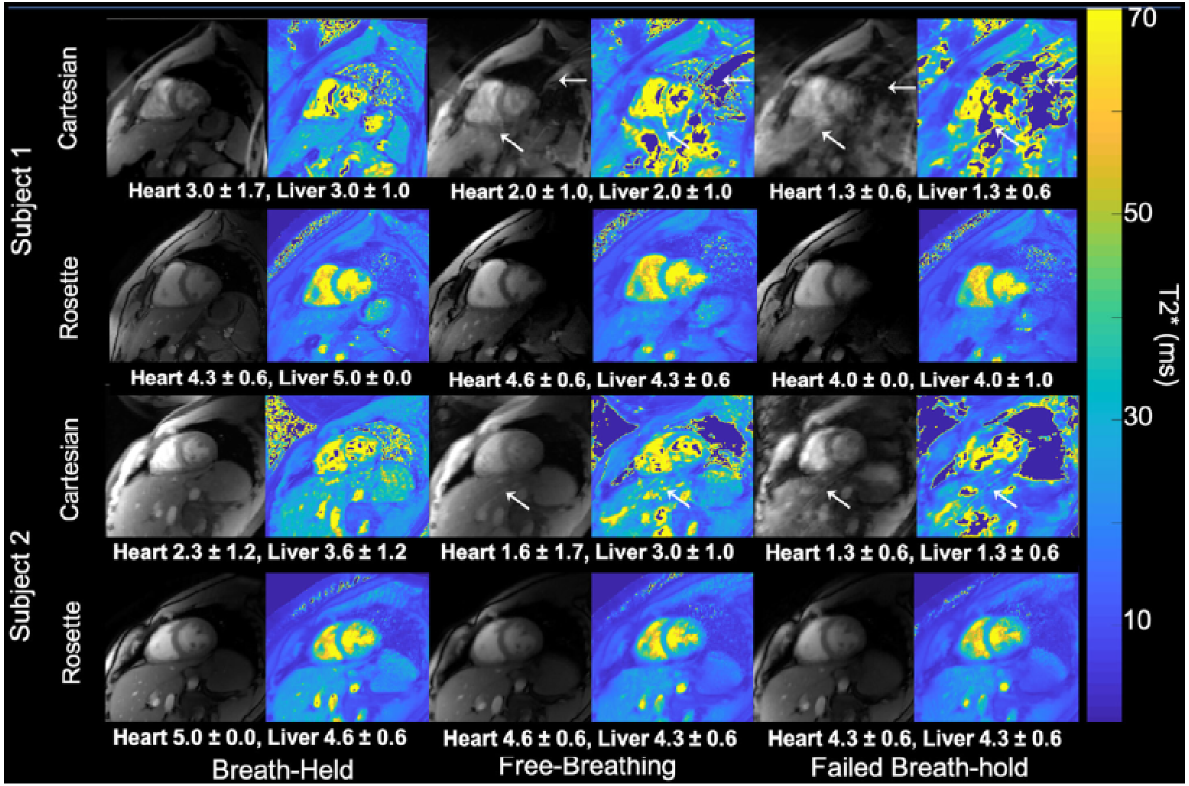
TABLE 1. Imaging Parameters Used in Cartesian and Rosette Multicho, Gradient Echo Pulse Sequences

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

Rosette Sequence



Results


Subject 1
Cartesian
Rosette
Subject 2
Cartesian
Rosette
Heart 3.0 ± 1.7, Liver 3.0 ± 1.0
Heart 2.0 ± 1.0, Liver 2.0 ± 1.0
Heart 1.3 ± 0.6, Liver 1.3 ± 0.6
Heart 4.3 ± 0.6, Liver 5.0 ± 0.0
Heart 4.6 ± 0.6, Liver 4.3 ± 0.6
Heart 4.0 ± 0.0, Liver 4.0 ± 1.0
Heart 2.3 ± 1.2, Liver 3.6 ± 1.2
Heart 1.6 ± 1.7, Liver 3.0 ± 1.0
Heart 1.3 ± 0.6, Liver 1.3 ± 0.6
Heart 5.0 ± 0.0, Liver 4.6 ± 0.6
Heart 4.6 ± 0.6, Liver 4.3 ± 0.6
Heart 4.3 ± 0.6, Liver 4.3 ± 0.6
Breath-Held
Free-Breathing
Failed Breath-hold
70
50
30
10
T2* (ms)

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:

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

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

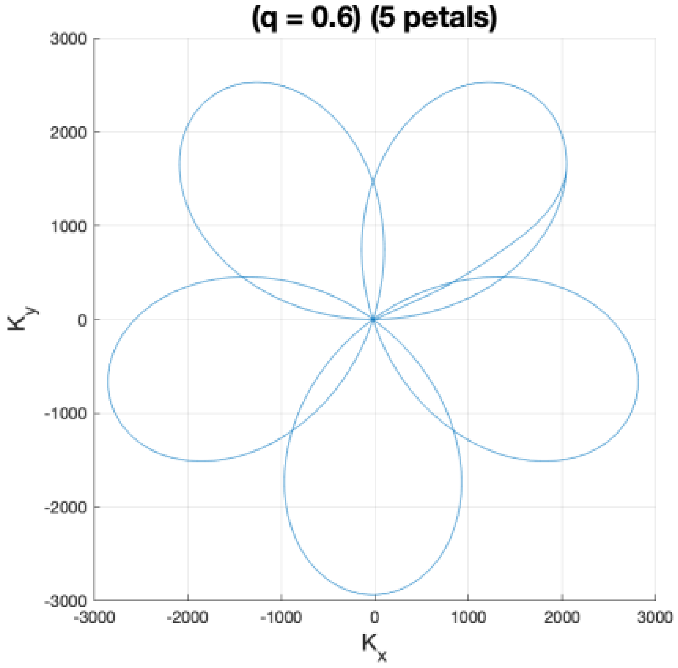
N is the number of petals

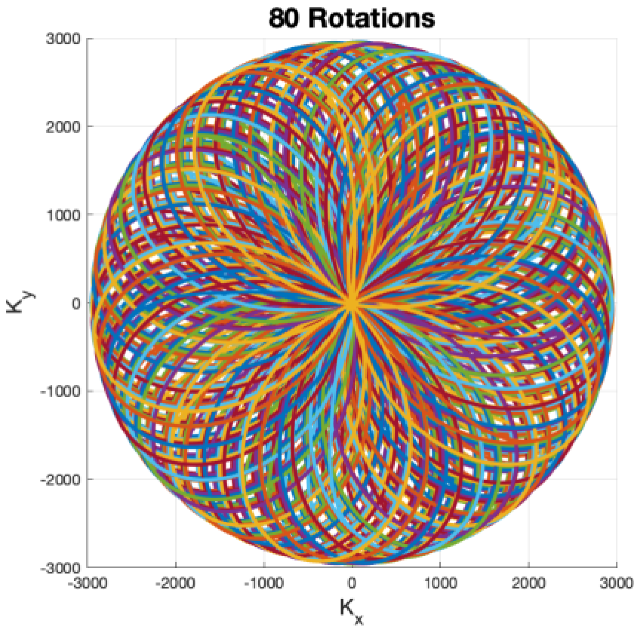
q is a shape parameter = ω_2/ω_1 ($\omega_1 >> \omega_2$) *[Noll, IEEE 1997]*

Imaging Parameters

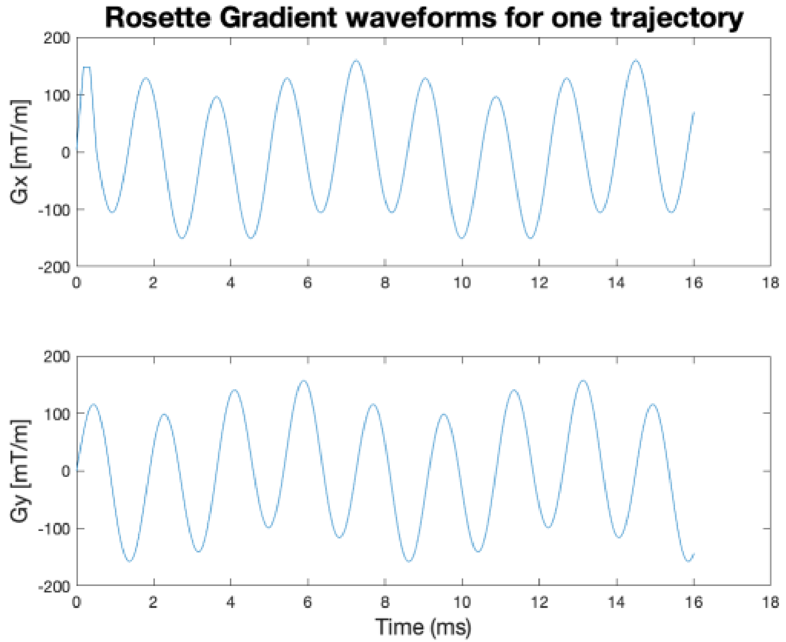
- Max slew rate = 80 mT/m/s
- Gradient amplitude = 40 mT/m
- Total of 80 repetitions
- Total readout time per shot = 16 ms
- Number of petals = 5, 7, 11, 13

