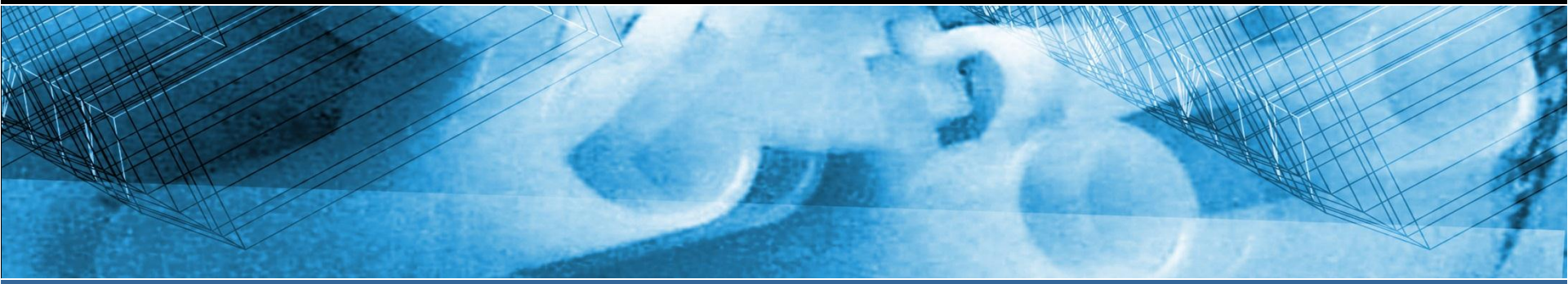

Accelerated DSI with Compressed Sensing using Adaptive Dictionaries

Berkin Bilgic[1], Kawin Setsompop[2,3], Julien Cohen-Adad[4],

Van Wedeen[2,3], Lawrence L. Wald[2,3,5], Elfar Adalsteinsson[1,5]

1 MIT
2 Martinos Center for Biomedical Imaging
3 Harvard Medical School
4 Ecole Polytechnique de Montreal
5 Harvard-MIT Division of Health Sciences and Technology

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Diffusion Spectrum Imaging (DSI)

- DSI offers detailed information on complex distributions of intravoxel fiber orientations

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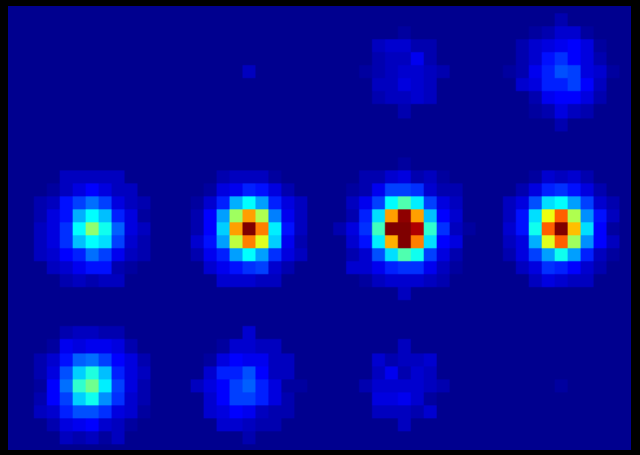
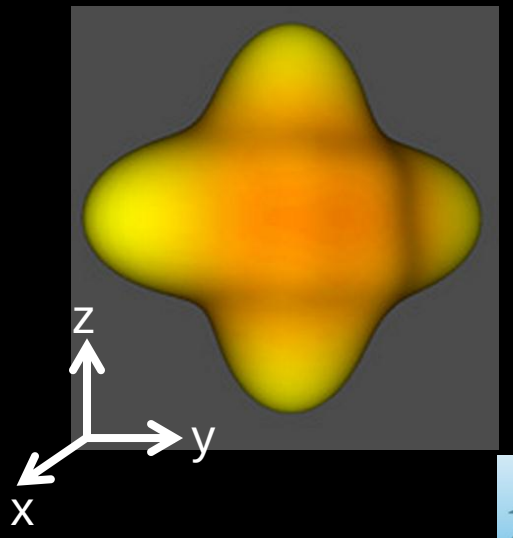
Q-space of a single voxel
515 directions



DFT

Probability Density Function (pdf)
of a single voxel



Sampling full q-space takes ~1 hour

rle AT MIT

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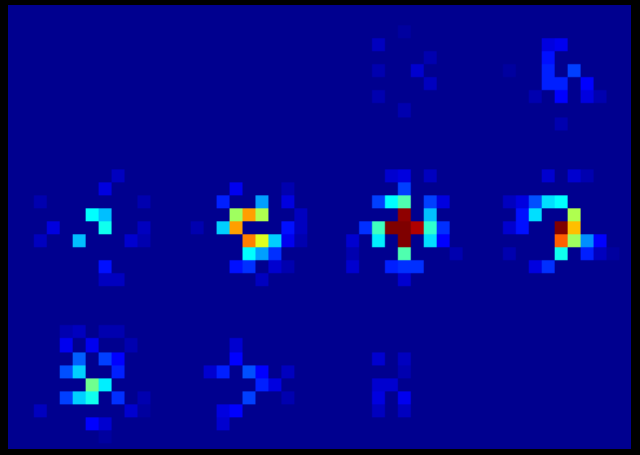
Undersampled DSI

- To reduce scan time, undersample q-space
- Use sparsity prior to reconstruct the pdfs [1]

$$min_{\boldsymbol{p}} \|\mathbf{F}_{\Omega}\boldsymbol{p} - \boldsymbol{q}\|_2{}^2 + \alpha \cdot \|\boldsymbol{\Psi}\boldsymbol{p}\|_1 + \beta \cdot \mathrm{TV}(\boldsymbol{p})$$

