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Multishot high-resolution brain diffusion-weighted imaging using phase regularized reconstruction

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Declaration of Financial Interests or Relationships

Speaker Name: Yuxin Hu

I have the following financial interest or relationship to disclose with regard to the subject matter of this presentation:

Company Name: GE Healthcare
Type of Relationship: Research Support

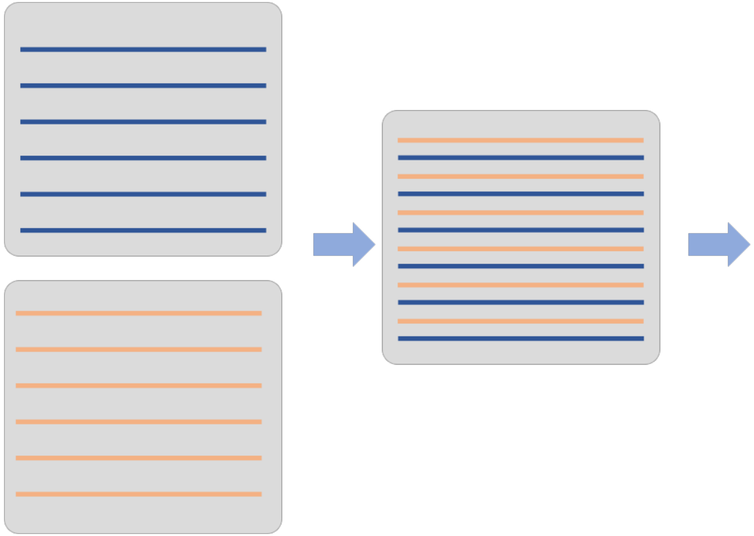
Diffusion-weighted imaging

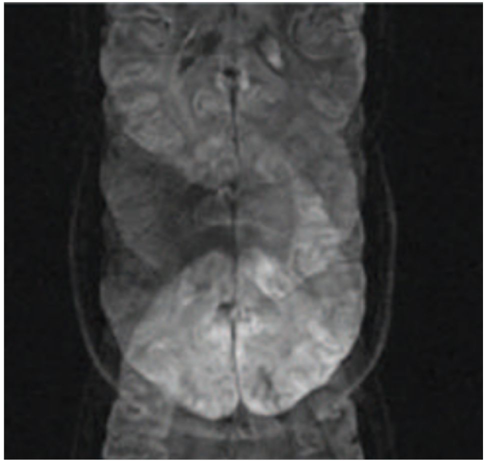
Single-shot imaging (fast, motion insensitive)

- Limited resolution and SNR
- Heavy distortion

Multi-shot imaging

- Motion sensitive





Multi-shot DWI

#0750

- Motion-induced phase $e^{-j\theta(x,y)}$ (random and spatially smooth)
- MUSE/POCS-MUSE

$$\min_{x,\theta_{1,\dots,N_S}} \sum_{i=1}^{N_S} \left\| D_i F S e^{j\theta_i} x - y_i \right\|_2^2$$

x: image to be reconstructed

θ: motion-induced phase to be estimated

D_i and y_i: the sampling operator and acquired data of the i^{th} shot.

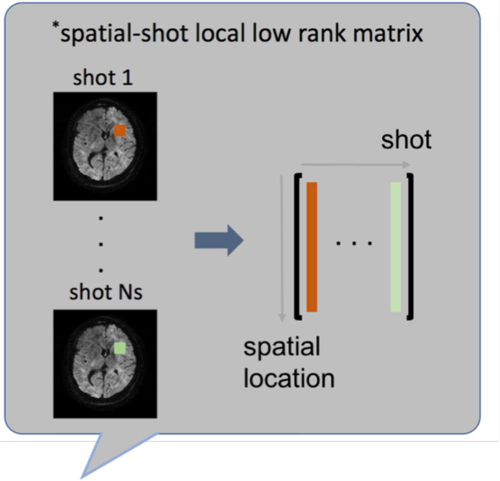
F: Fourier transform

S: sensitivity map

- Step1: parallel imaging on each shot* and take the low-resolution** results to estimate $e^{j\theta_i}$
- Step2: estimate x

Multi-shot DWI

- Motion-induced phase $e^{-j\theta(x,y)}$ (random and spatially smooth)
- Shot locally low-rank (shot-LLR)
  - "calibration-less parallel imaging*"
  - Spatial-shot matrices
  - Slow-phase variations = low-rank



$$\min_{x_{1,\ldots,N_S}} \sum_{i=1}^{N_S} \|D_i F S x_i - y_i\|_2^2 + \lambda \sum_{b\in\Omega} \left\|R_b\{x_{1,\ldots,N_S}\}\right\|_*$$

Data consistency term

LLR regularization

*Trzasko J, et al. IEEE TMI 2011.

