Field-Dependence of White Matter T_1 Through Macromolecular Relaxation and Magnetization Transfer

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Declaration of
Financial Interests or Relationships

Speaker Name: Yicun Wang

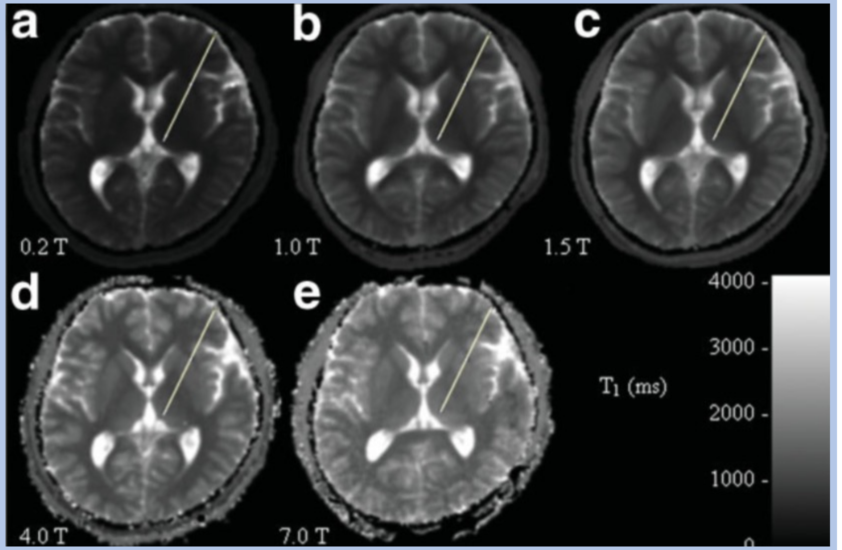
I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Introduction

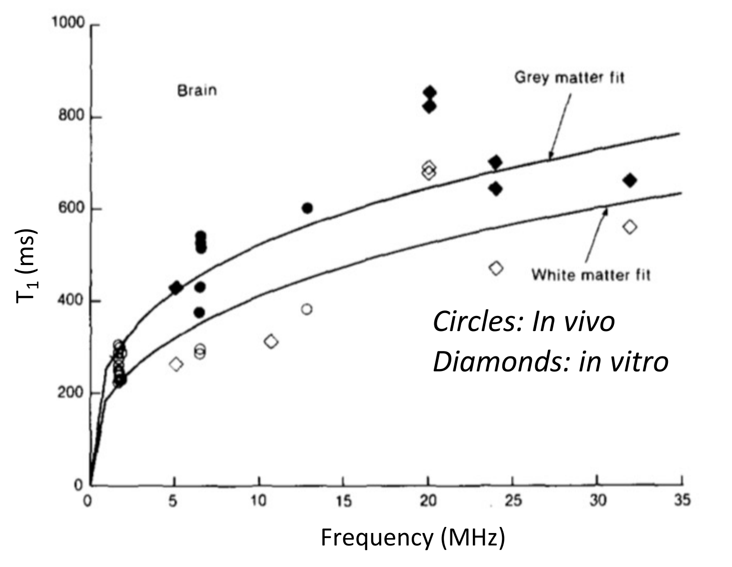
- $^{1}H_2O$ T_1 *in vivo* in the human brain is dependent on
  - Macromolecular proton content (lipids, proteins, etc.)
  - Paramagnetic compounds (dominated by ferritin when contrast agent is absent)
  - Main magnetic field strength B_0
- Models for brain tissue T_1
  - A phenomenological power-law model *(Bottomley et al., 1984)*

    $R_1 = \frac{1}{T_1} = AB_0{}^{-b}$; $b = 0.308$ for gray matter, 0.348 for white matter
  - A multi-regression model *(Rooney et al., 2007)*

