BuckyBall: Reproducible gradient-echo MRI measurements with variable magnetic field directions

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Purpose

- The gradient-echo signal in brain white matter depends on the direction of the external magnetic field, which is typically fixed.
- We have developed an apparatus and methods for analysing the dependence of the MR signal on the magnetic field direction $\hat{B}_0$.

Tensor estimation framework

- R_2^*-relaxivity tensor $\boldsymbol{R}_2^*(t)$ at echo time t recovered from the gradient-echo signal magnitude using weighted least-squares regression

$$S(\hat{B}_0, t) = S_0 \exp(-t\, \hat{B}_0^T \boldsymbol{R}_2^*(t) \hat{B}_0)$$

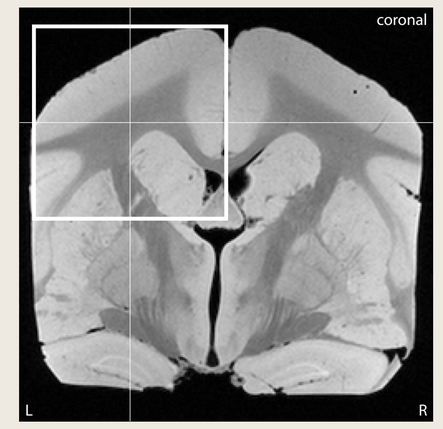
- Frequency shift tensor $\boldsymbol{\Omega}_{\mathrm{TE}_1}(t)$ at echo time t estimated from the frequency difference signal (Schweser *et al.*, 2011; Wharton & Bowtell, 2012)

$$\delta\omega_{\mathrm{TE}_1}(\hat{B}_0, t) = \hat{B}_0^T \boldsymbol{\Omega}_{\mathrm{TE}_1}(t) \hat{B}_0$$

Experiments

Ex-vivo study

- Cubic block of $12 \times 12 \times 12\,\mathrm{mm}^3$ brain tissue from a female adult owl monkey



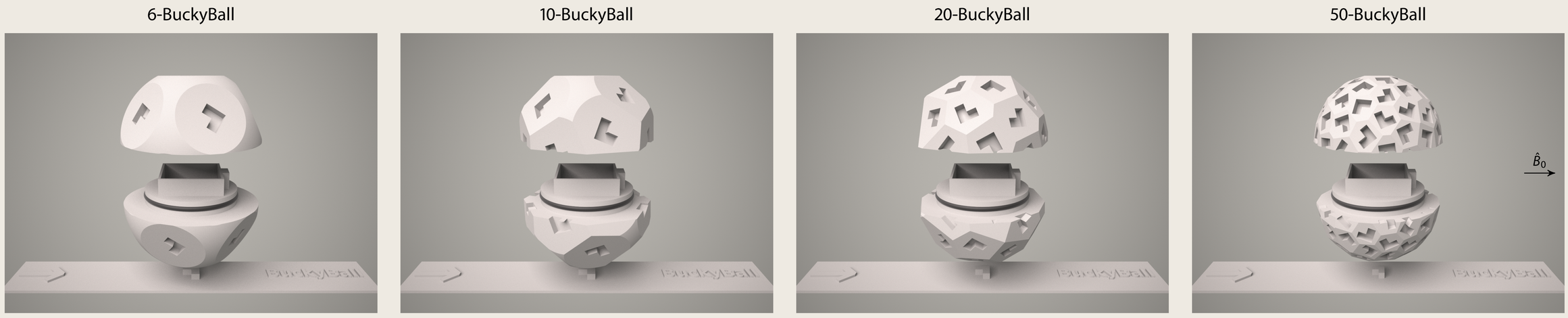
Gradient-echo scan

- 15.2 T BioSpec scanner (Bruker, Billerica, USA) with 35 mm quadrature volume coil
- 3D multi-echo gradient-echo experiment with 45° flip angle, TR = 100 ms, TE_1 = 1.8 ms, ESP = 3 ms and 250 µm isotropic resolution
- 50 evenly distributed magnetic field directions using a bespoke sample holder