Multi-shot DWI

- Motion-induced phase $e^{-j\theta(x,y)}$ (random and spatially smooth)
- MUSE/POCS-MUSE (non-convex)

$$\min_{x,\theta_{1,\ldots,N_S}} \sum_{i=1}^{N_S} \left\| D_i F S e^{j\theta_i} x - y_i \right\|_2^2$$

- Shot locally low-rank (shot-LLR) (**convex**)

$$\min_{x_{1,\ldots,N_S}} \sum_{i=1}^{N_S} \| D_i F S x_i - y_i \|_2^2 + \lambda \sum_{b \in \Omega} \left\| R_b \{ x_{1,\ldots,N_S} \} \right\|_*$$

~~**x**: image to be reconstructed~~

$\mathbf{x_i}$: the i^th^ shot image to be reconstructed

~~**θ**: motion-induced phase to be estimated~~

$\mathbf{D_i}$ **and** $\mathbf{y_i}$: the sampling operator and acquired data of the i^th^ shot.

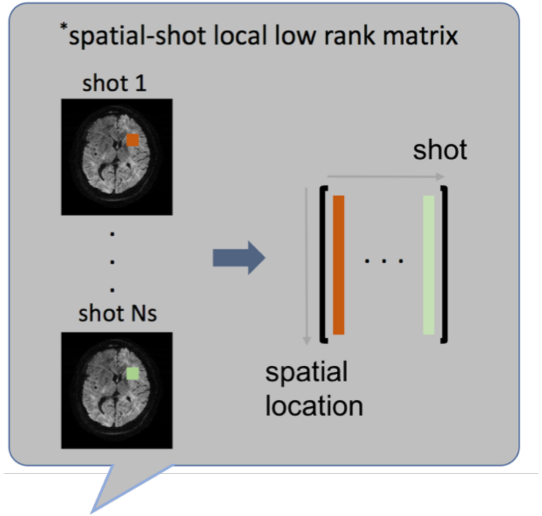
F: Fourier transform

S: sensitivity map

Multi-shot DWI

- Motion-induced phase $e^{-j\theta(x,y)}$ (random and spatially smooth)
- MUSE/POCS-MUSE (non-convex)

