


**Advanced Angiographic Imaging Techniques:
Non-Cartesian**

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Dynamic Contrast Enhanced MRA

Challenge
Need high spatial resolution to resolve vessels, but also need a high temporal resolution to separate arterial and venous phases.

Increased frame rates can be provided by:

- Parallel Imaging
- Partial Fourier
- Keyhole
- View Sharing
- Non Cartesian Acquisitions
- Compressed Sensing / HYPR




Background: Cartesian

Cartesian Imaging

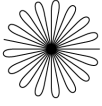


- Used by nearly all clinical MRI pulse sequences
- Very robust to gradient errors
- Image Reconstruction is Easy
- Parallel Imaging is Easy
- Anisotropic FOV is Easy

Drawbacks

- Sensitive to flow/motion
- Slow
- Uniform Undersampling -> Coherent Aliasing Artifact



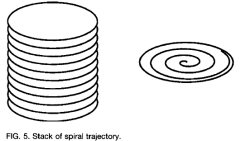
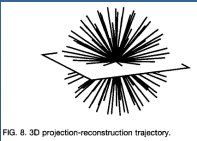
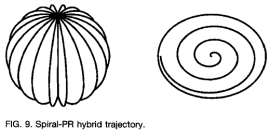
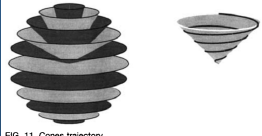
Background: Non-Cartesian

Radial EPI	Rosette	VD Spiral
		

Non-Cartesian Imaging

- Offers unique benefits for a subset of applications
- Sensitive to Gradient Errors
 - Gradient Delays
 - Eddy Currents
 - Concomitant Gradients
- Image Reconstruction More Difficult

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








 FIG. 5. Stack of spiral trajectory.	 FIG. 8. 3D projection-reconstruction trajectory.
 FIG. 9. Spiral-PR hybrid trajectory.	 FIG. 11. Cones trajectory.

Figures From: P. Irarrazabal and D.Nishimura
MRM 1995; Vol. 33 p.656

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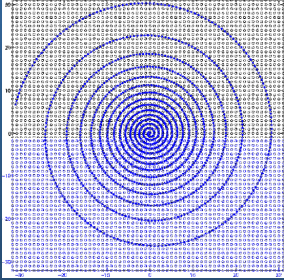
Background: Non-Cartesian

Incoherent Aliasing Artifacts

Cartesian	Radial EPI	Rosette	VD Spiral	
				
True Object				
				

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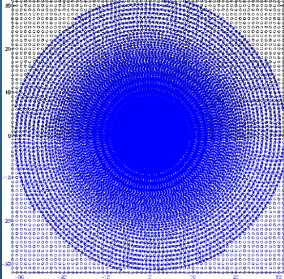
Background: Gridding



¹ O'Sullivan et al. IEEE Trans. Med. Imaging 1985, 4(4):200-207
¹ Jackson et al. IEEE Trans. Med. Imaging 1991, 10(3):473-478

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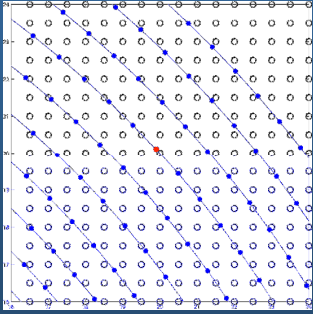
Background: Gridding



¹ O'Sullivan et al. IEEE Trans. Med. Imaging 1985, 4(4):200-207
¹ Jackson et al. IEEE Trans. Med. Imaging 1991, 10(3):473-478

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Gridding Example



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Gridding Example

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Gridding Example

Gridded data $\xrightarrow{\text{IFFT}}$ \downarrow Crop \rightarrow \times \leftarrow $1/\text{FFT}(\text{kernel})$

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Background: Gridding/NUFFT Software

Jeff Fessler's Image Reconstruction Toolbox:
<http://www.eecs.umich.edu/~fessler/code/index.html>
Matlab-based implementations of NUFFT and much more

NUFFT: <http://www-user.tu-chemnitz.de/~potts/nfft/>
Implementations of various Non-uniform FFTs in C (Linux-based)


Jim Pipe has some stuff here: http://www.ismrm.org/mri_unbound/

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Dynamic CE-MRA

Reduce aliasing artifacts via:

- 3D projection reconstruction acquisition (VIPR¹)
 - incoherent aliasing artifacts
- Acquire multiple radial lines in a single shot
- Pre-contrast subtraction
 - removes aliasing of the background tissue
 - vessel images are sparse (< 5% non-zero)



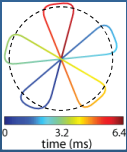
2560 projections
3D MIP

¹ Barger et al. MRM 48:297-305 (2002)


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Dynamic CE-MRA: Methods

Implemented a 2D radial EPI sequence:



3D spherical k-space is progressively filled in by pseudo-random rotations of this 2D pattern:



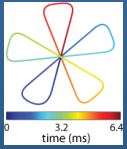
16 shots 64 shots 256 shots

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Methods:

Acquisition

- 3T Siemens System with 12-channel head coil
- 3D FLASH, FA= 20 degrees
- TR= 8.68 ms for 1.0 mm isotropic resolution
- TR= 10 ms for 0.8 mm isotropic resolution
- 5 radial lines per shot
- 4096 unique shots repeated 4 times (~2.5 mins)



Rep 1 Rep 2 Rep 3 Rep 4

Precontrast Baseline Contrast Injection

Use all data to obtain coil sensitivities and field map

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Methods:

Contrast
Single dose (0.1 mmol/kg) of gadolinium-based contrast agent.
Injection rate: 3 mL/s

Reconstruction Approaches:

- 1.) CG-SENSE¹: initialize each frame with the previous timeframe
- 2.) CG-SENSE with BM4D² denoising: Lee et al. Proc. ISMRM 2012, #2257 initializes each frame with zeros

In both cases: time-segmented reconstruction³ for field map correction

¹ Pruessmann et al. Mag Reson Med 2001; 46: 638-651
² Maggioni et al. IEEE Trans. Image Process. 2012 (In Press)
³ Noll et al. IEEE Trans Med Imaging 1991; 10(4):629-637

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CG-SENSE

MR signal formation can be written as a system of linear equations:

$$y = Ax$$

For multi-coil MRI data

$$\begin{bmatrix} y_1 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} EC_1 \\ \vdots \\ EC_N \end{bmatrix} x$$

Labels: K-space data, Encoding Matrix, Coil Sensitivities, image

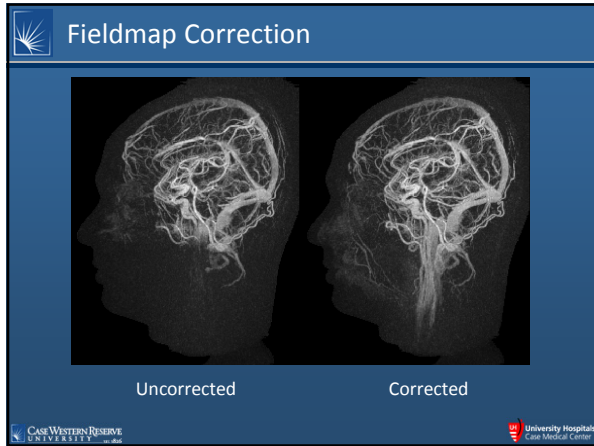
Use the conjugate gradient algorithm to solve

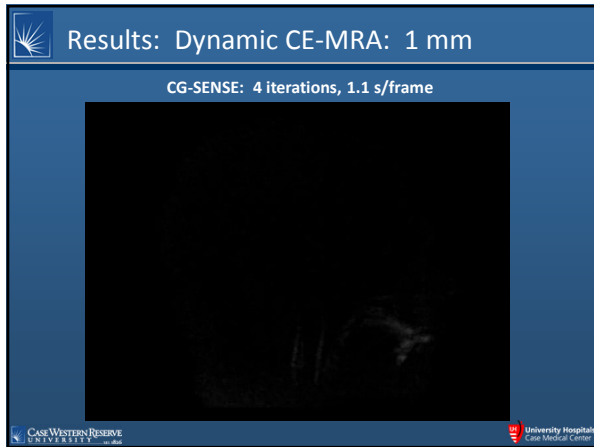
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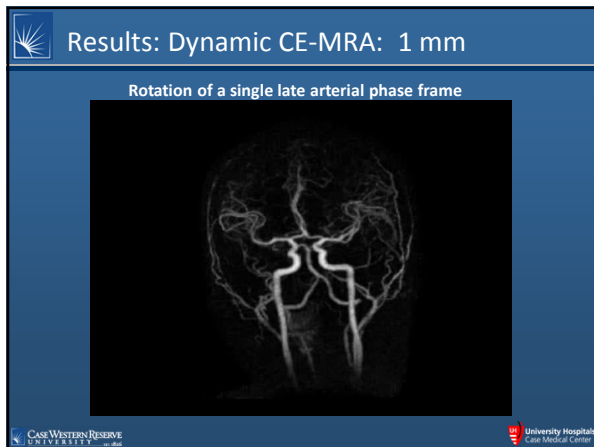
Field Map Estimation