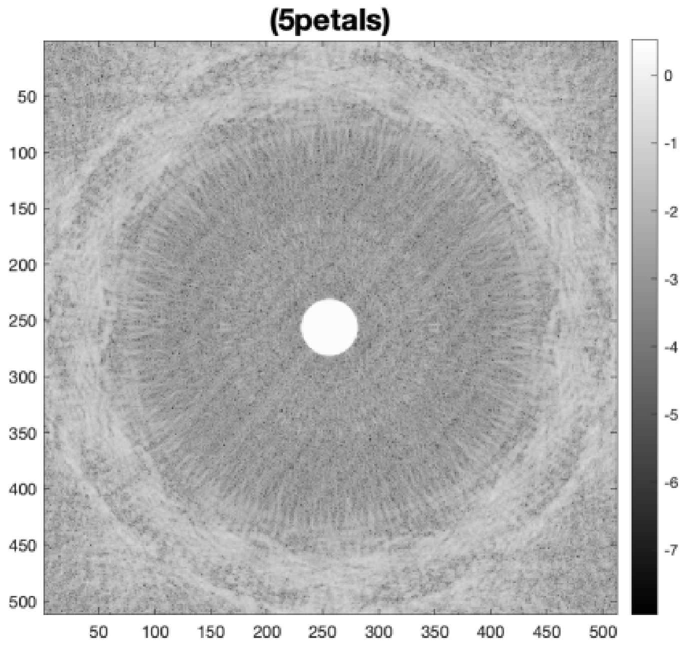
Single Trajectory and 80 rotations





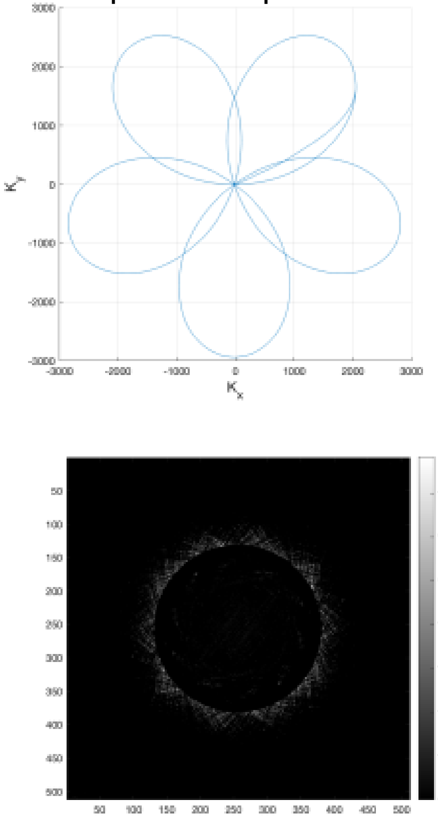
Gradient waveforms and Image reconstruction



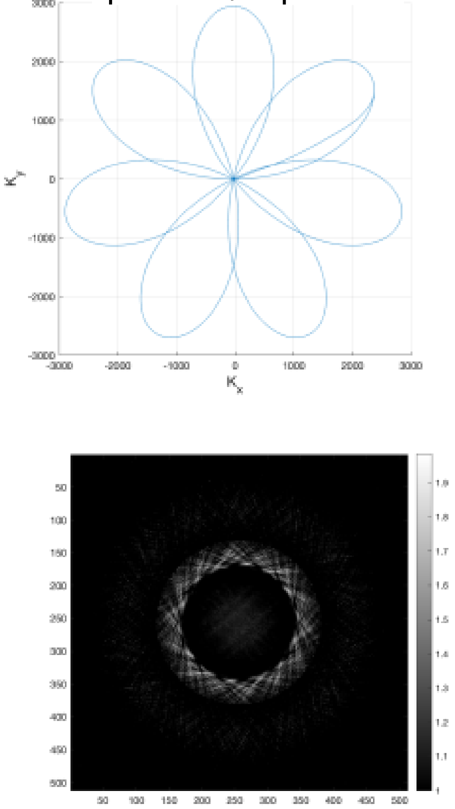


Performance of motion artifacts on dynamic LV

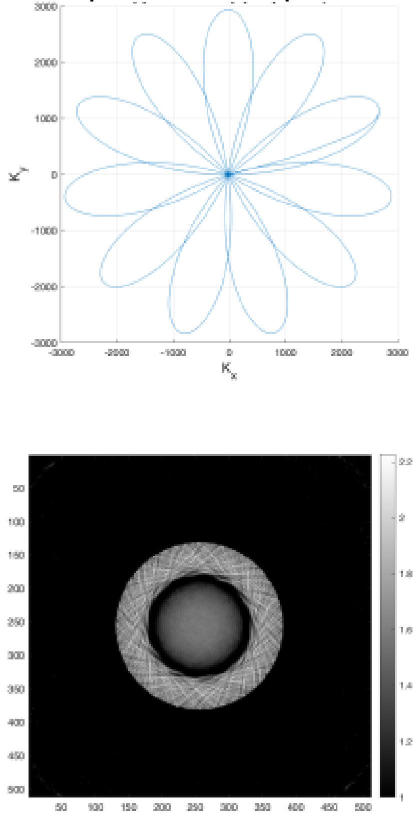
q = 0.6, 5 petals



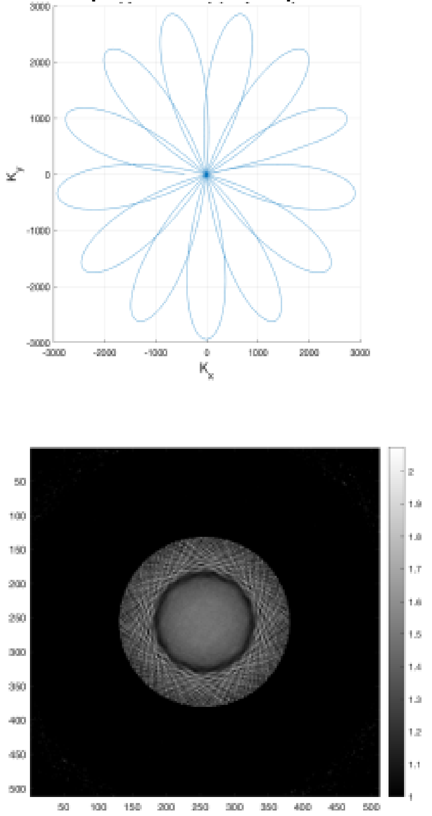
q = 0.43, 7 petals



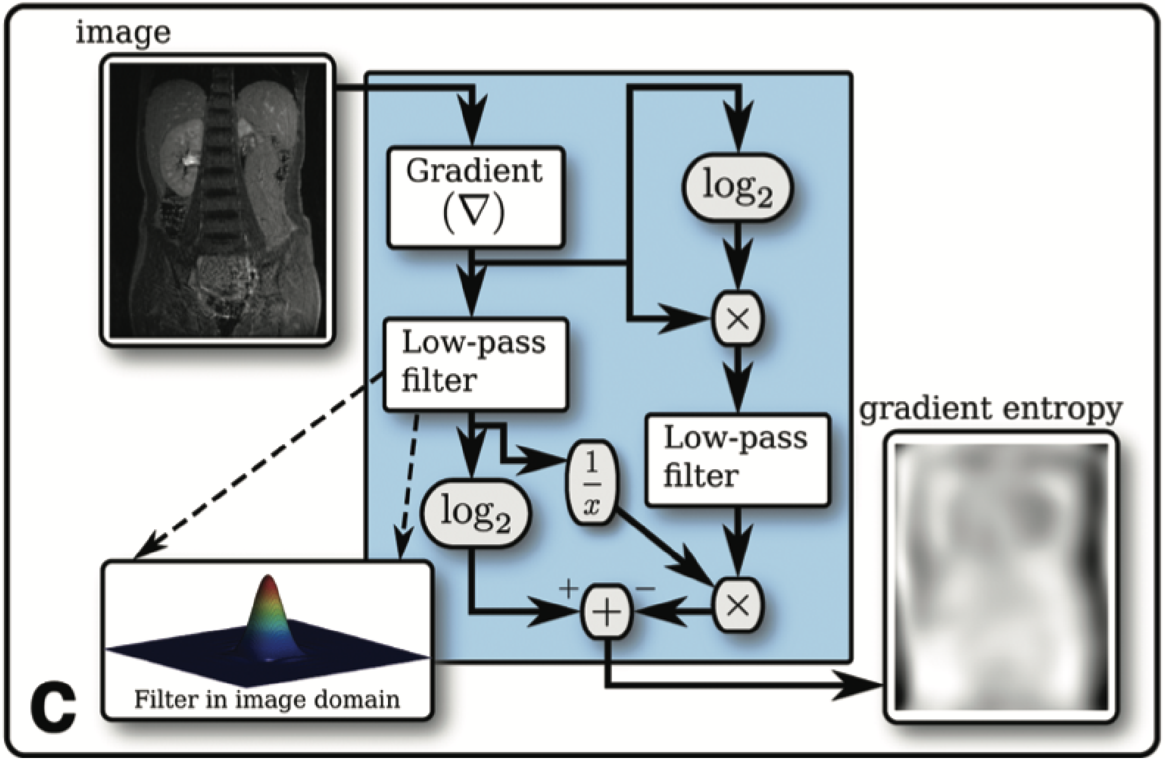
q = 0.27, 11 petals



q = 0.23, 13 petals



Calculate motion artifacts metric



Input:

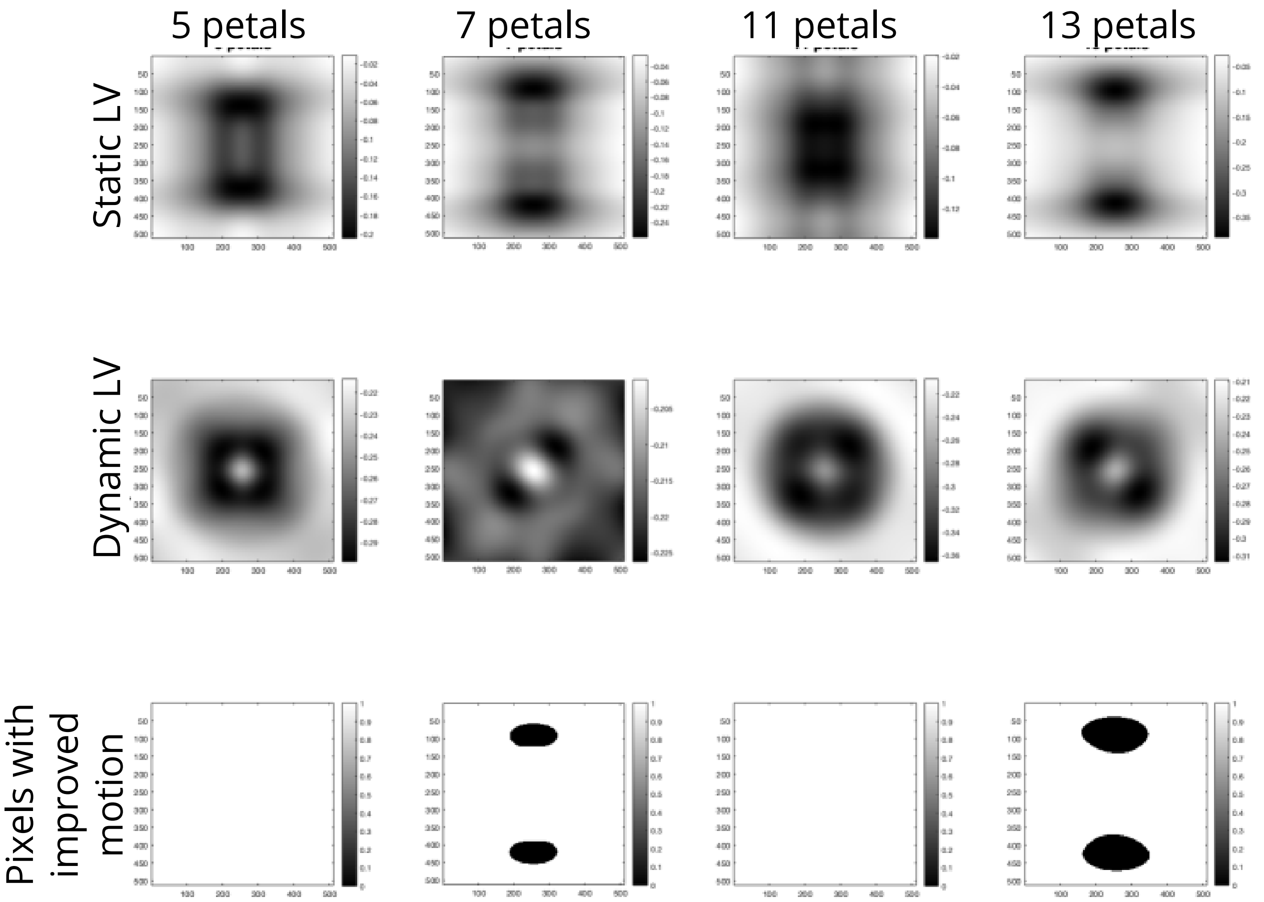
- Image data
- The localization of the motion metric calculation in X, Y

Output:

- Gradient entropy metric

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

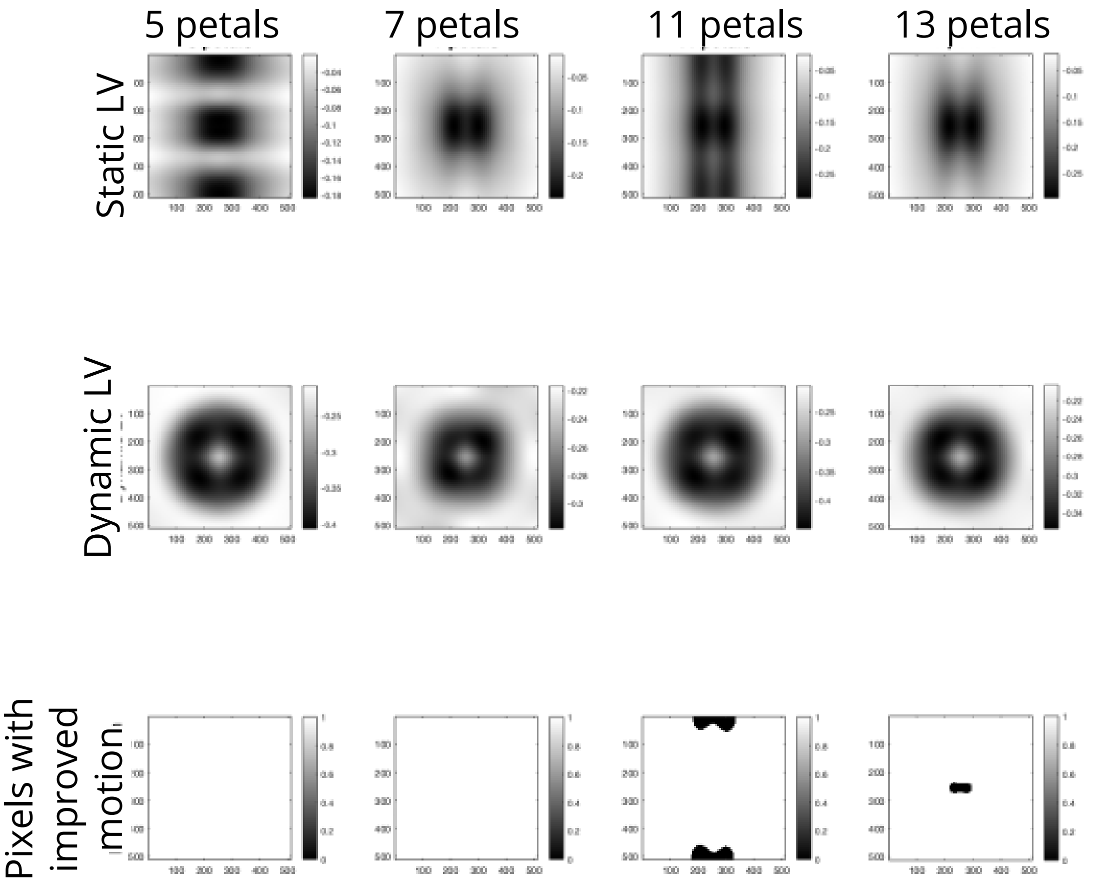
Performance of motion artifacts on phantom images for 80 rotations



Pixels with improved image motion artifacts

= Dynamic motion < Static motion

Performance of motion artifacts with 800 rotations



Overall Results

	5 petals	7 petals	11 petals	13 petals
Gradient Amplitude (mT/m)	26.28	28.17	29.57	29.86
Computational Time (s)	1.64	1.68	1.98	2.53
Average T2*	2707	2166	3907	3987

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:

$$SNR = 20 * \log_{10}\left(\frac{signal}{noise}\right)$$

Signal = mean(Entire_Image)

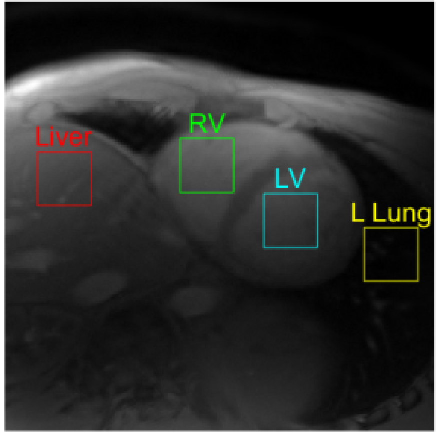
Noise of each ROI = std (ROI_Image)