Diffusion scan

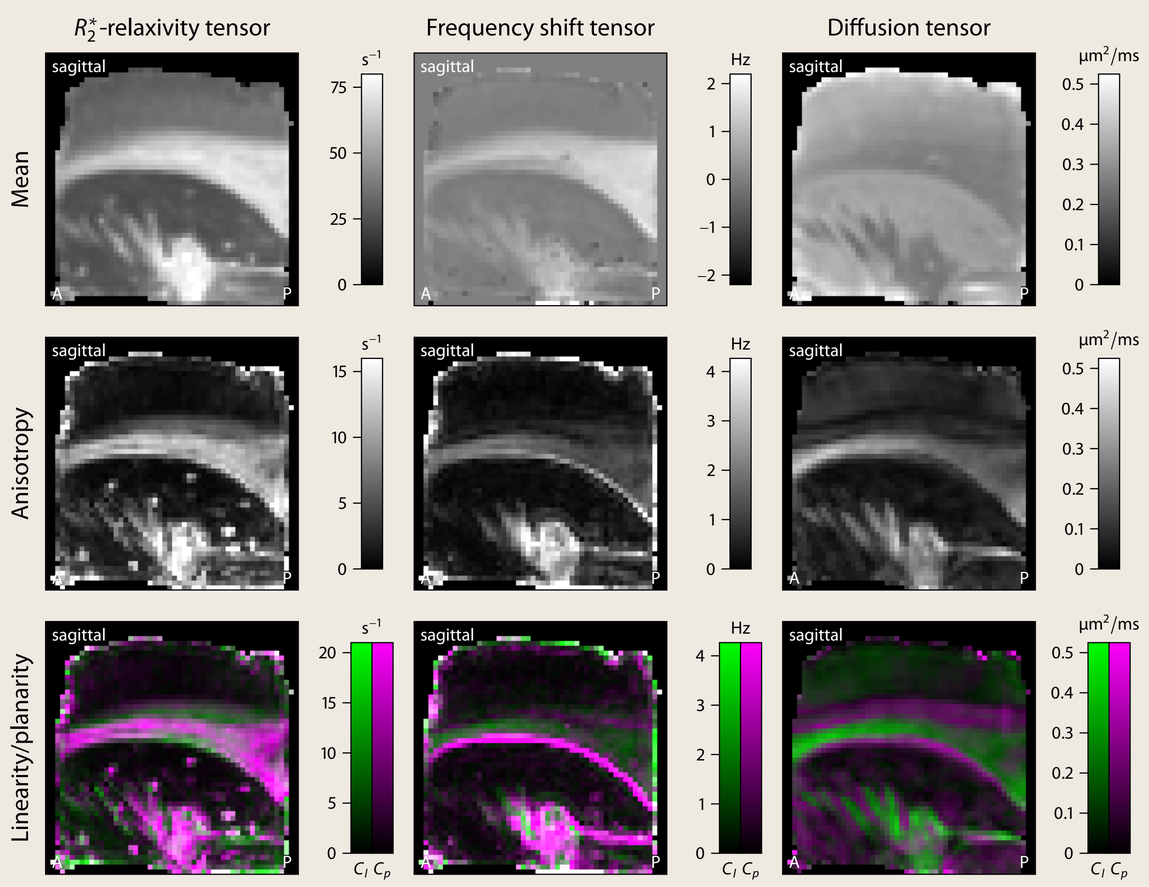
- 3D RARE sequence with TR = 400 ms, TE = 19.3 ms, 60 gradient directions over two b-shells of $\{3000, 6000\}$ s/mm^2 and 250 µm isotropic resolution