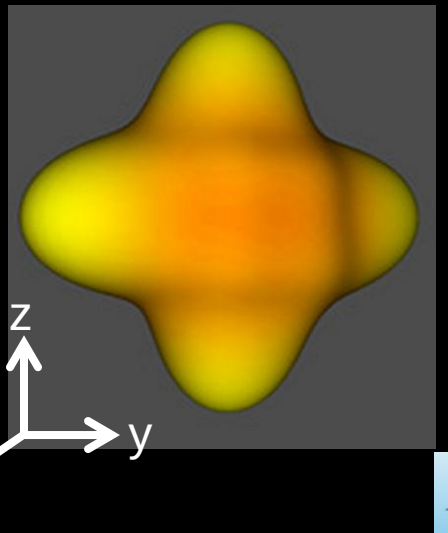
- $\mathbf{F}_{\Omega}$: undersampled DFT
- $\boldsymbol{p}$: pdf
- $\boldsymbol{q}$: q-samples
- $\boldsymbol{\Psi}$: wavelet
- $\mathrm{TV}(\boldsymbol{p})$: total variation

Undersampled q-space of a single voxel



CS

Probability Density Function (pdf) of a single voxel



1. Menzel MI et al MRM 2011

K-SVD algorithm for DSI

- Is pdf sparse in TV and wavelet?
- Use a transform tailored for sparse representation of pdfs

Step1: Create dictionary from a training pdf dataset [P]

$$min_{\mathbf{P},\mathbf{D}} \sum_i \|\boldsymbol{x}_i\|_0 \quad \text{subject to} \quad \|\mathbf{P} - \mathbf{D}\mathbf{X}\|_F{}^2 \leq \epsilon$$

K-SVD[1] iterative algorithm was used to obtain [D]

Step2: Use dictionary to impose sparsity constraint

$$min\|\boldsymbol{x}\|_1 \quad \text{such that} \quad \mathbf{F}_\Omega \mathbf{D}\boldsymbol{x} = \boldsymbol{q}$$

FOCUSS[2] was used to provide parameter free recon

1. Aharon M, et al IEEE Trans Signal Processing 2006
2. Gorodnitsky IF, et al IEEE Trans Signal processing 1997

Methods

- 3 healthy volunteers, 3T Siemens Skyra

Methods

- 3 healthy volunteers, 3T Siemens Skyra
- Connectom gradients†, 64-chan head coil [1]

Gmax = 300 mT / m

Conventional = 45 mT / m

† MAGNETOM Skyra CONNECTOM system (Siemens Healthcare)

1. Keil B, et al MRM 2012

Methods

- 3 healthy volunteers, 3T Siemens Skyra
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- 2.3 mm isotropic, bmax = 8000 s/mm^2

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- Recon experiments at accelerations R = 3, 5 and 9

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- <u>Comparison of methods:</u>
  i. Wavelet + TV (Menzel et al [2])
  ii. L1-FOCUSS (apply L1 penalty on pdfs)
  iii. Dictionary-FOCUSS (proposed)

1. Keil B, et al MRM 2012
2. Menzel MI et al MRM 2011

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- 10 average collected at 5 q-space points
  Low-noise data, serve as ground truth

1. Keil B, et al MRM 2012
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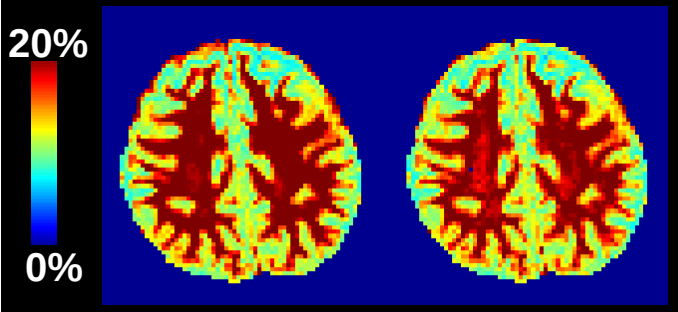
- <u>Tractography comparison:</u>
  - Fully-sampled vs. R = 3 Dictionary-FOCUSS
  - Fractional Anisotropy compared for 18 major fiber bundles

1. Keil B, et al MRM 2012
2. Menzel MI et al MRM 2011

Subject A, pdf reconstruction error

Wavelet+TV ℓ_1-FOCUSS



15.8% RMSE 15.0% RMSE

Acceleration
R = 3

Wav+TV @ R=3 **15.8% error**

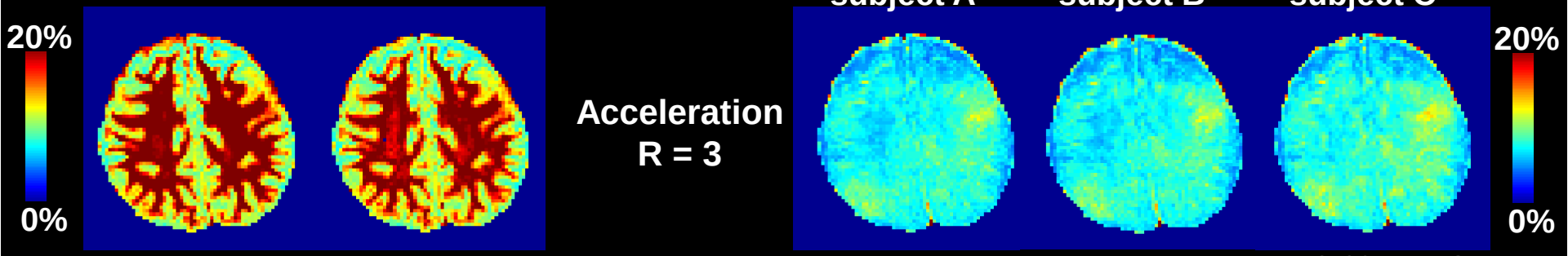
ℓ_1-FOCUSS @ R=3 **15.0% error**

Subject A, pdf reconstruction error

Slice 40

Dictionary-FOCUSS

Wavelet+TV | ℓ_1-FOCUSS | Trained on subject A | Trained on subject B | Trained on subject C