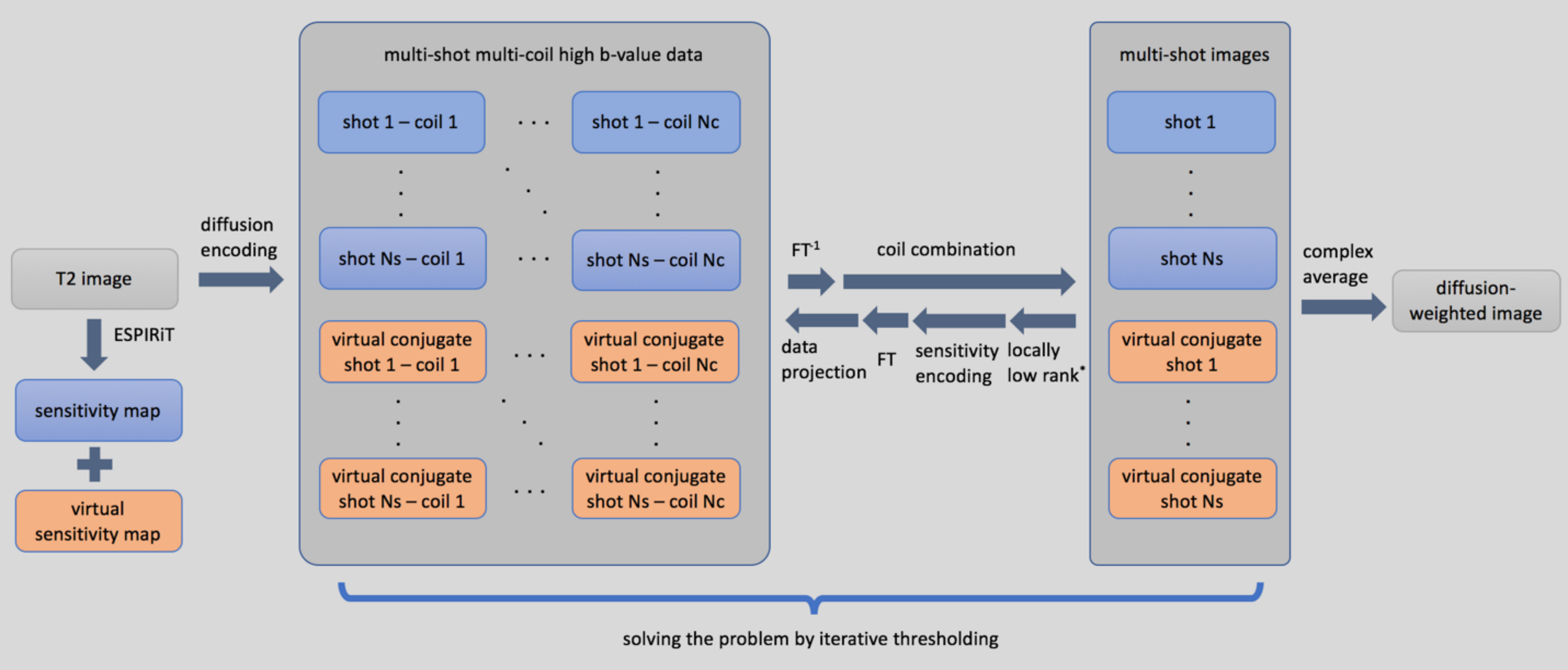
$$\min_{x,\theta_{1,\ldots,N_s}} \sum_{i=1}^{N_s} \left\| D_i F S e^{j\theta_i} x - y_i \right\|_2^2$$



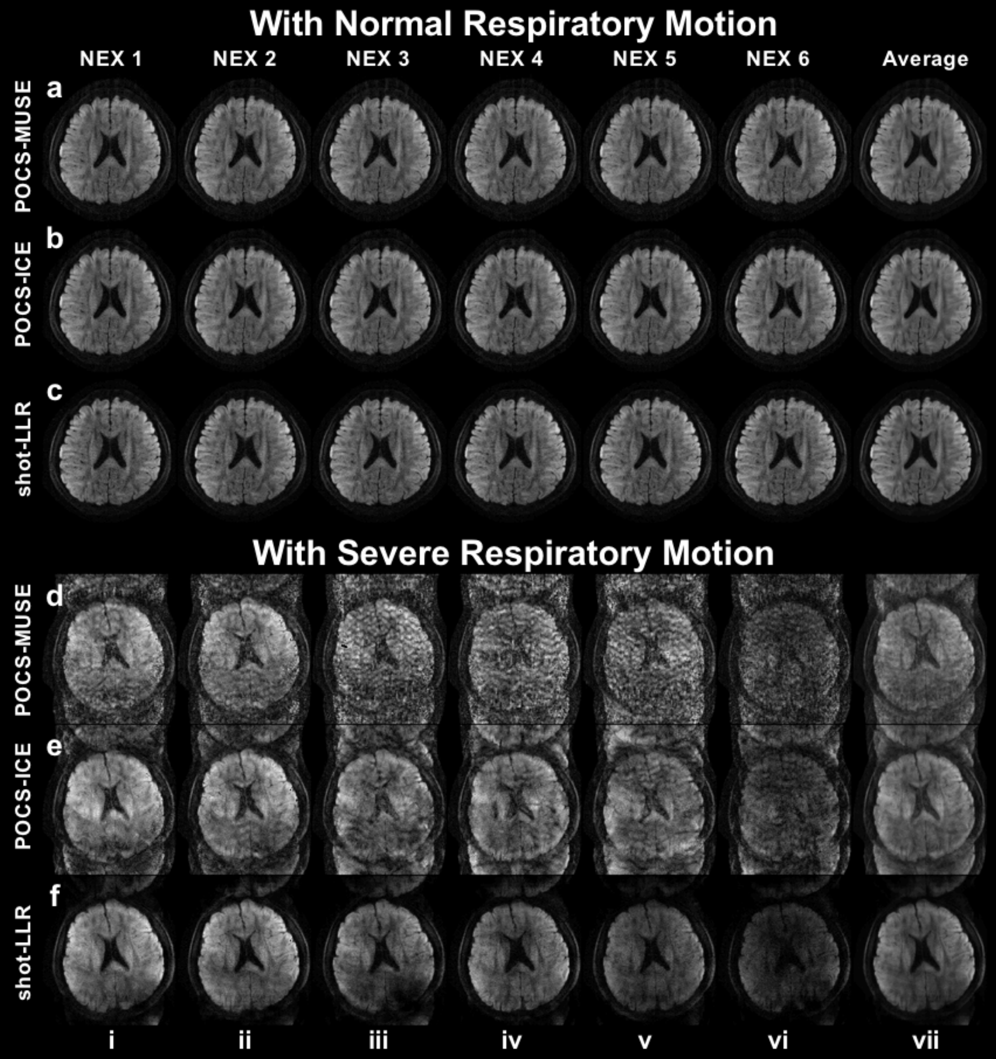
- Shot locally low-rank (shot-LLR) (**convex**)

