SUPER-RESOLUTION MULTI-FASCICLE IMAGING REVEALS THE PRESENCE OF BOTH RADIAL AND TANGENTIAL DIFFUSION IN THE MATURE CORTEX USING A CLINICAL SCANNER

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PURPOSE.

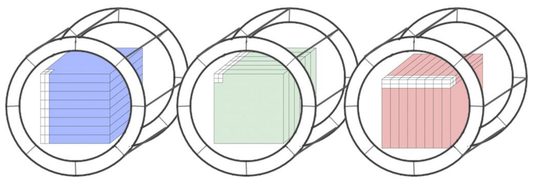
- Radial diffusion has been reported at early stages in cortical development[1]
- In the mature cortex: the dominance of radial[2] diffusion or tangential[3] diffusion is matter of debate
- McNab et al[4] : while mostly radial diffusion persists, tangential diffusion may exist in very particular cortex areas.
- Previous studies: diffusion tensor imaging, an over-simplified model

Aim: to investigate the pattern of diffusion in the mature cortex with super-resolution multi-fascicle imaging.

1. McKinstry, R.C. et al, Radial Organization of Developing Preterm Human Cerebral Cortex Revealed by Non-invasive Water Diffusion Anisotropy MRI, Cereb. Cortex, 12, 1237-43; **2.** Miller K.L. et al., Diffusion imaging of whole, post-mortem human brains on a clinical MRI scanner, Neuroimage, 2011, 57, 167-181; **3.** Golay, X et al, High-resolution isotropic 3D diffusion tensor imaging of the human brain, 2002, Magn. Reson. Med. 47, 837–843; **4.** McNab J.A. et al, Surface based analysis of diffusion orientation for identifying architectonic domains in the in vivo human cortex, Neuroimage, 2013, 69, 87-100.

QUANTITATIVE SUPER-RESOLUTION RECONSTRUCTION - Isotropic HR k-space sampling by imaging of a series of anisotropic acquisitions

1 ACQUISITION. Orthogonal thick-slices acquisitions, high in-plane resolution



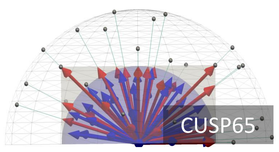
- Siemens 3T Trio with
- 32 channel head coil
- FOV = 240 mm
- Matrix = 192x192
- In-plane resolution = 1.25x1.25mm^2
- Slice-thickness = 2mm
- Moderate gradient strength (40mT/m)

+ For each orientation, pair of b=0 with opposite phase encoding directions, Geometric & intensity distortion compensation for each DW image

(Scherrer et al, 2012B)

Total acquisition time: ~ 45min.

Gradient encoding scheme: Cube and Sphere (CUSP)



(Scherrer et al, 2012A)

- Projection of a two-shell HARDI
- Gradient orientations maximally separated
- Timings parameters Δ and δ defined by the inner-shell
- High b-values up to 3 bnominal
- Low echo time (TE)

Image multiple non-zero b-values with high SNR

↖ Necessary to estimate a mixture of tensors

2 SUPER-RESOLUTION RECONSTRUCTION OF EACH DW-IMAGE, based on an image generative model

Forward Model:

$$\mathbf{y}_k = \mathbf{D}_k\mathbf{B}_k\mathbf{M}_k\mathbf{x} + \epsilon_k$$

Observed LR volume k — Residual error

Down-sampling matrix — PSF of the MRI acquisition — Warping matrix — **Unknown HR Volume**

Reconstruction = Compute the inverse problem:

Reconstruction at 1x1x1mm3

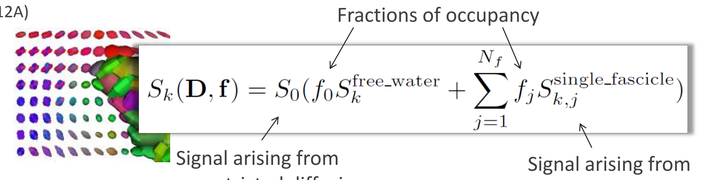
(Number of HR voxels to estimate matches the number of LR observations)

$$\widehat{\mathbf{x}}^{n+1} = \widehat{\mathbf{x}}^{n} - \alpha\left[\sum_{k=1}^{K}\mathbf{M}_k^T\mathbf{B}_k^T\mathbf{D}_k^T\left(\mathbf{D}_k\mathbf{B}_k\mathbf{M}_k\widehat{\mathbf{x}}^{n} - \mathbf{y}_k\right) + \lambda Q^T Q\widehat{\mathbf{x}}^{n}\right]$$

(Scherrer et al, 2012B)

3 MULTI-FASCICLE MODEL ESTIMATION

(Scherrer et al, 2012A)



Fractions of occupancy

$$S_k(\mathbf{D},\mathbf{f}) = S_0\left(f_0 S_k^{\text{free\_water}} + \sum_{j=1}^{N_f} f_j S_{k,j}^{\text{single\_fascicle}}\right)$$