15.8% RMSE | 15.0% RMSE | 7.8% RMSE | 7.8% RMSE | 8.2% RMSE

Wav+TV @ R=3 — 15.8% error

ℓ_1-FOCUSS @ R=3 — 15.0% error

Dictionary @ R=3 — 7.8% error

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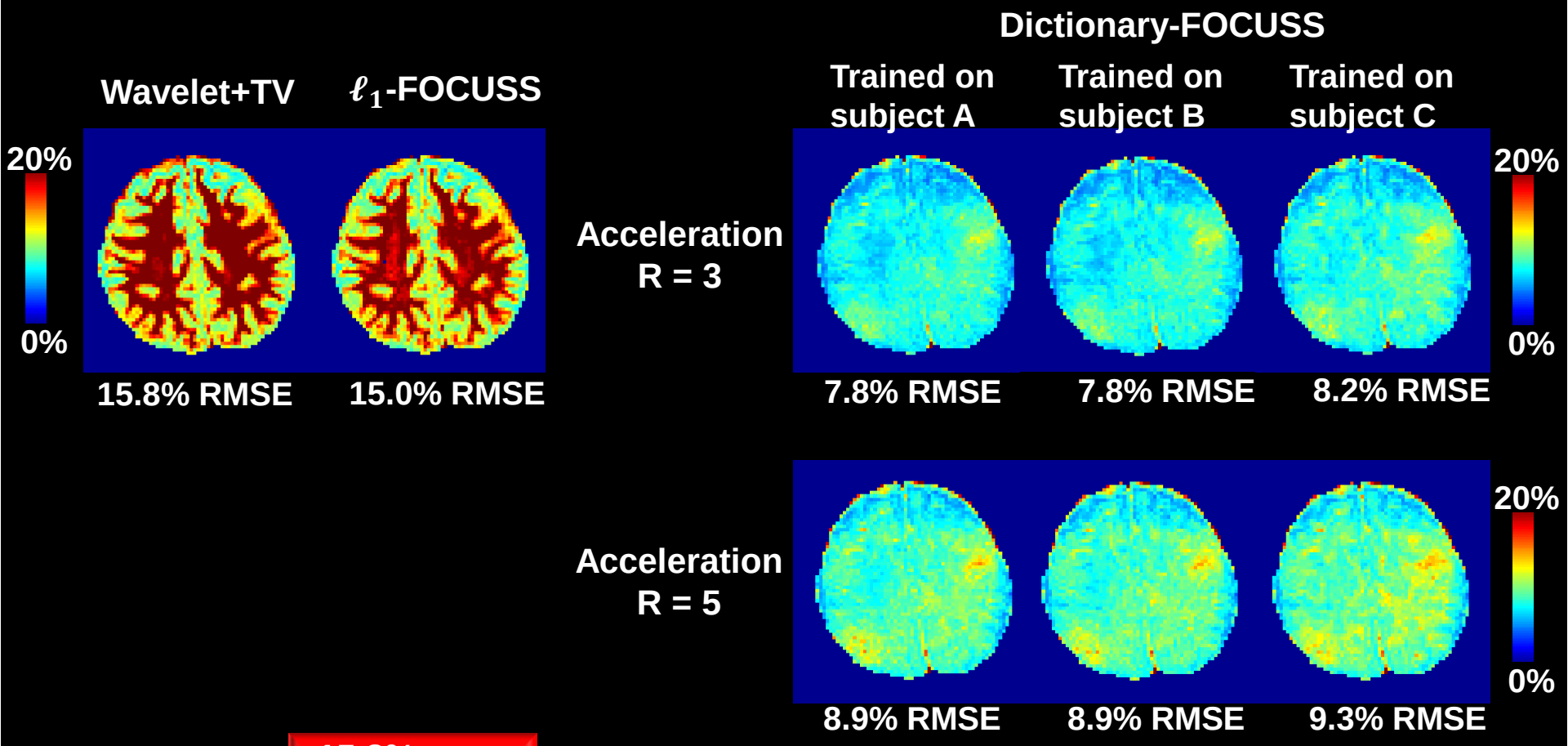
Subject A, pdf reconstruction error