Noise = mean(Noise_of_each_ROI)

SNR Comparison of Rosette and Cartesian Data

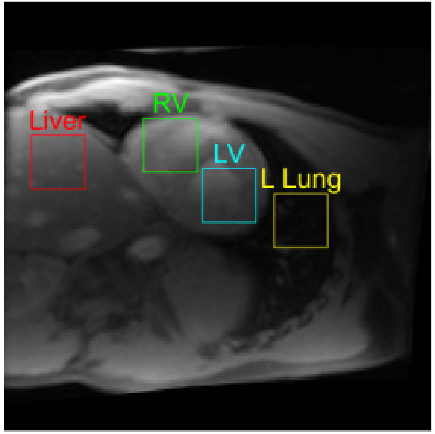
- ROIs are 32x32 pxls
- Cover relatively the same anatomy signal for each type of image
- Limitation: FOVs are NOT the same
- Calculate noise for each ROI and average for SNR calculation

Rosette Image ROIs



256x256 pxls
5 Echo Images

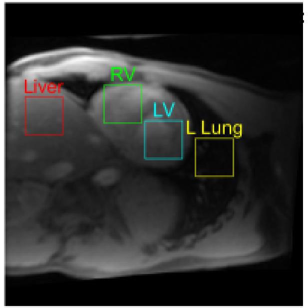
Cartesian Image ROIs

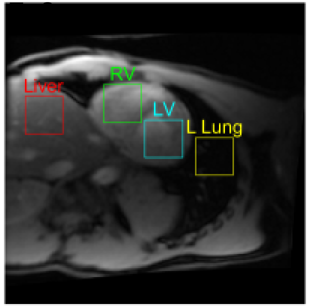


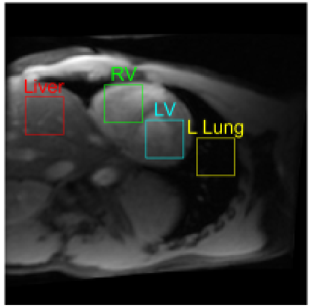
256x256 pxls
8 Echo Images

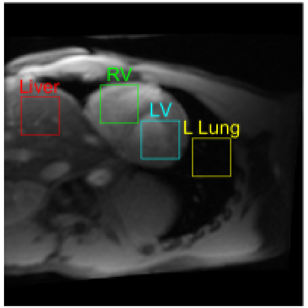
SNR of Cartesian Data

TE = 1.1ms TE = 2.4ms TE = 3.7ms



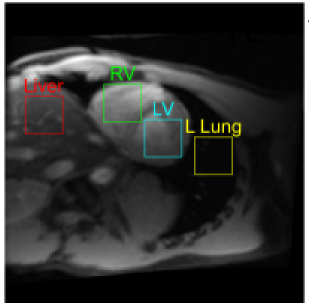


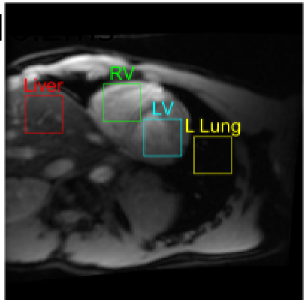


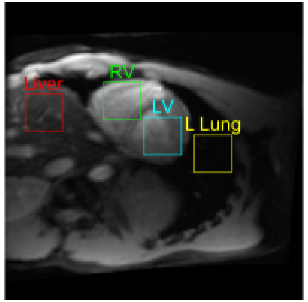


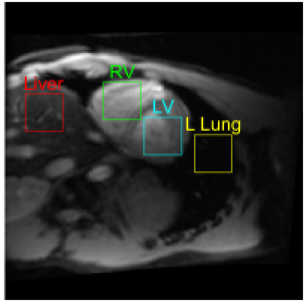
SNR = 8.69 SNR = 7.62 SNR = 7.78 SNR = 8.11

TE = 6.3ms TE = 7.6ms TE = 8.9ms









SNR = 7.38 SNR = 6.40 SNR = 6.62 SNR = 6.52

Average Cartesian SNR = 7.39

Average Liver ROI SNR = 13.41

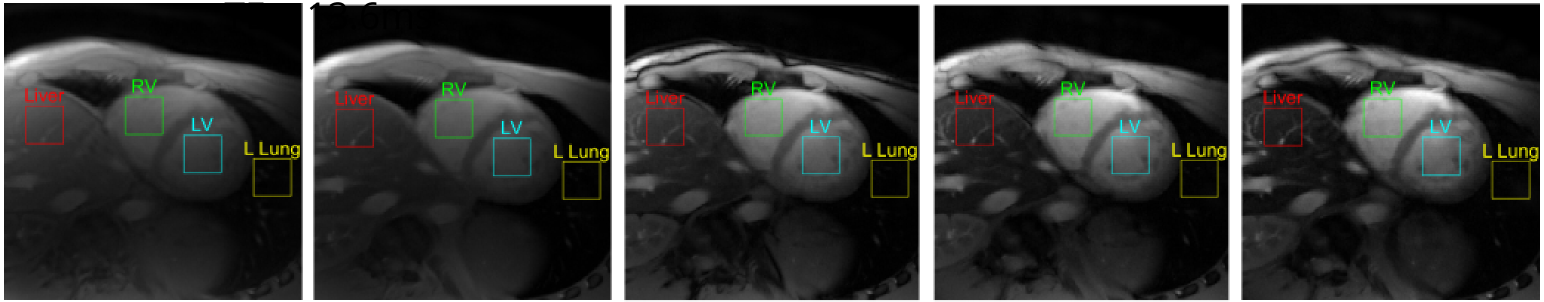
Average RV ROI SNR = 13.56

Average LV ROI SNR = 11.14

Average Lung ROI SNR = 10.12

SNR of Rosette Data

TE = 0.8ms | TE = 4.6ms | TE = 7.6ms | TE = 10.6ms



SNR = 13.9 | SNR = 13.86 | SNR = 11.60 | SNR = 10.93 | SNR = 9.76

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
  - lumend = 180;
  - walld = 250;
- Captured Image Signal with added complex Noise and without Noise w/ rosette_test.m:

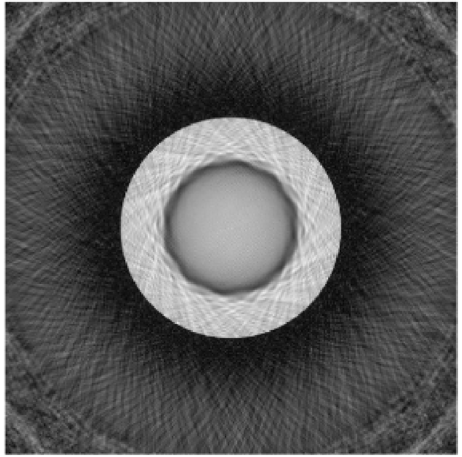
Random Noise = 10^(-6*randn(k-trajectory value))

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

Noisy Image



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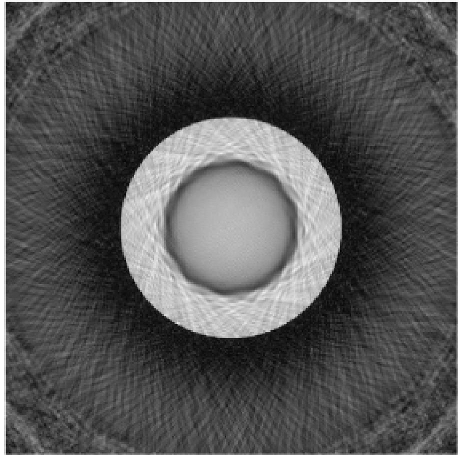
Pure Signal Image