$$\min_{x_{1,\ldots,N_s}} \sum_{i=1}^{N_s} \left\| D_i F S x_i - y_i \right\|_2^2 + \lambda \sum_{b \in \Omega} \left\| R_b\{x_{1,\ldots,N_s}\} \right\|_*$$

Flowchart of shot-LLR reconstruction with virtual conjugate shots



4-shot, nex = 6
a-c: normal
d-f: with severe motion



Non-convex model

$$\min_{m,\theta_1,\ldots,\theta_{Ns}} \sum_{i=1}^{Ns} \frac{1}{2} ||D_i F S m \cdot e^{j\theta_i} - y_i||_2^2 + \lambda_1 g_m(m) + \lambda_2 \sum_{i=1}^{Ns} g_\theta(\theta_i)$$

- Using shot-LLR as initialization
- Regularization terms on magnitude and phase
  - to improve the results
  - constraints on phase helps avoid partial Fourier reconstruction
- Phase cycling to solve artifacts from phase wrapping*

m: real-valued image to be reconstructed

θ: motion-induced phase to be estimated

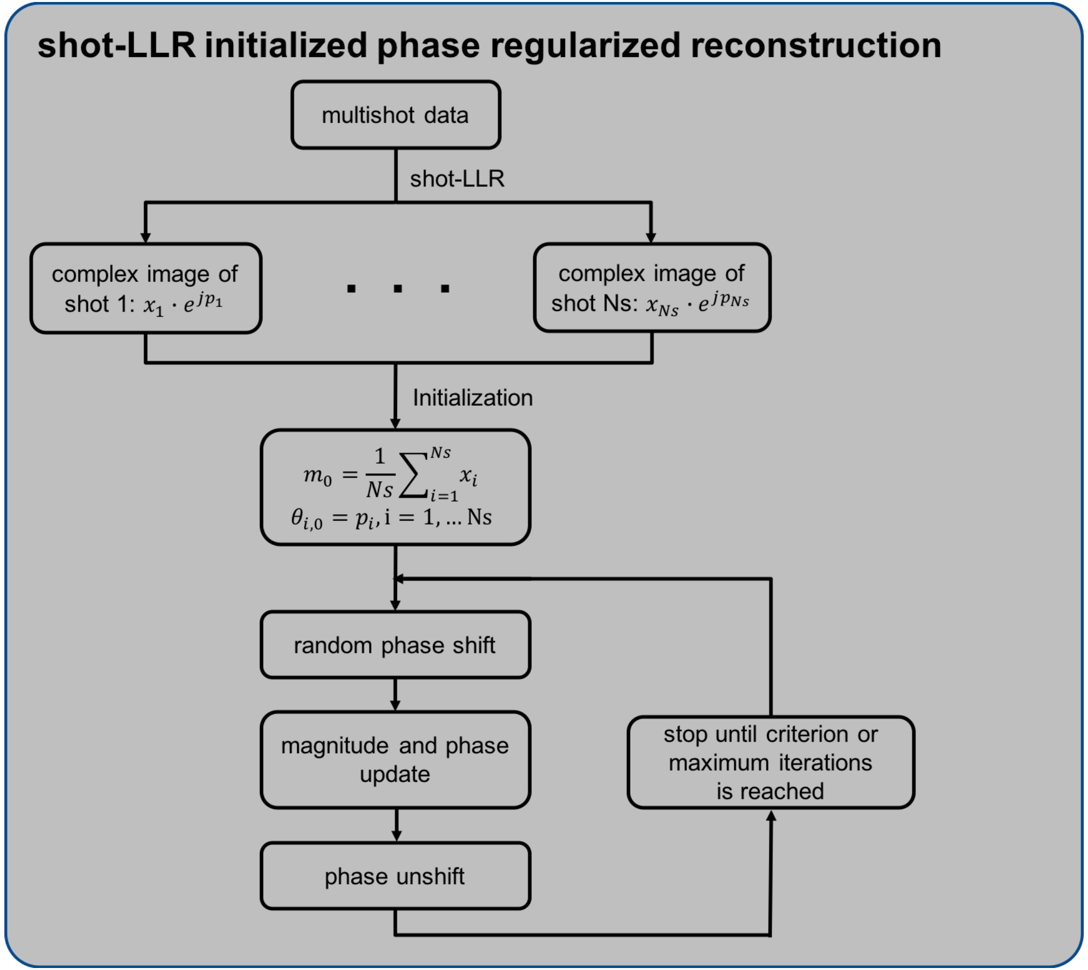
$\mathbf{D_i}$ **and** $\mathbf{y_i}$: the sampling operator and acquired data of the i^{th} shot.