Slice 40



Wav+TV @ R=3 — 15.8% error

ℓ_1-FOCUSS @ R=3 — 15.0% error

Dictionary @ R=3 — 7.8% error

Dictionary @ R=5 — 8.9% error

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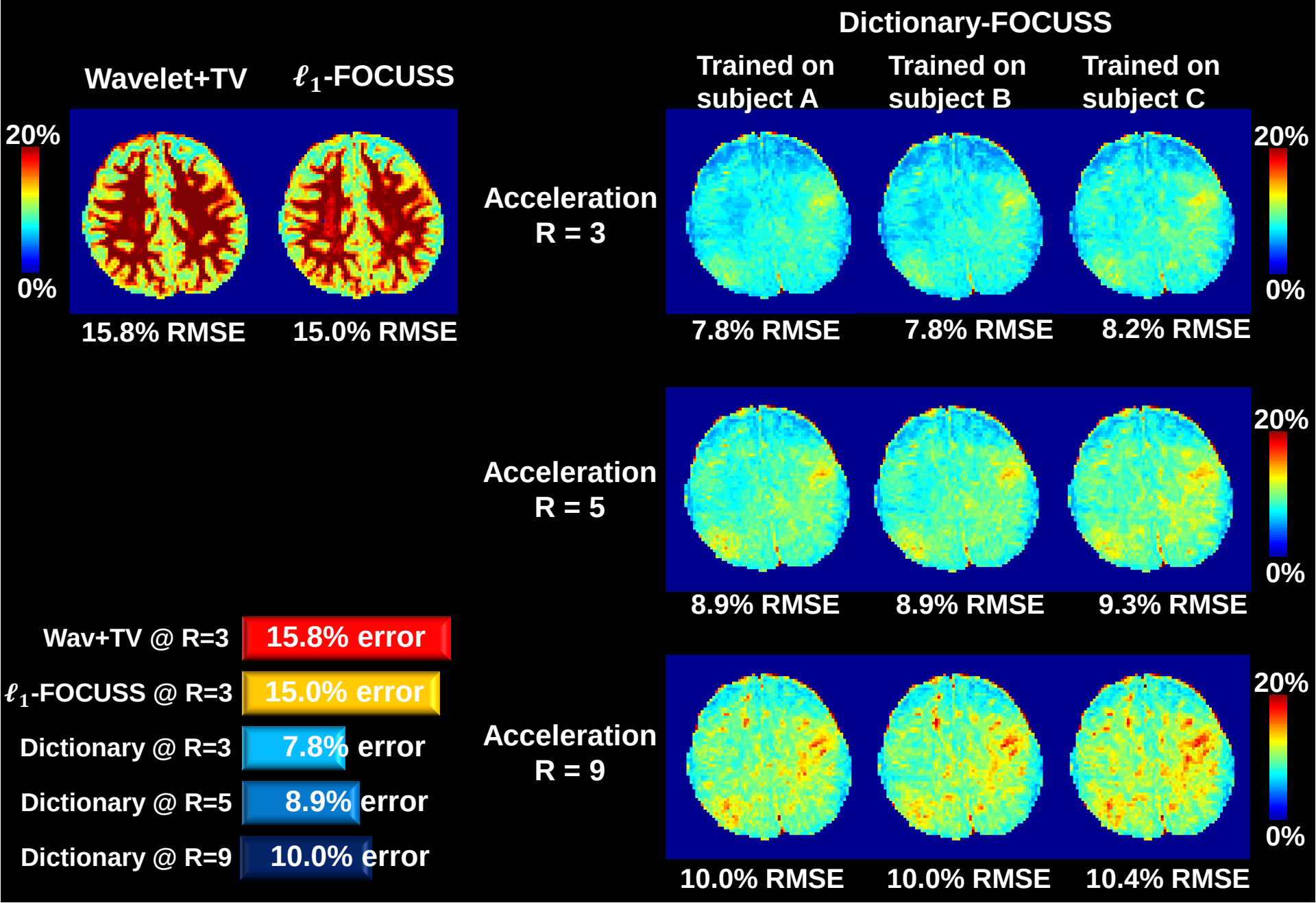
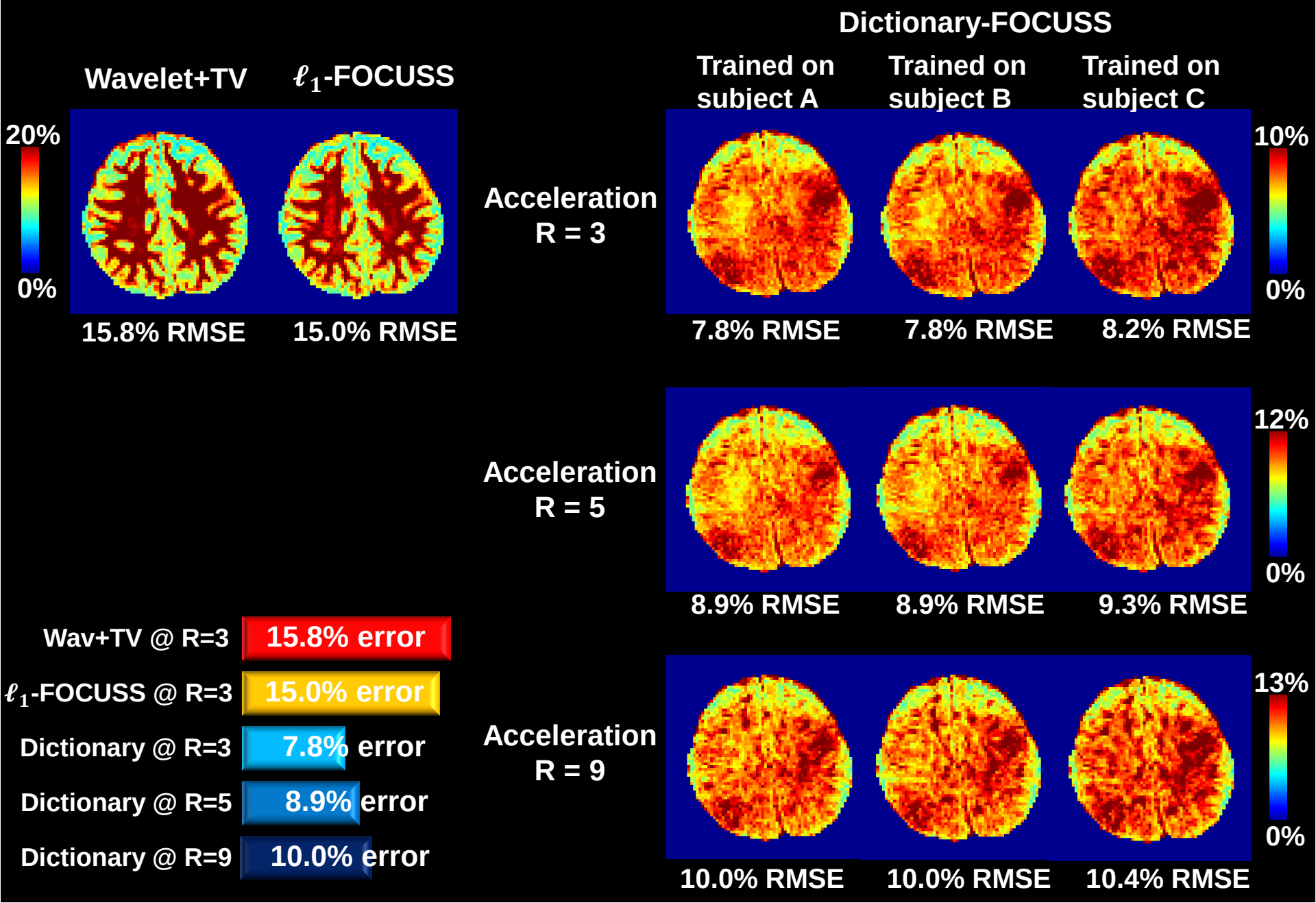
Subject A, pdf reconstruction error