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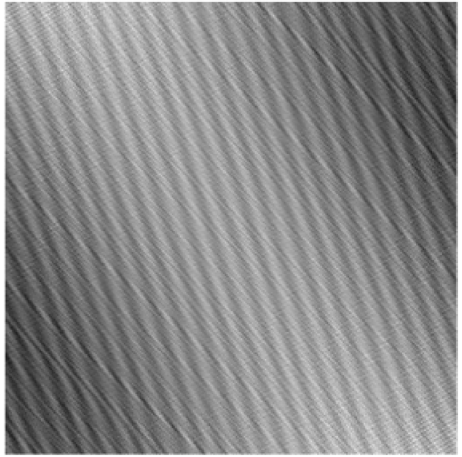
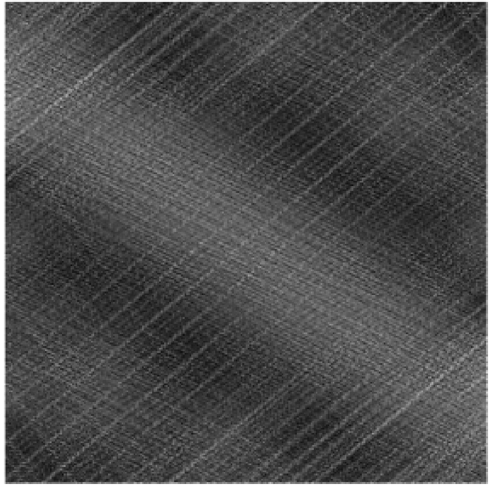
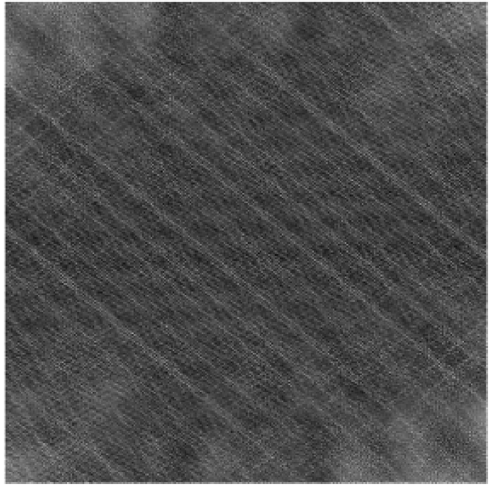
Only Noise Image

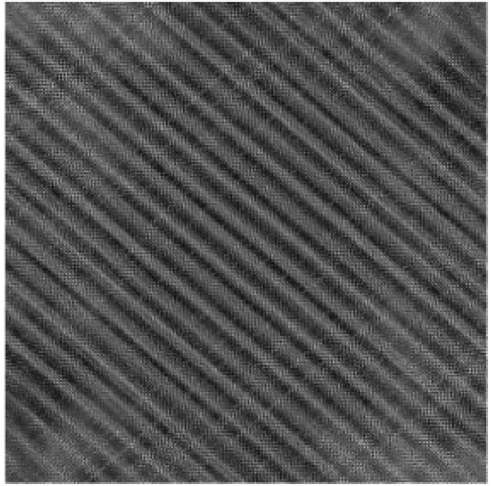


Signal = mean(Pure_Signal_Image)
Noise = mean(Only_Noise_Image)

Some Other Cool Images of Noise

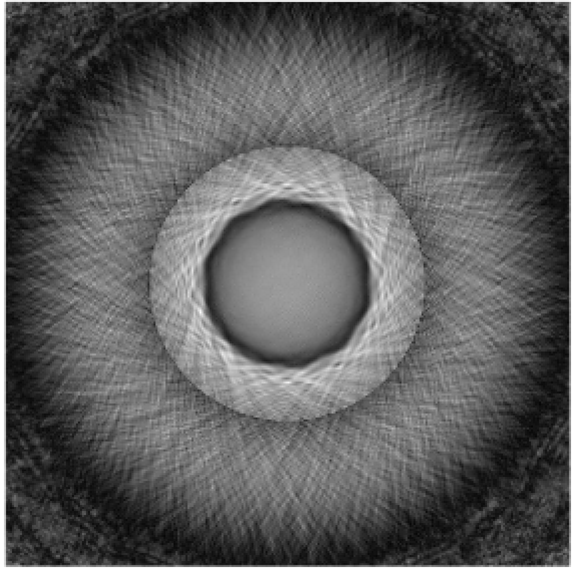






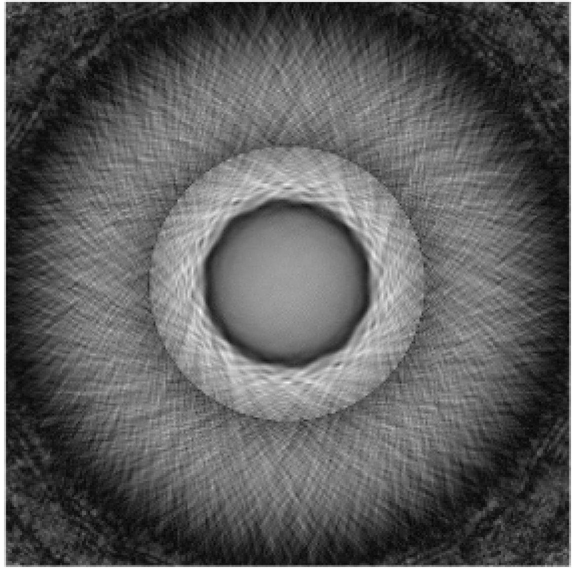
SNR of Rosette Phantom Data

Static Image



Average SNR = 8.33

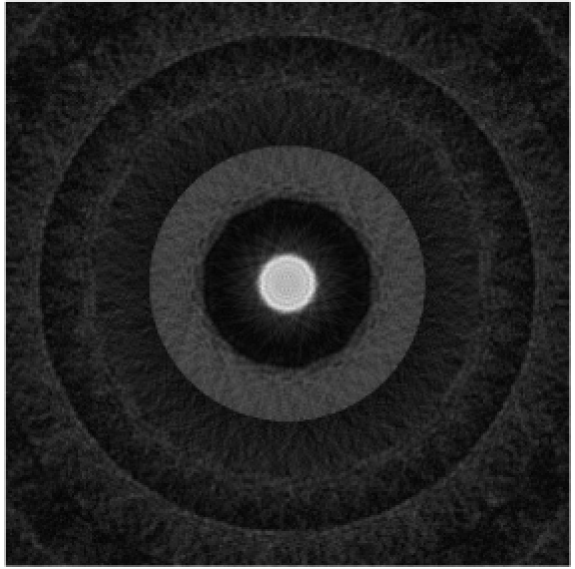
Dynamic Image



Average SNR = 46.83

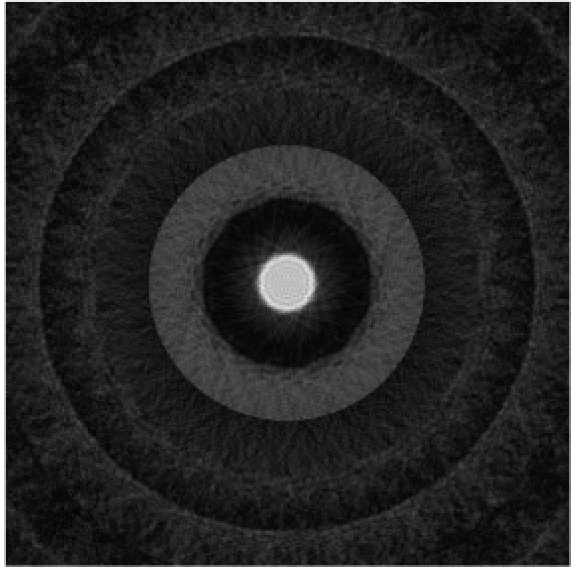
SNR of Rosette Phantom Data with ½ Sampling

Static Image



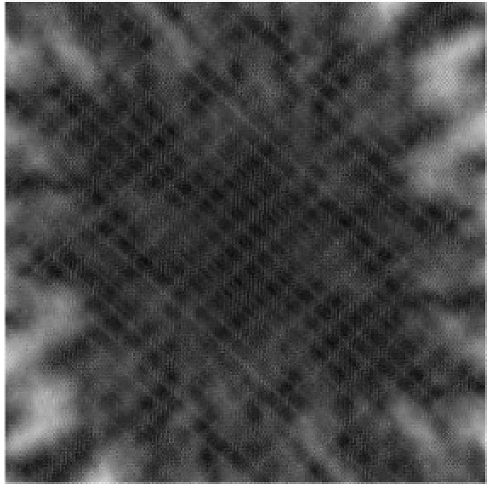
Average SNR = 8.68

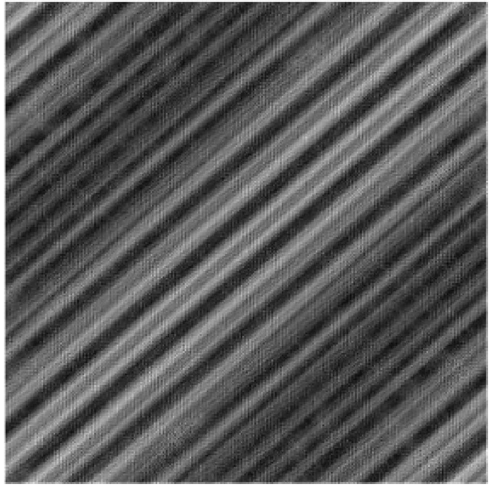
Dynamic Image

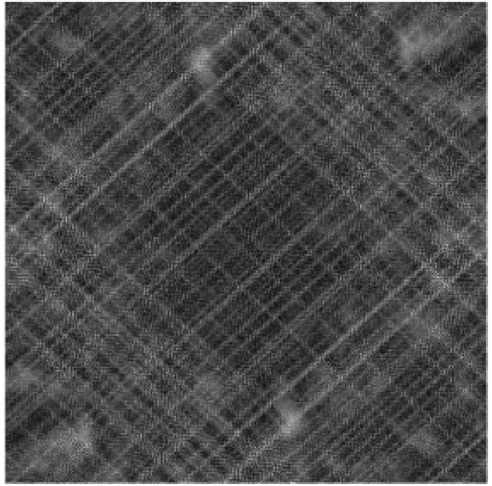


Average SNR = 62.20

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 (15.37dB)**
- 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