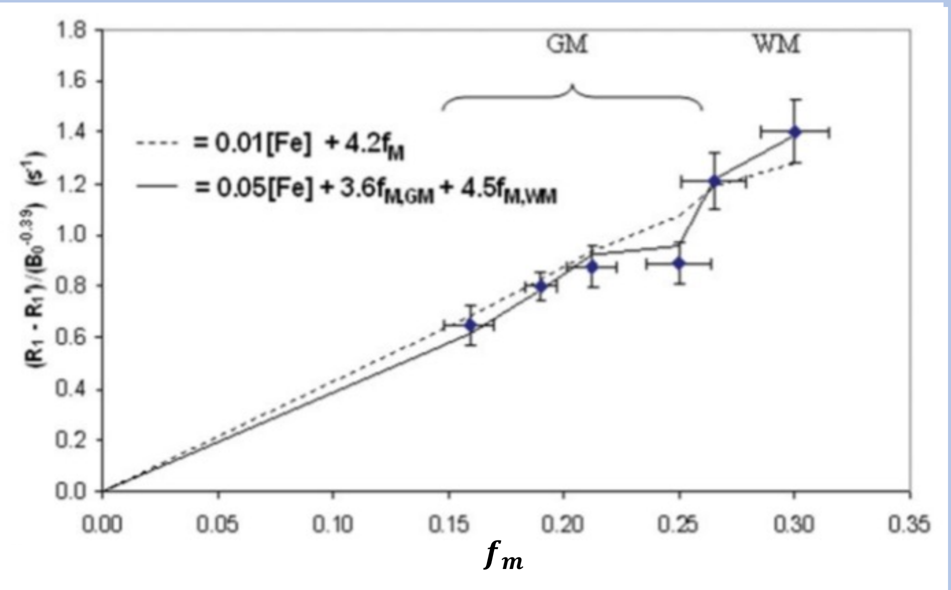
    $R_1 = R_1' + \alpha_{1m} f_m + \alpha_{1Fe}[Fe] + \alpha_{1CR}[CR]$



Rooney et al., MRM 2007



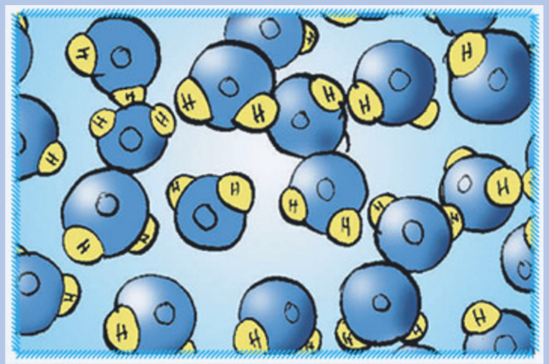
Bottomley et al., Med Phys, 1984



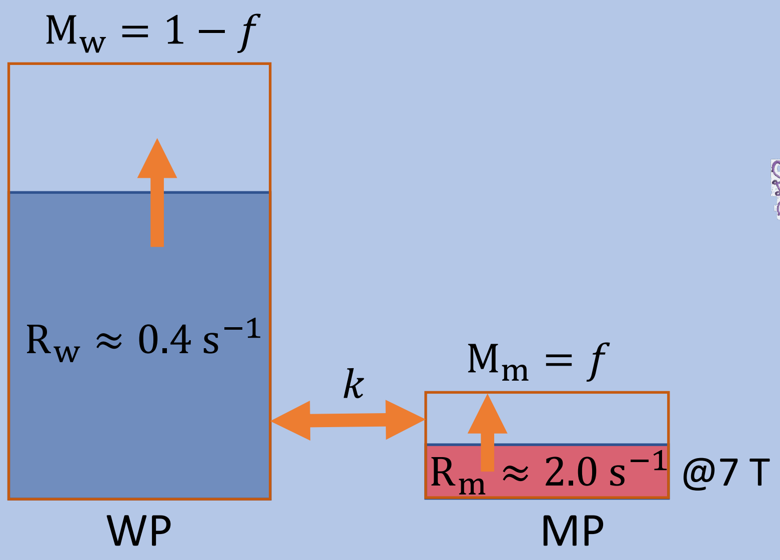
Rooney et al., MRM 2007

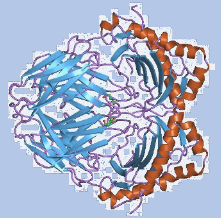
Introduction

- Magnetization transfer between water proton (WP) and macromolecular proton (MP) pools
  (Edzes and Samulski, 1977; Gochberg et al., 1997)
- Analytical solution $\begin{pmatrix} \mathrm{S_m} \\ \mathrm{S_w} \end{pmatrix} = a_\mathrm{s} \begin{pmatrix} p_\mathrm{s} \\ 1 \end{pmatrix} e^{-\lambda_\mathrm{s} t} + a_\mathrm{f} \begin{pmatrix} p_\mathrm{f} \\ 1 \end{pmatrix} e^{-\lambda_\mathrm{f} t}$
- The two-pool exchange model may be used to understand $\mathrm{B_0}$ dependence of brain T_1
  - MP relaxation rate $\mathrm{R_m} = a\mathrm{B_0}^{-b}$ for chain molecules such as proteins and lipids *(Korb and Bryant, MRM 2002)*
  - WP relaxation rate $\mathrm{R_w}$ expected to be weakly $\mathrm{B_0}$ dependent *(Gossuin et al., MRM 2000)*
  - MP fraction f tissue intrinsic property
  - Exchange rate k consists of chemical exchange and dipole-dipole magnetic effects