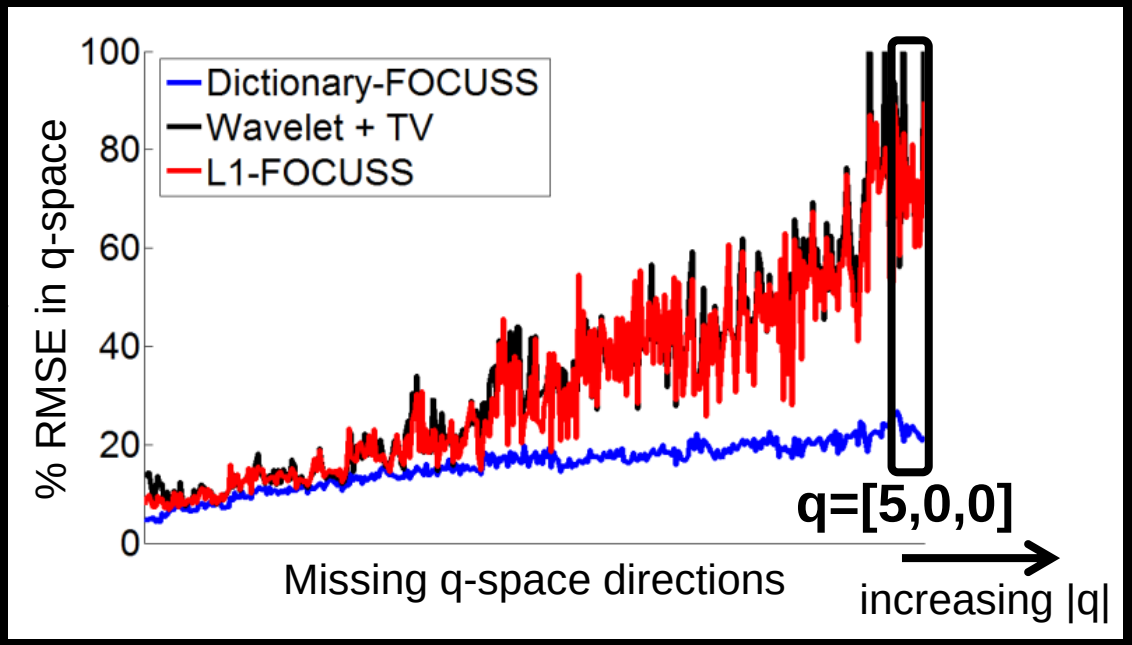
Slice 40



Subject A, pdf reconstruction error

Slice 40

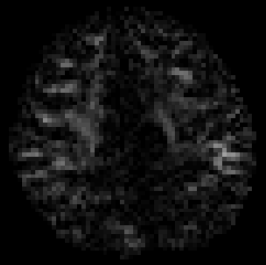




q-space reconstructions at q=[5,0,0]

Wavelet+TV

ℓ_1-FOCUSS



Dict-FOCUSS

Fully-sampled

1 average

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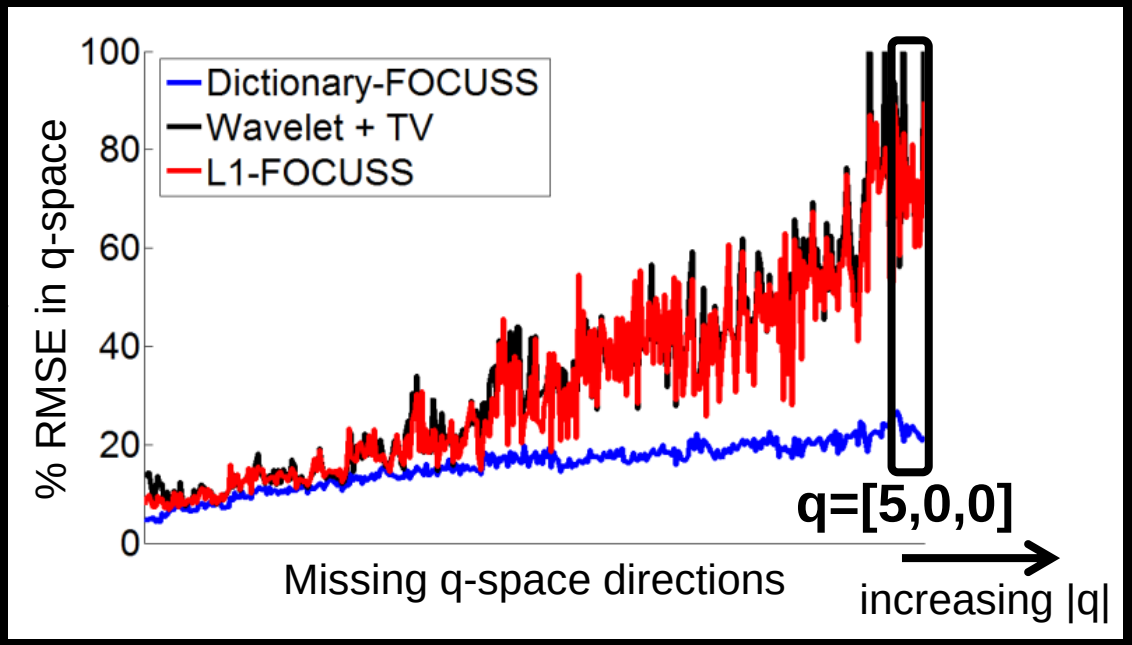


q-space reconstructions at q=[5,0,0]