BuckyBall



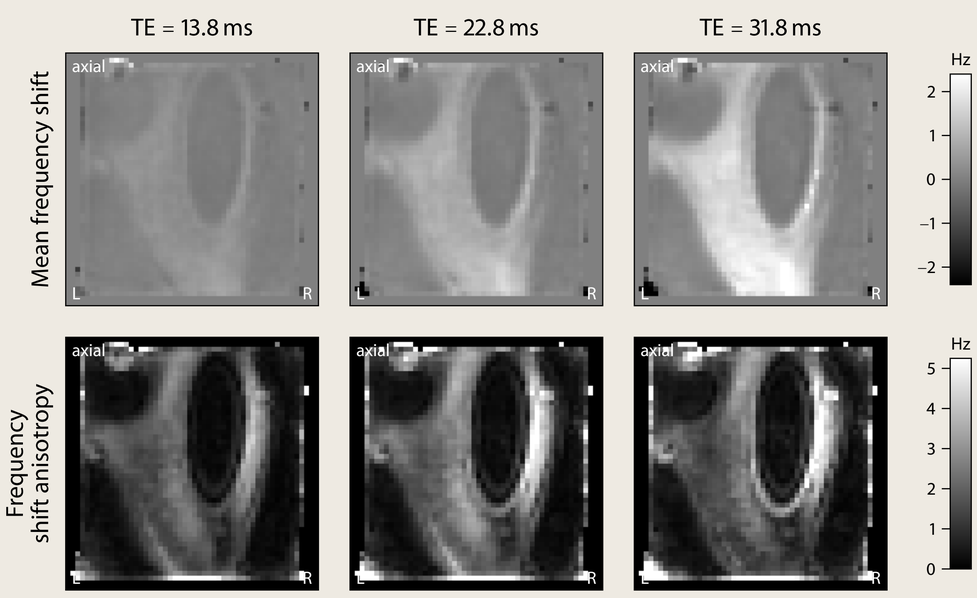
- The custom BuckyBall holder, manufactured using 3D printing (shown with various directional encodings), facilitates the repeatable measurement of a sample at predefined orientations relative to the external magnetic field. The O-ring seals the device and fixes the two halves releasably together.

Relaxivity and frequency shift tensor



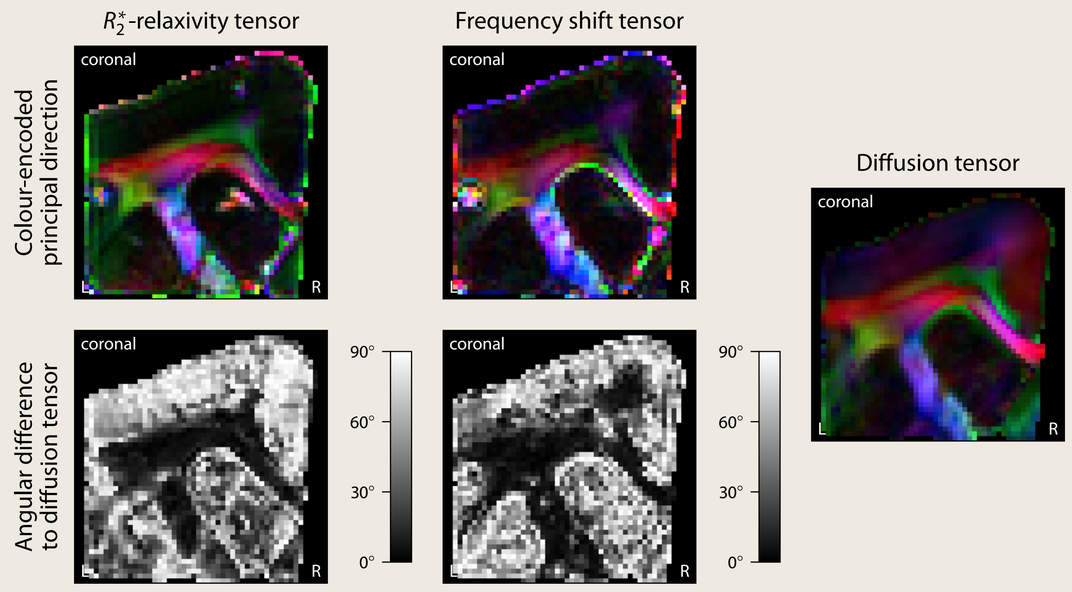
- The anisotropy metric is defined as the absolute difference between the axial and radial tensor eigenvalues.
- The linearity C_l and planarity C_p characterise the shape of the respective tensor (Westin *et al.*, 2002). Black indicates isotropic shape.

Time dependence



- The gradient-echo frequency depends on the echo time in brain tissue.

Directional information



- In brain white matter, the principal tensor directions differ only slightly for gradient-echo and diffusion measurements.

Software

- The software is available online at *https://ekaden.github.io*.

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