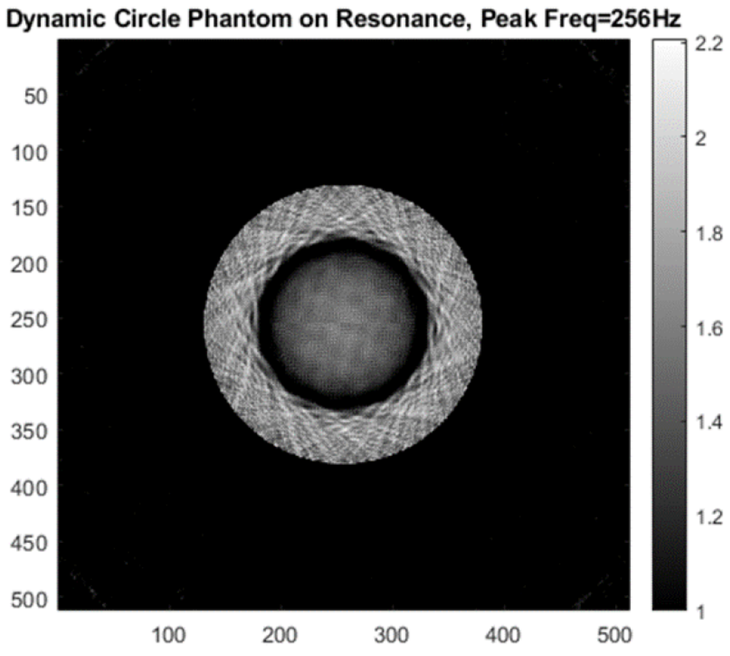
- The receive signal at baseband:

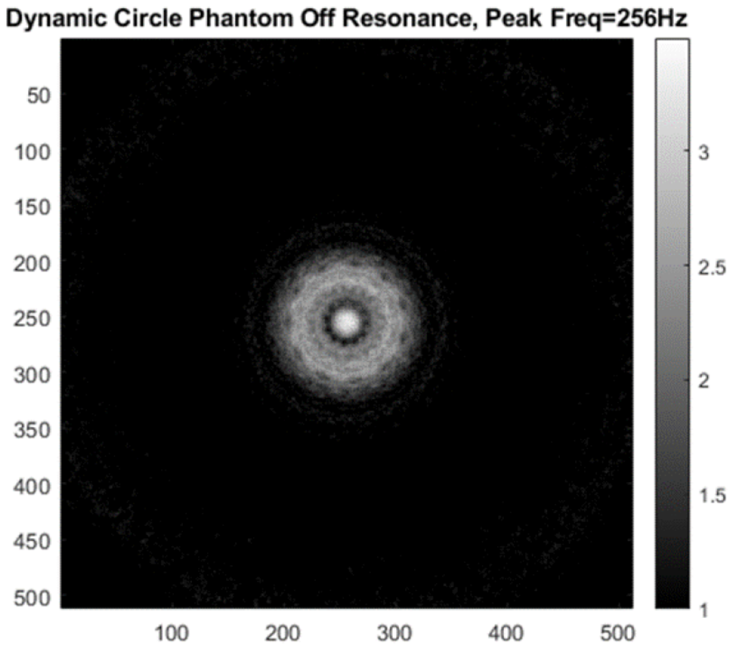
$$s(t) = \int_{x,y} m(x,y)\, e^{-2\pi i(k_x + k_y)}\, dxdy$$

The receive signal at baseband with off-resonance sources:

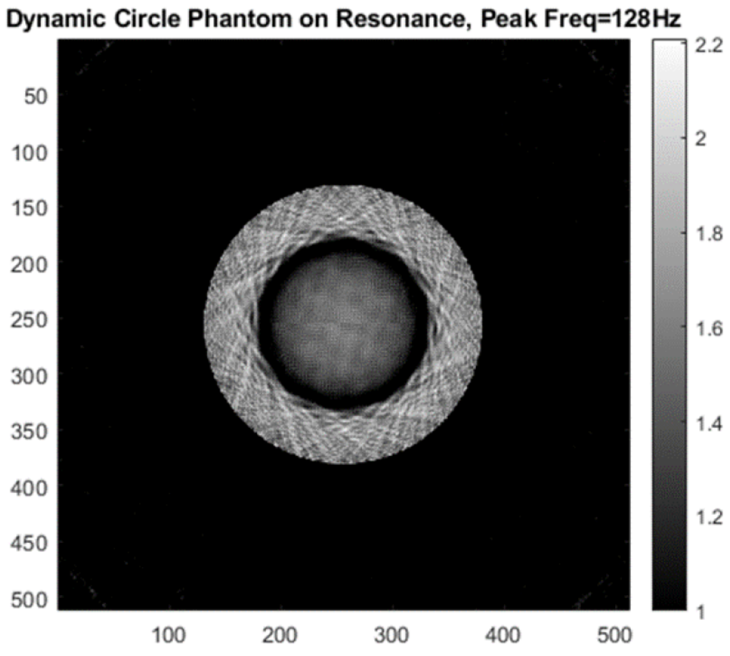
$$s(t) = \int_{x,y} m(x,y)\, e^{-2\pi i(k_x + k_y)} e^{-2\pi i \Delta f t}\, dxdy$$