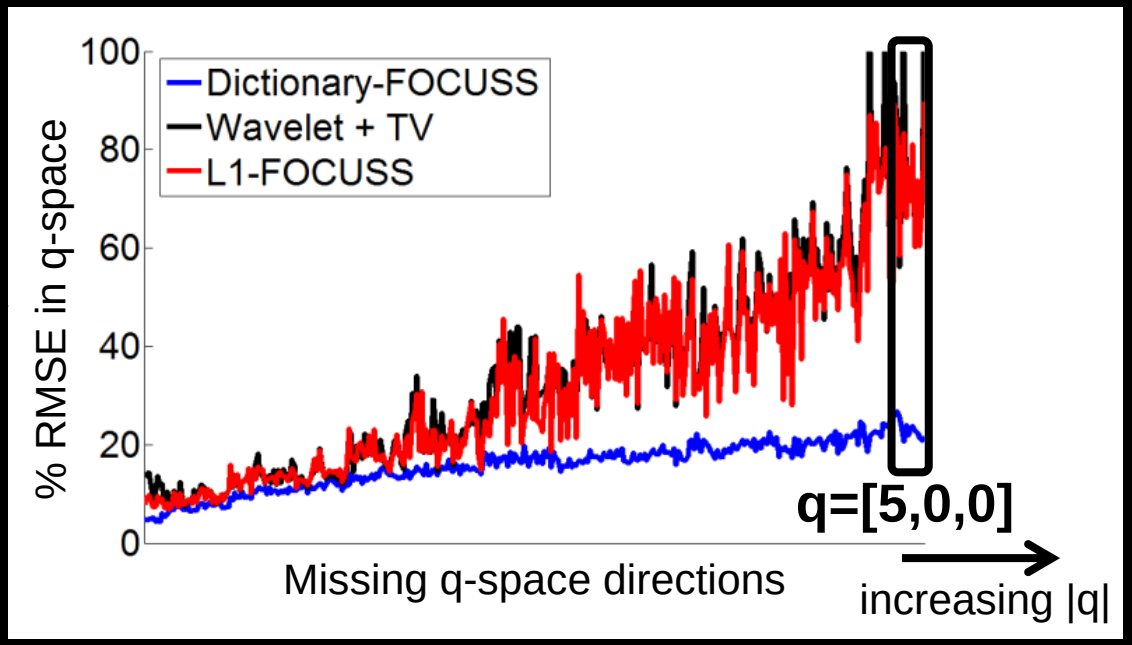
Wavelet+TV

ℓ_1-FOCUSS

Dict-FOCUSS

Fully-sampled

10 average



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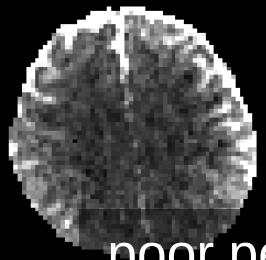
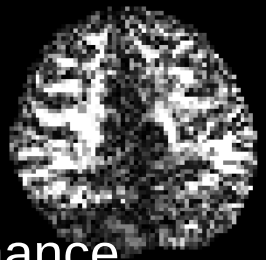


ℓ_1-FOCUSS



poor performance

same ℓ_2 norm as 10 average

Dict-FOCUSS

good performance

Fully-sampled

10 average

- SNR drops substantially at the outer q-space
- RMSE computed relative to 1 average fully-sampled data includes noise and recon error

- To isolate recon error, collected 10 avg on 5 q-space points

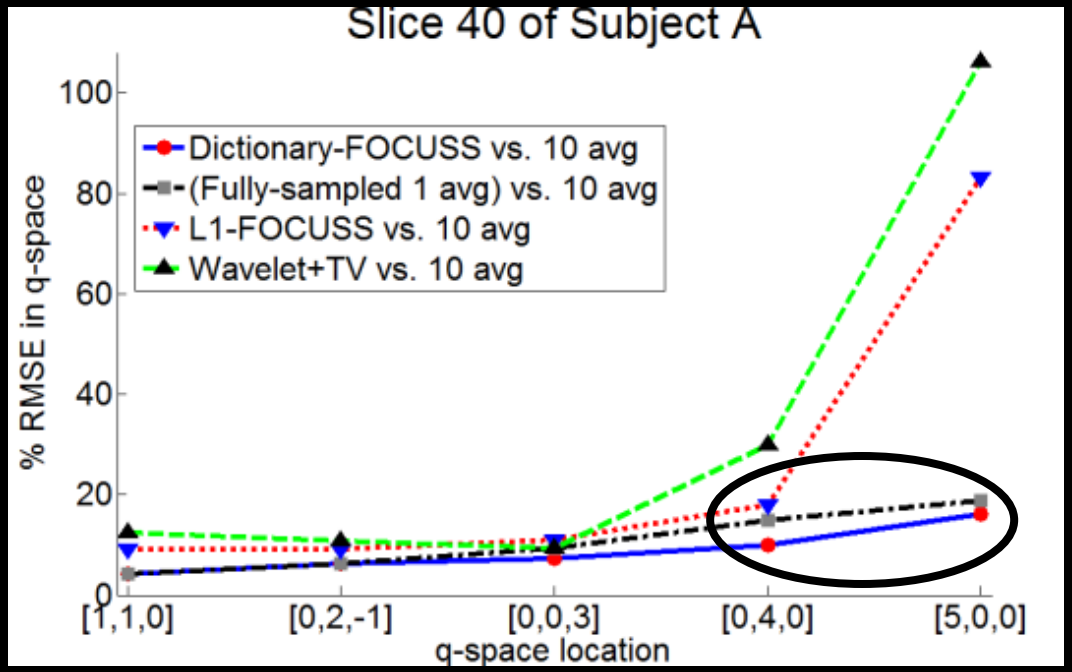
- SNR drops substantially at the outer q-space
- RMSE computed relative to 1 average fully-sampled data includes noise and recon error