Signal arising from unrestricted diffusion — Signal arising from each fascicle

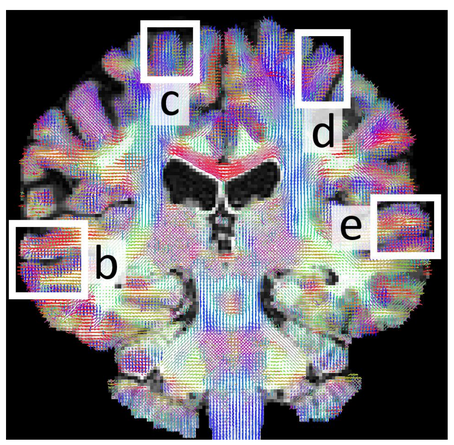
$$S_k^{\text{free\_water}} = e^{-b_k D_{\text{iso}}}$$
$$S_{k,j}^{\text{single\_fascicle}} = e^{-b_k \mathbf{g}_k^T \mathbf{D}_j \mathbf{g}_k}$$

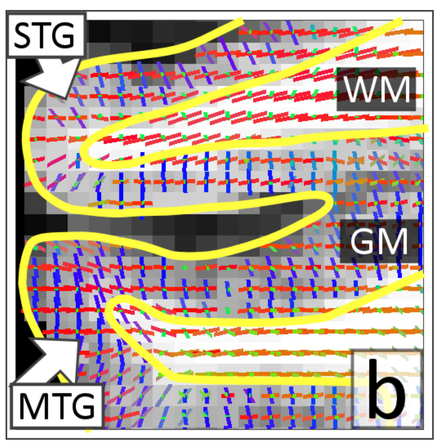
+ Estimation of the number of fascicles at each voxel : minimization of the generalization error

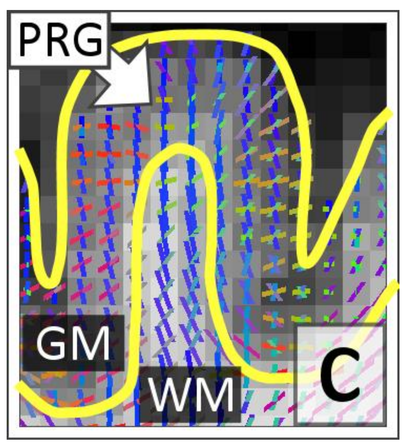
(Scherrer et al, 2013)

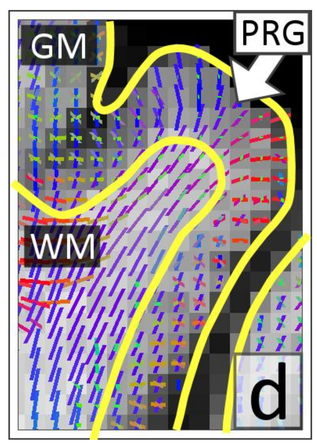
[Scherrer et al, 2012A] Scherrer B., Warfield S.K., *Parametric Representation of Multiple White Matter Fascicles from Cube and Sphere Diffusion MRI*, PLoS ONE, 7(11), 2012 ; [Scherrer et al, 2012B] Scherrer B., Gholipour A., Warfield S.K., *Super-resolution reconstruction to increase the spatial resolution of diffusion weighted images from orthogonal anisotropic acquisitions*, Med Imag Analysis, 16(7), 2012, 1465-1476 ; [Scherrer et al, 2013] Scherrer B. *, Taquet M. *, Warfield S.K., *Reliable Selection of the Number of Fascicles in Diffusion Images by Estimation of the Generalization Error*, Proc. of the 23rd Int Conf Inf Process Med Imaging (IPMI), LNCS 7917, Asilomar, USA, 2013, 742--75

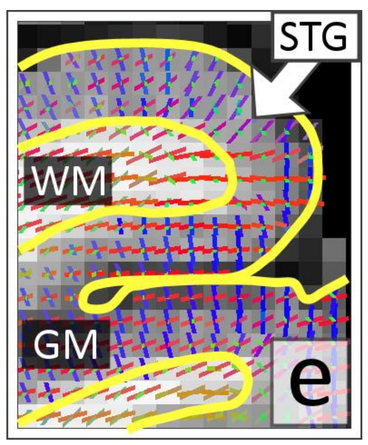
RESULTS





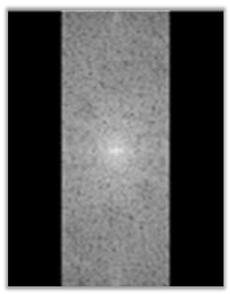






STG: Superior Temporal Gyrus — MTG : Middle Temporal Gyrus — PRG: Precentral Gyrus

DISCUSSION



Super-resolution reconstruction from anisotropic images

- Reduces the scanner burden, achieves higher SNR.
- Reconstruction with an image generative model
- Does sample higher-frequencies in k-space

⇨ In contrast to Tract-Density Imaging, the imaged resolution is increased

Quantitative super-resolution approach

We demonstrate that, in the mature cortex, both radial and tangential diffusion can be observed using a clinical scanner.

Future work: using multi-slice (multi-band) acquisitions : 15min acquisition?
Impact of missing the corners of k-space during the SRR ?