The diagram illustrates the process of field map estimation. It starts with a multi-coil MRI setup (represented by a color wheel and a coil array). Four different echo times (TE) are used: 1.63, 2.89, 4.15, and 5.41. These are processed using CG-SENSE to produce magnitude images (|S|) and phase images (∠S). The phase images are then used to estimate the field map, which is shown as a grayscale image with a scale from -100 to 100 Hz.

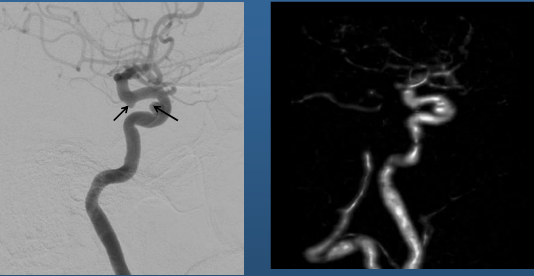
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Case 1: LICA aneurysm




2D x-ray DSA MRA: volume rendering

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This slide shows two medical images. On the left is a 2D x-ray DSA (Digital Subtraction Angiography) image of the internal carotid artery (ICA) with two black arrows pointing to a small, rounded aneurysm. On the right is an MRA (Magnetic Resonance Angiography) volume rendering of the same area, showing the 3D structure of the artery and the aneurysm.

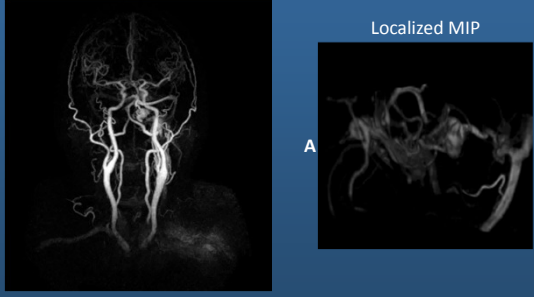
Case 2: AVM



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This slide features a 3D volume rendering of an Arteriovenous Malformation (AVM) in a lateral profile of a human head. The AVM is visible as a complex, tangled mass of blood vessels on the surface of the brain.

Case 2: AVM



Localized MIP

A P

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This slide shows two views of an AVM. On the left is a Maximum Intensity Projection (MIP) image of the brain's vasculature. On the right is a 'Localized MIP' image, which is a zoomed-in view of the AVM, showing its complex structure. The letters 'A' and 'P' are placed on either side of the localized MIP image.

Compressed Sensing

The theory of compressed sensing is a relatively recent development:

E. Candes et. al. IEEE Trans. Information Theory 2006; 52:489-509
D. Donoho. IEEE Trans. Information Theory 2006; 52:1289-1306

Early work in applying CS to MRI was performed by :
M. Lustig et al. Magn. Reson. Med. 2007; 58:1182-1195

Three key components required:

- Transform sparsity
- Incoherent aliasing artifacts in the transform domain
- Nonlinear image reconstruction that promotes sparsity

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CG-SENSE + Denoising

Adluru et al. JMRI 2012; 32:1217-1227 proposed a reconstruction approach which employed Non-local Means (NLM) denoising to remove incoherent aliasing artifacts.

Lee et. al. Proc. ISMRM 2012 #2257 proposed alternating CG-SENSE iterations with application of the BM4D¹ denoising algorithm.

¹ Maggioni et al. IEEE Trans. Image Process. 2012 (In Press)

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CG-SENSE + Denoising

Fig.1: Coronal MIPs for various reconstructions of a late arterial phase frame using 640 projections (1.33 seconds of data).

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CG-SENSE + Denoising


	320 Projections Temporal Footprint 0.66s	640 Projections Temporal Footprint 1.33s	1280 Projections Temporal Footprint 2.65s
Gridding			
CGDN, 16 iter, (N _{CS} = 2)			
CGDN, detail			

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Results: 32 channel coil, 0.8 mm

CG-SENSE + Denoising: 2 sec / frame every 0.5 s
Each frame initialized with zeros



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Projection Ordering

Goal:
sample uniformly, regardless of time scale
e.g. Short time scale used for individual frames, but long time scale used when estimating coil sensitivities and field map.