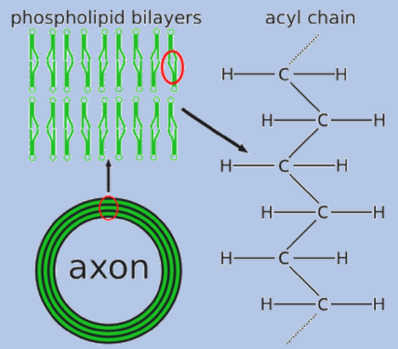


Free water





Protein



Lipid

Study Goals

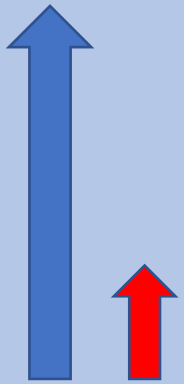
- To examine the field dependence of $\mathrm{T_1}$ in white matter (high macromolecular content, i.e. high f) driven by $\mathrm{R_m}$ through magnetization transfer
- To validate and determine the model parameters in $\mathrm{R_m} = a\mathrm{B_0}^{-b}$ *in vivo* in human brain within clinically relevant $\mathrm{B_0}$ range

General Approach

- Acquisition of Inversion Recovery (IR) and Saturation Transfer (ST) data at 4 fields from 0.55-7 T in the same group of healthy subjects
- Joint analysis of IR & ST data based on the two-pool exchange model to retrieve $\mathrm{R_m}$

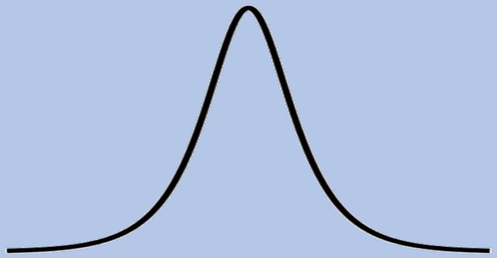
Methods

t=0

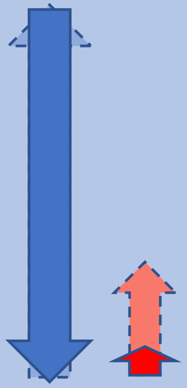


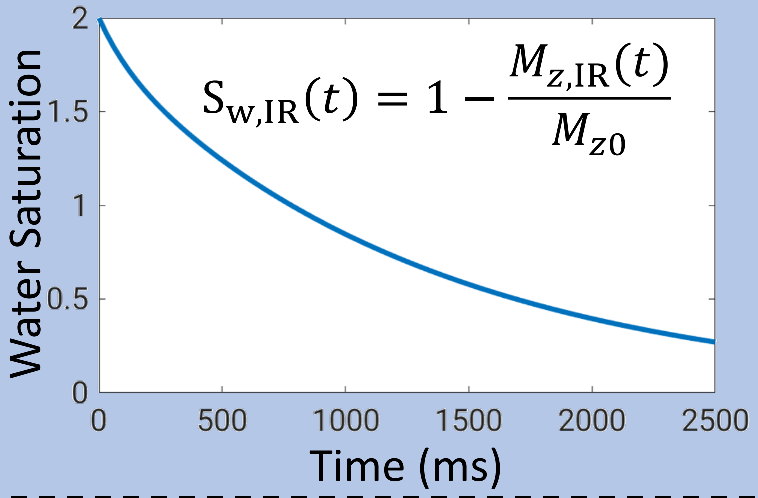
$M_{z,WP}$ $M_{z,MP}$

Inversion Recovery

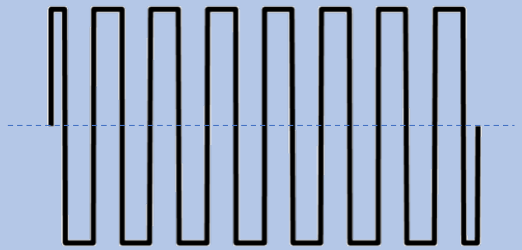


Inversion RF pulse
Hyperbolic Secant shape
Duration 7 ms; β 1026 s^{-1};
Peak B_1 833 Hz (19.6 uT)