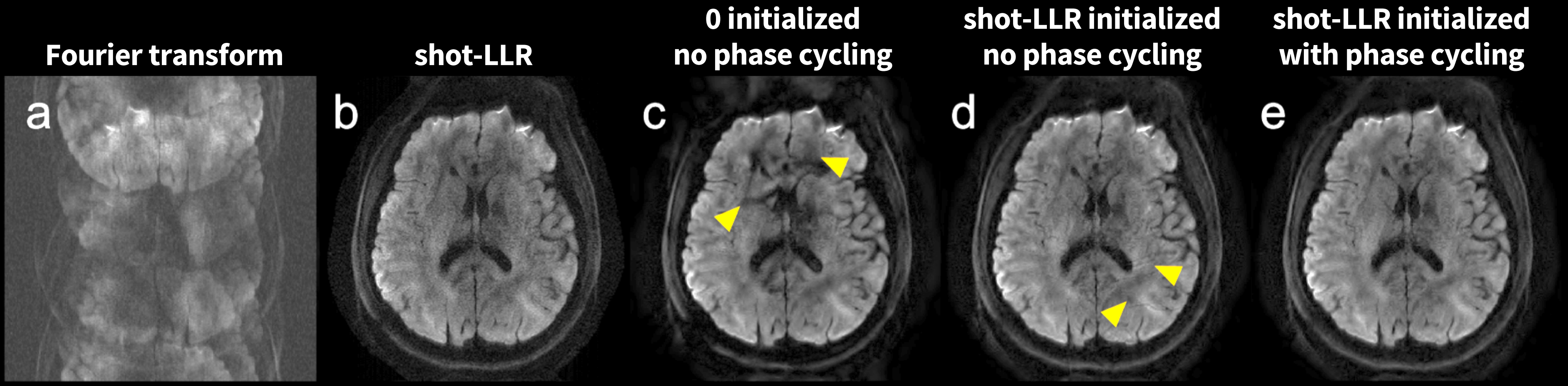
F: Fourier transform

S: sensitivity map

g_m **and** g_θ **:** regularization terms on magnitude and phase

*Ong, F., Cheng, J. Y., & Lustig, M., MRM 2018.


shot-LLR initialized phase regularized reconstruction
multishot data
shot-LLR
complex image of shot 1: $x_1 \cdot e^{jp_1}$
complex image of shot Ns: $x_{Ns} \cdot e^{jp_{Ns}}$
Initialization
$m_0 = \frac{1}{Ns}\sum_{i=1}^{Ns} x_i$
$\theta_{i,0} = p_i, \mathrm{i} = 1, \ldots \mathrm{Ns}$
random phase shift
magnitude and phase update
phase unshift
stop until criterion or maximum iterations is reached