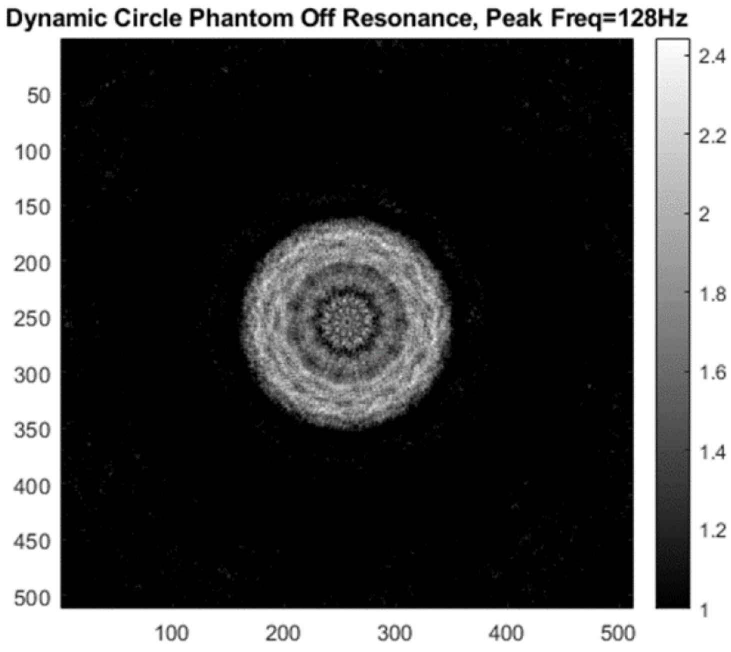
Shifted phase effects on image quality



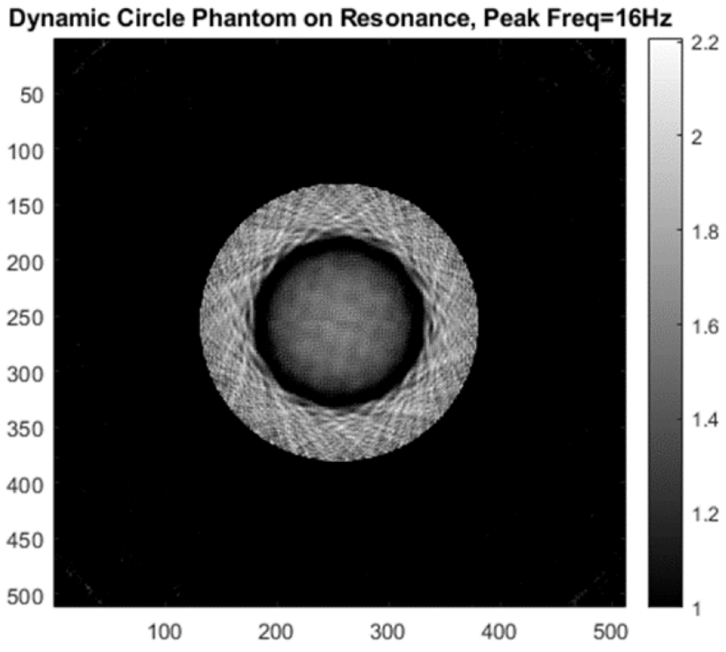


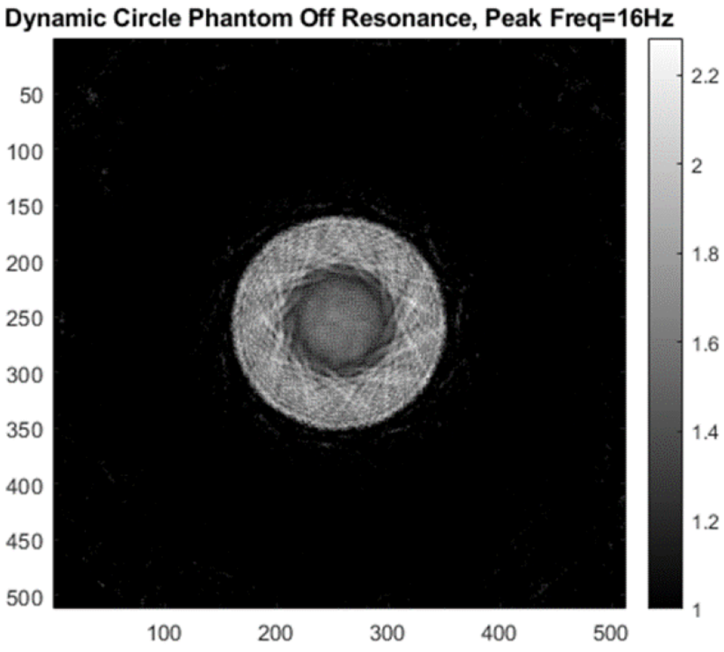
Shifted phase effects on image quality



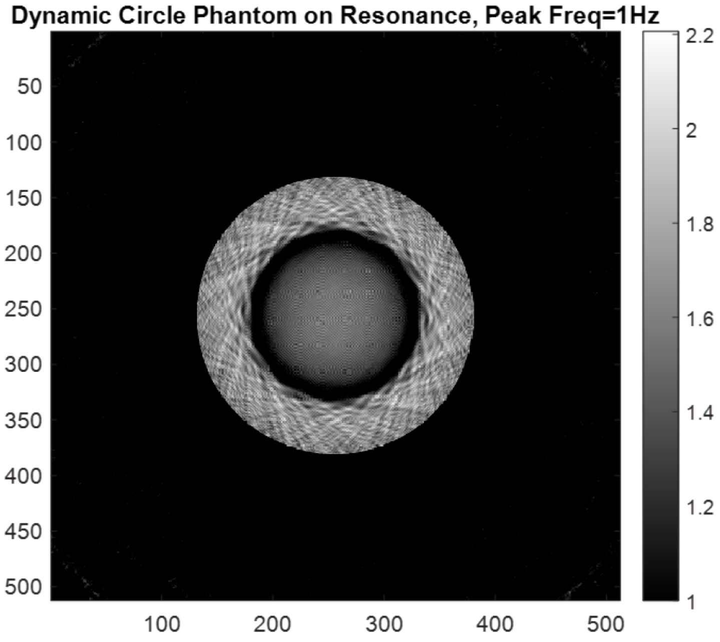


Shifted phase effects on image quality





Shifted phase effects on image quality



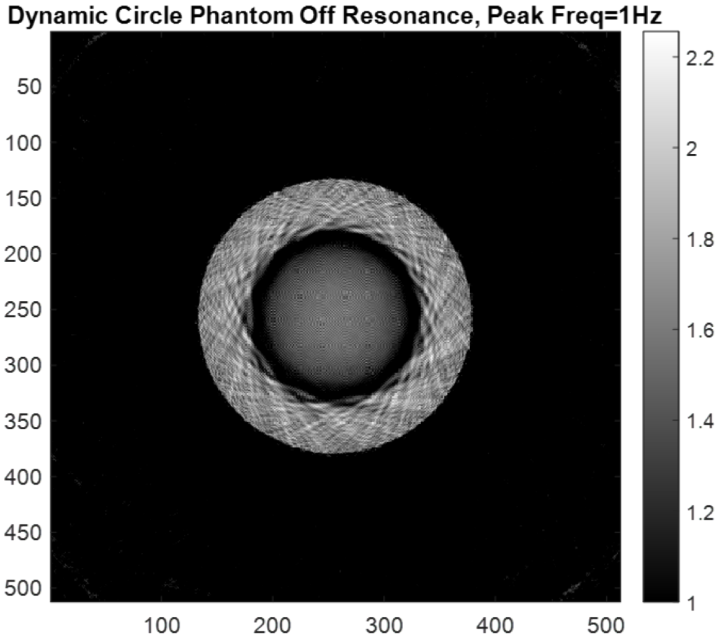


Image Quality Evaluation

› Magn Reson Med. 2019 Oct;82(4):1398-1411. doi: 10.1002/mrm.27825. Epub 2019 May 22.

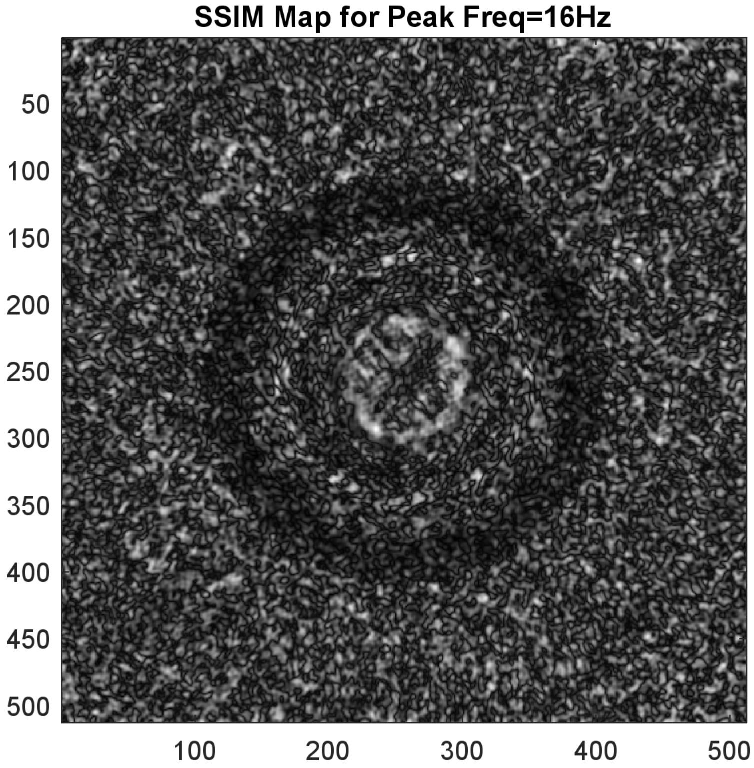
Deep residual network for off-resonance artifact correction with application to pediatric body MRA with 3D cones

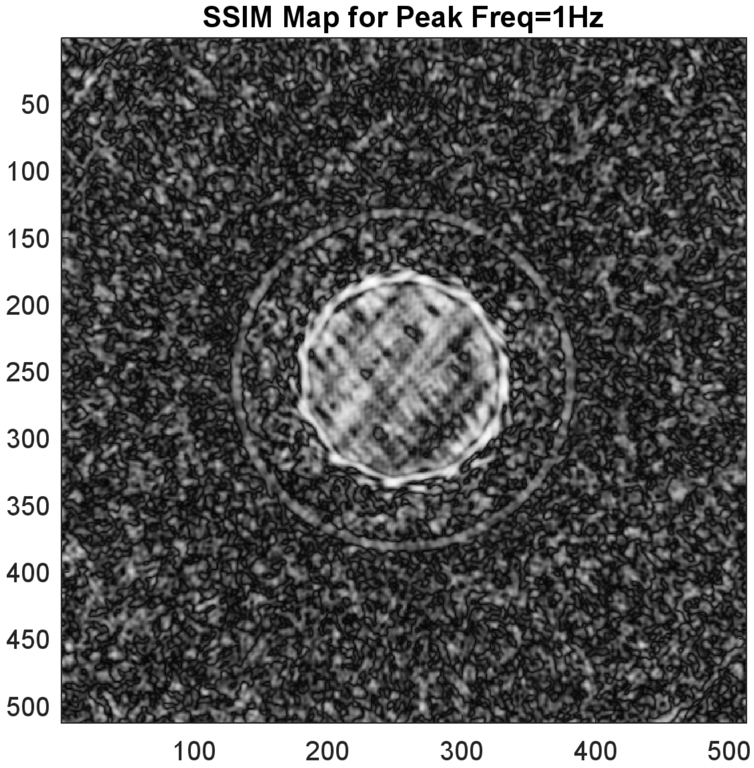
David Y Zeng [1], Jamil Shaikh [2], Signy Holmes [2], Ryan L Brunsing [2], John M Pauly [1], Dwight G Nishimura [1], Shreyas S Vasanawala [2], Joseph Y Cheng [2]