1 avg fully-sampled

10 avg fully-sampled

q = [5,0,0]

- SNR drops substantially at the outer q-space
- RMSE computed relative to 1 average fully-sampled data includes noise and recon error

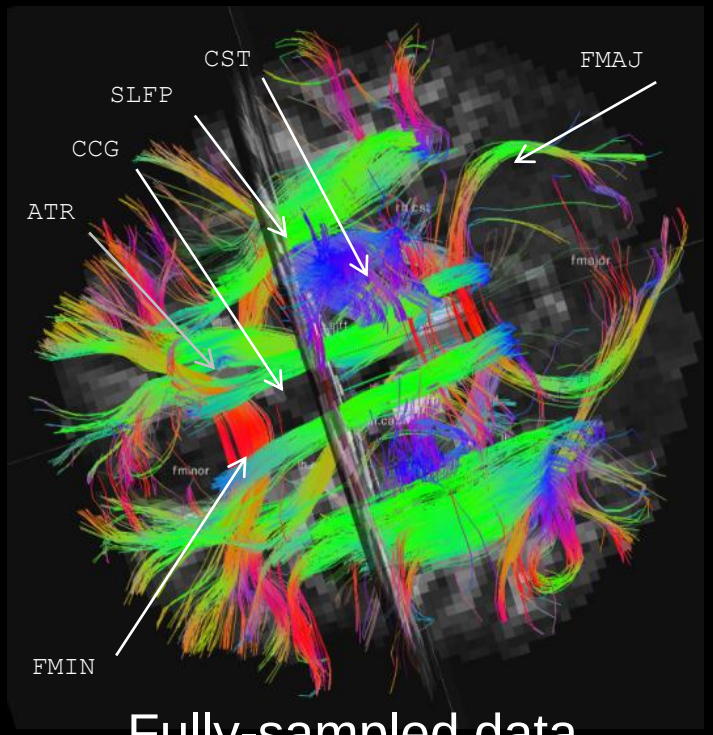


Lower RMSE than acquired data

Denoising effect [1]

1. Patel V, et al ISBI 2011, p1805

Tractography solutions for subject A



Fully-sampled data

Dictionary-FOCUSS recon with 3-fold acceleration

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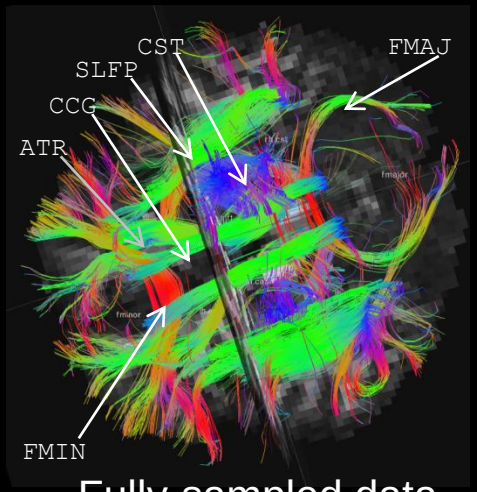

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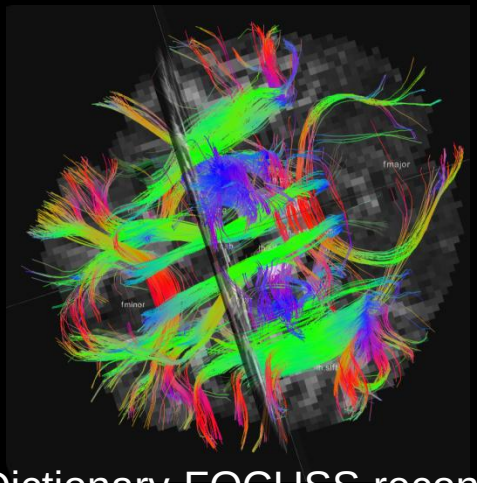
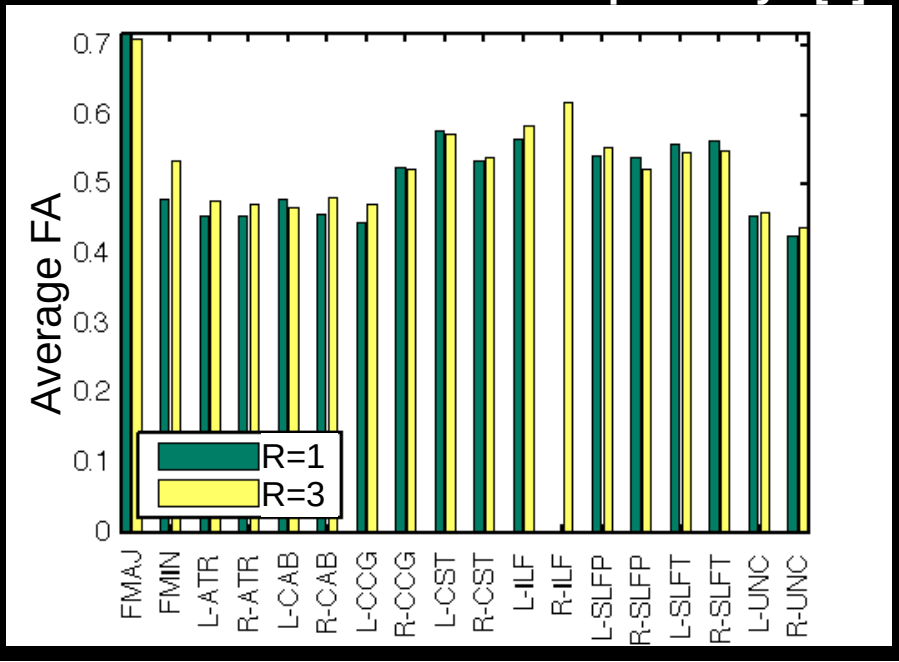


Dictionary-FOCUSS recon
with 3-fold acceleration

Average Fractional Anisotropy for 18 labeled white-matter pathways [1]