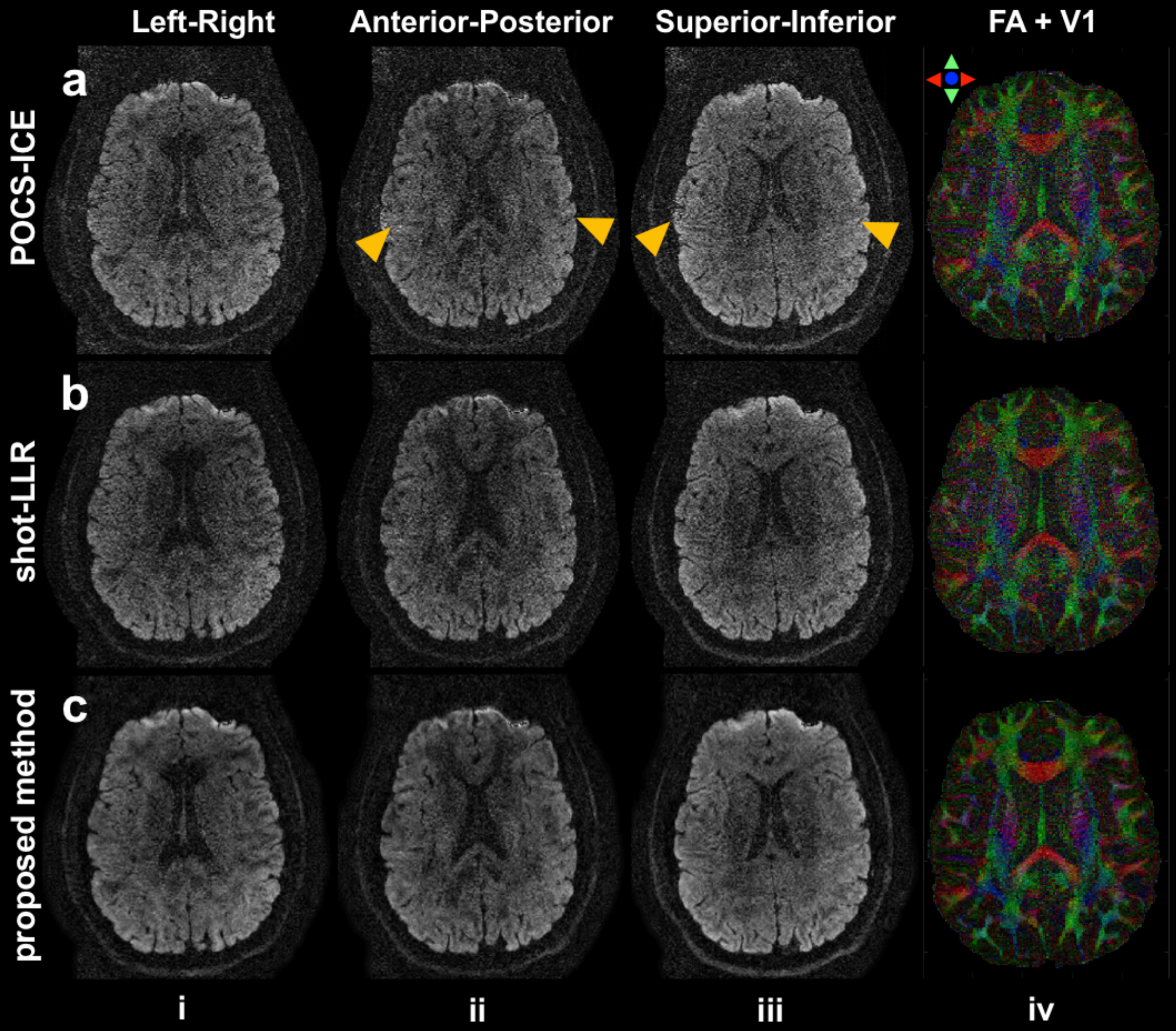
4-shot brain DW images (res: 0.85 x 0.85 x 3 mm^3, b-value = 1000 s/mm^2, nex = 1) reconstructed by Fourier transform (a), shot-LLR (b), proposed method with zero-filled data as initialization (c), proposed method with shot-LLR as initialization and without/with phase cycling (d/e).The yellow triangles point where the errors are.