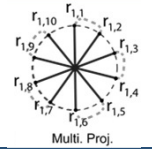
Existing approach:
When only one projection is acquired per TR, the 3D golden angle approach of Chan et al. (MRM 2009) can be used.
No known algorithm for cases with multiple-projections per TR

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Projection Ordering: Multi-projection

Proposed approach:
 Treat the end points of the projections as charged particles on the surface of a sphere. Treat each shot as a rigid body.



Multi. Proj.

$$\vec{F}_{i,k} \propto \sum_{s=1}^{N_s} \sum_{p=1}^{N_p} \frac{\vec{r}_{i,k} - \vec{r}_{s,p}}{|\vec{r}_{i,k} - \vec{r}_{s,p}|^3}$$

$$\vec{\tau}_{i,k} = \vec{r}_{i,k} \times \vec{F}_{i,k}$$

$$\vec{\tau}_i = \sum_{k=1}^{N_p} \vec{\tau}_{i,k}$$

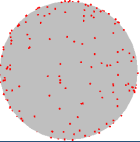
$$\vec{u}_i = \frac{\vec{\tau}_i}{|\vec{\tau}_i|} \quad \phi_i = \alpha |\vec{\tau}_i|$$

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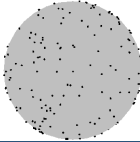
Projection Ordering: Multiclass

Initialize with Random Points

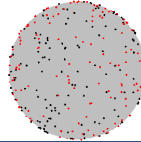
Set 1



Set 2



Set 1 + Set 2

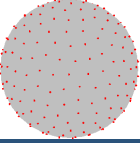


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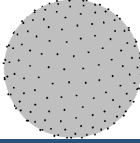
Projection Ordering: Multiclass

Weighted toward subsets

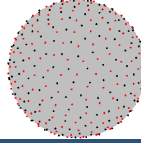
Set 1



Set 2



Set 1 + Set 2



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Projection Ordering: Multiclass

Weighted toward full set

Set 1 Set 2 Set 1 + Set 2

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Detailed description: This slide shows three circular plots. The first plot, labeled 'Set 1', contains only red dots. The second plot, labeled 'Set 2', contains only black dots. The third plot, labeled 'Set 1 + Set 2', contains a mixture of red and black dots, representing a weighted combination of the two sets. The dots are distributed across the circle, with some clustering.

Projection Ordering: Multiclass

Intermediate weighting

Set 1 Set 2 Set 1 + Set 2

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Detailed description: This slide shows three circular plots. The first plot, labeled 'Set 1', contains only red dots. The second plot, labeled 'Set 2', contains only black dots. The third plot, labeled 'Set 1 + Set 2', contains a mixture of red and black dots. The distribution of dots in the third plot appears more uniform than in the 'Weighted toward full set' case.

Projection Ordering: Multiclass

Multi-projection case has fewer degrees of freedom so uniformity is not as good as the case when all charges are allowed to move independently

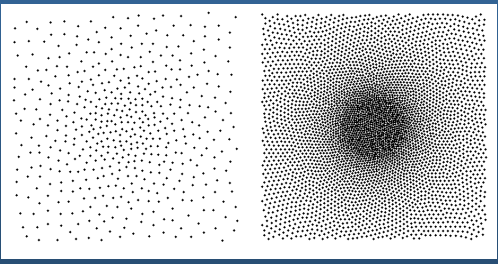
Set 1 Set 2 Set 1 + Set 2


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Detailed description: This slide shows three circular plots. The first plot, labeled 'Set 1', contains only red dots. The second plot, labeled 'Set 2', contains only black dots. The third plot, labeled 'Set 1 + Set 2', contains a mixture of red and black dots. The distribution of dots in the third plot shows significant clustering and non-uniformity, indicating fewer degrees of freedom.

Projection Ordering: 3D Cartesian Example

First 1/8 of samples Full Set of Samples





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Conclusions

Summary

- Time-resolved 3D acquisition at 0.8 – 1 mm isotropic resolution with temporal resolution of ~ 1 s / frame
- Reconstruction at acceleration factors > 100 .
- Iterative reconstruction is computationally intensive
- Field maps and coil sensitivities can be obtained from the same dataset



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