High-Resolution Multishot Diffusion-Weighted Body and Breast MRI using Locally Low-rank regularization

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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:

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Diffusion-weighted imaging

- DWI is sensitive to **molecular motion** and **bulk motion**.
- DWI: \( I(x, y) e^{-bD(x,y)} e^{-i\theta(x,y)} \)
- Spatially smooth phase \( e^{-i\theta(x,y)} \) after diffusion encoding
  - Random: because bulk motion is **different** during each application of the diffusion encoding gradients (multi-shot, multi-nex).
Diffusion-weighted imaging

- Single-shot imaging (fast)
  - Limited resolution and SNR
  - Heavy distortion
- Multi-shot imaging (slow)
  - Motion sensitive
Multi-shot DWI

- Higher resolution; reduced distortion.
- Motion-induced phase $e^{-j\theta(x,y)}$ between shots (random).
Multi-shot DWI

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

\[ \min_{\mathbf{x}, \theta_1, \ldots, \theta_N} \sum_{i=1}^{N_S} \left\| D_i F S e^{j\theta_i} \mathbf{x} - y_i \right\|^2 \]

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

$x$: image to be reconstructed
$\theta$: 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
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

\[
\min_{x_1,\ldots,x_{N_s}} \sum_{i=1}^{N_s} \left\| D_i FS x_i - y_i \right\|_2^2 + \lambda \sum_{b \in \Omega} \left\| R_b \{ x_1,\ldots,x_{N_s} \} \right\|_*
\]

Data consistency term
LLR regularization

Multi-shot DWI

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

\[
\min_{x,\theta_1,\ldots,\theta_N} \sum_{i=1}^{N} \left\| D_i F S e^{j\theta_i} x - y_i \right\|_2^2
\]

\[
\min_{x_1,\ldots,x_N} \sum_{i=1}^{N} \left\| D_i F S x_i - y_i \right\|_2^2 + \lambda \sum_{b \in \Omega} \left\| R_b \{ x_1,\ldots,x_N \} \right\|_*
\]

- $x$: image to be reconstructed
- $x_i$: the $i$th shot image to be reconstructed
- $\theta$: 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
Multi-shot DWI

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

$$\min_{x, \theta_1, \ldots, \theta_N} \sum_{i=1}^{N_s} \| D_i FS e^{j\theta_i} x - y_i \|_2^2$$

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

$$\min_{x_1, \ldots, x_N} \sum_{i=1}^{N_s} \| D_i FS x_i - y_i \|_2^2 + \lambda \sum_{b \in \Omega} \| R_b \{ x_1, \ldots, x_N \} \|_*$$
Flowchart of shot-LLR reconstruction with virtual conjugate shots

T2 image → ESPIRIT → sensitivity map → virtual sensitivity map

multi-shot multi-coil high b-value data

shot 1 – coil 1 →...→ shot 1 – coil Nc

shot Ns – coil 1 →...→ shot Ns – coil Nc

virtual conjugate shot 1 – coil 1 →...→ virtual conjugate shot 1 – coil Nc

virtual conjugate shot Ns – coil 1 →...→ virtual conjugate shot Ns – coil Nc

FT⁻¹ → coil combination → FT⁻¹ →...→ FT⁻¹ → coil combination

data projection → sensitivity encoding → locally low rank

complex average → diffusion-weighted image

solving the problem by iterative thresholding
in-plane resolution = 1.44 mm
slice thickness = 4 mm
b-value = 600 s/mm²
in-plane resolution = 1 mm
slice thickness = 4 mm
b-value = 600 s/mm$^2$

POCS-MUSE

POCS-ICE

shot-LLR

conventional,
$R = 4, 1.44\text{mm}$
in-plane resolution = 1.1 mm
slice thickness = 4 mm
b-value = 500 s/mm²
Summary

Multi-shot DWI
- Reduced distortion and high resolution
- Shot-to-shot phase variations

Shot-LLR
- using a relaxed model, non-convex -> convex
- constraint on sum of ranks (rank of some matrix can still be high -> high frequency phase variations)