1. Yendiki A et al
Front Neuroinform 2011

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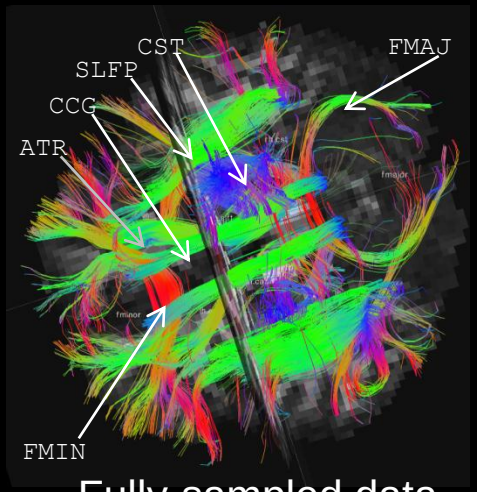

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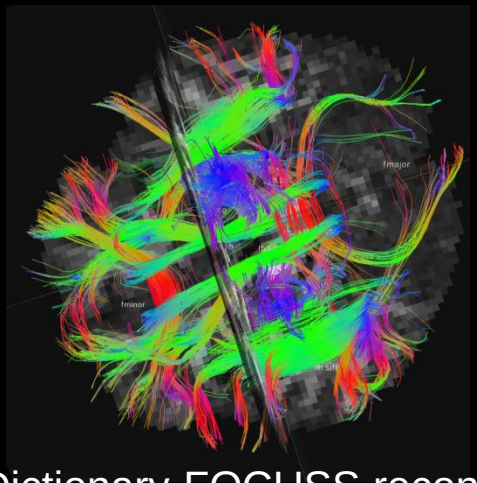
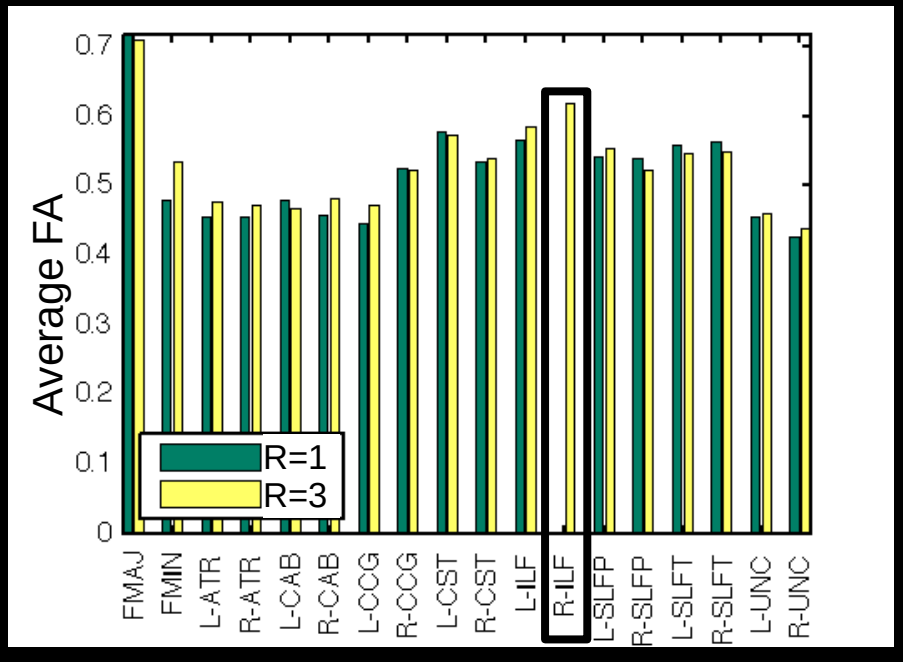


Dictionary-FOCUSS recon
with 3-fold acceleration

Mean FA error = 3%



1. Yendiki A et al
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Concluding Remarks

- Up to 2-times RMSE reduction in pdf domain
  - Dictionary-FOCUSS (proposed) vs. Wavelet+TV [1]

1. Menzel MI et al MRM 2011

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- 3-fold accelerated Dict-FOCUSS ≈ Fully-sampled data
  - Low-noise 10 average data validation
  - Tractography comparison

1. Menzel MI et al MRM 2011

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- Up to 2-times RMSE reduction in pdf domain
  - Dictionary-FOCUSS (proposed) vs. Wavelet+TV [1]
- 3-fold accelerated Dict-FOCUSS ≈ Fully-sampled data
- Parallel imaging with Simultaneous Multi-Slice (SMS) [2]
  - 3-fold acceleration with minor loss in SNR
  - Orthogonal to CS, 3×3 = 9-fold acceleration combined

1. Menzel MI et al MRM 2011
2. Setsompop K et al MRM 2012

Concluding Remarks

- Up to 2-times RMSE reduction in pdf domain
  - Dictionary-FOCUSS (proposed) vs. Wavelet+TV [1]
- 3-fold accelerated Dict-FOCUSS ≈ Fully-sampled data
- Dictionary from single slice seems to generalizes to other slices and to other subjects

1. Menzel MI et al MRM 2011

Concluding Remarks

- **Voxel-by-voxel recon**
  - Dictionary-FOCUSS: 12 sec / voxel
  - Wavelet+TV: 27 sec / voxel in Matlab

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- Matlab code online at:

  http://web.mit.edu/berkin/www/software.html

Acknowledgments

Thanks to:

- Itthi Chatnuntawech
- Kawin Setsompop
- Stephen Cauley
- Julien Cohen-Adad
- Anastasia Yendiki
- Lawrence Wald
- Elfar Adalsteinsson

Sponsors:

- MIT-CIMIT Medical Engineering Fellowship
- Siemens Healthcare
- Siemens-MIT Alliance

Grants:

K99EB012107, U01MH093765, R01EB006847, R01EB007942, R01EB000790, P41RR14075

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