Image Quality Evaluation

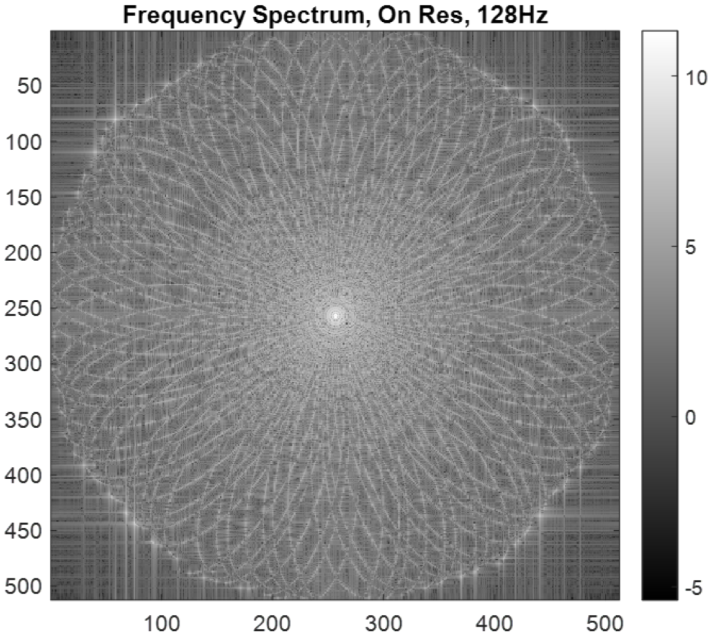
S. No.	Off-resonance Frequency Range (Hz)	NRMSE	PSNR	SSIM	R Value
1.	-256 to 256	0.19	55.45	0.23	0.73
2.	-128 to 128	0.17	56.21	0.20	0.78
3.	-16 to 16	0.12	56.75	0.19	0.80
4.	-1 to 1	0.089	62.33	0.25	0.95

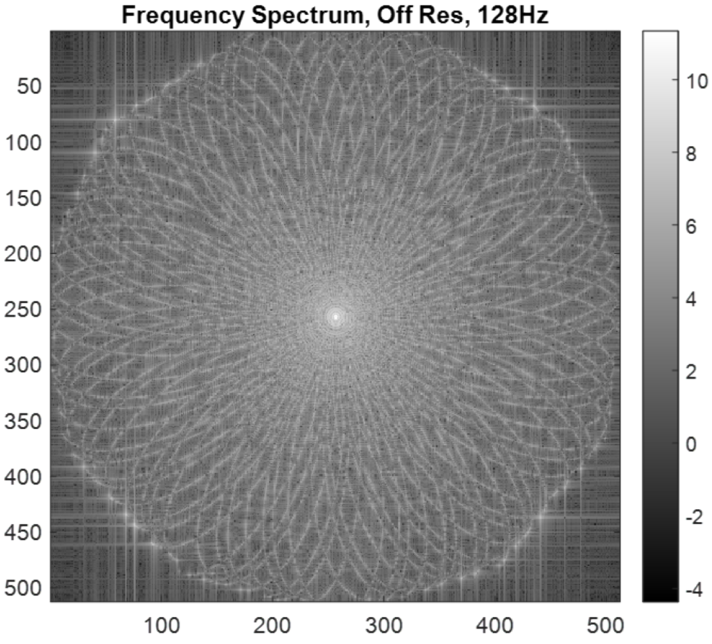
SSIM Maps


SSIM Map for Peak Freq=16Hz
50
100
150
200
250
300
350
400
450
500
100
200
300
400
500


SSIM Map for Peak Freq=1Hz
50
100
150
200
250
300
350
400
450
500
100
200
300
400
500

Frequency Spectrum





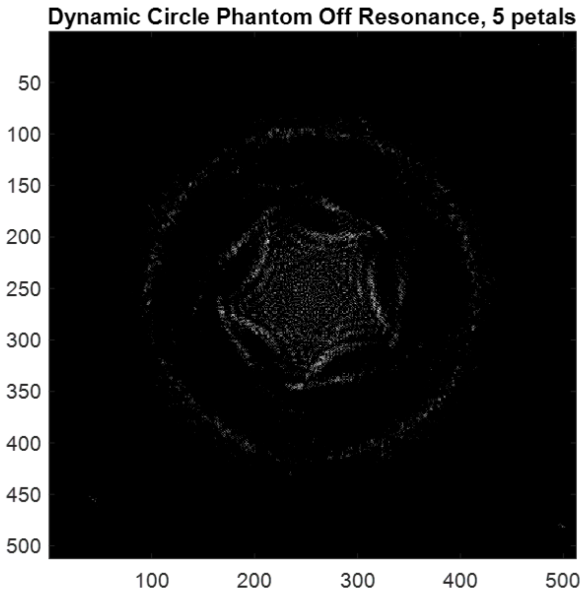
Effect of Changed Parameters on SNR

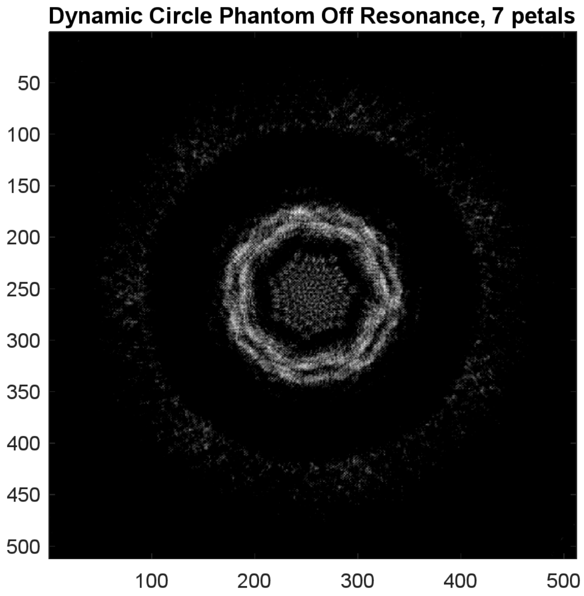
Objective:

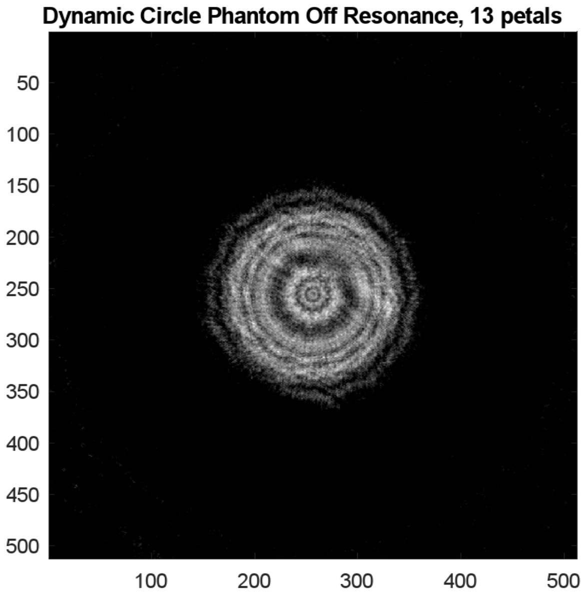
- To change the number of petals and add off-resonance sources in different ranges of frequency and calculate the SNR

Changing No. of Petals and adding Off-Resonance Sources

Peak Frequency = 128Hz







SNR Calculations for Off-Res Sources and Different No. of Petals

S. No.	Resonance Condition	Number of Petals	Peak Frequency (off-res)	SNR
1.	On-Resonance	5	-	80.94
	Off-Resonance	5	16Hz	80.30
2.	On-Resonance	7	-	101.96
	Off-Resonance	7	16Hz	100.69
3.	On-Resonance	11	-	129.23
	Off-Resonance	11	16Hz	118.31
4.	On-Resonance	13	-	76.24
	Off-Resonance	13	16Hz	70.63

SNR Calculations for Off-Res Sources and Different No. of Petals

S. No.	Resonance Condition	Number of Petals	Peak Frequency (off-res)	SNR
1.	On-Resonance	5	-	80.94
	Off-Resonance	5	512Hz	97.20
2.	On-Resonance	7	-	101.96
	Off-Resonance	7	512Hz	127.20
3.	On-Resonance	11	-	129.23
	Off-Resonance	11	512Hz	134.33
4.	On-Resonance	13	-	76.24
	Off-Resonance	13	512Hz	86.06

Discussion

- As the peak value of f reduces, the image approaches the on-resonance/ original image
- Image Metrics:

$$F_{max} \propto NRMSE$$

$$F_{max} \propto \frac{1}{PSNR} \propto \frac{1}{R^2}$$

- 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