4-shot DTI

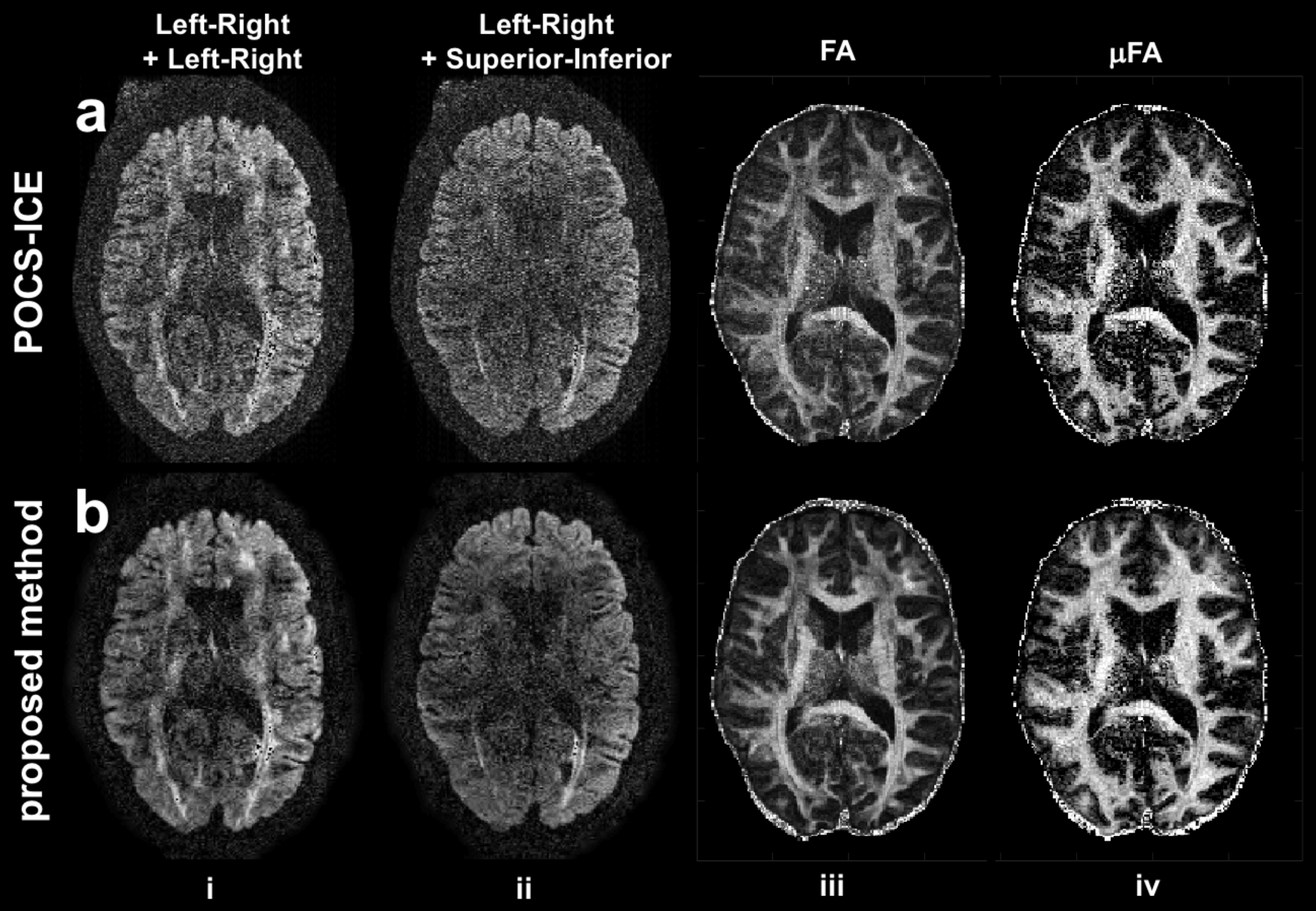
res = 0.8 mm isotropic

b-value = 1000 s/mm^2

#directions = 45



4-shot double-diffusion encoding imaging
res = 1 x 1 x 2 mm^3
b-value = 2000 s/mm^2
#directions = 120



Summary

To solve inter-shot phase variations in multi-shot DWI without navigator

- MUSE/POCS-MUSE/POCS-ICE
  - two steps: 1) explicit phase estimation; 2) final image reconstruction
- Shot-LLR
  - a relaxed model without phase estimation
- Shot-LLR initialized non-convex method
  - works well when SNR is low (high resolution/high b-value brain imaging)
  - inherits the property of handling big phase variations from shot-LLR.