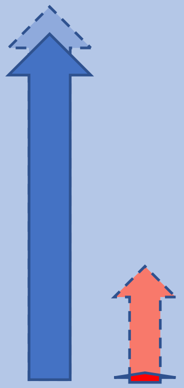


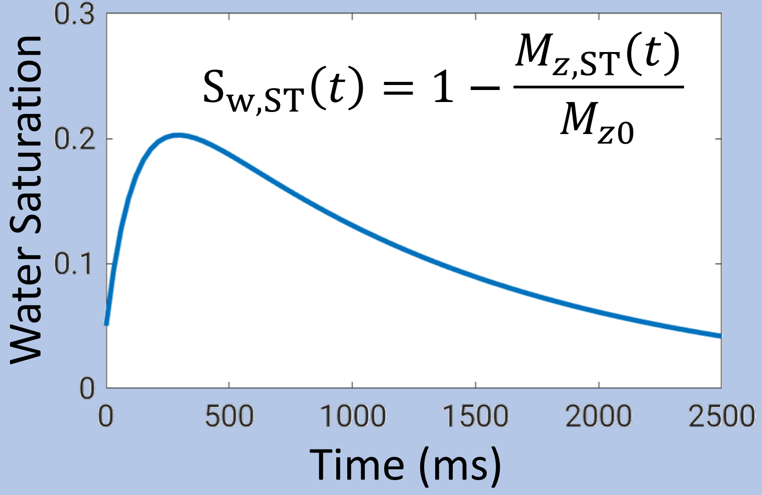


Saturation Transfer

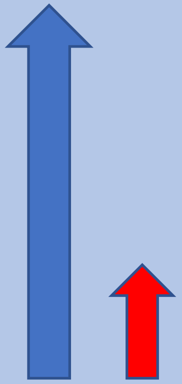


Saturation RF pulse
16 hard pulse train
Duration 6 ms;
Peak B_1 833 Hz (19.6 uT)





t=TR

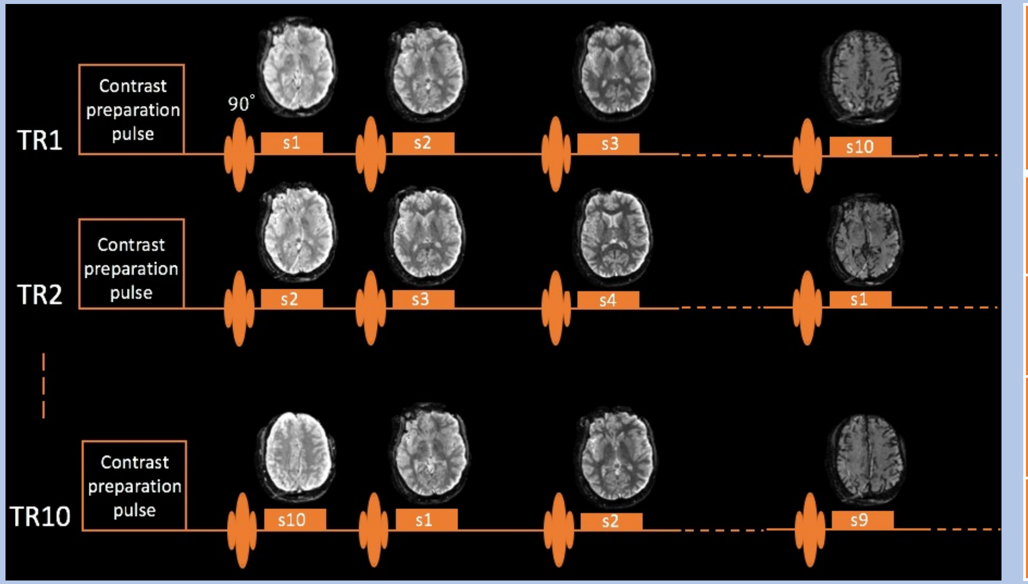


van Gelderen et al., Neuroimage 2016

Methods

- 8 healthy volunteers (age 21-32 years, mean 24.9; 3 females)
- Four B_0 fields
  - 0.55 T (Prototype scanner, ramped down from 1.5 T Aera), 16-ch receive array
  - 1.5 T Aera, 20-ch receive array
  - 3 T Prisma, 32-ch receive array
  - 7 T Magnetom, Nova transmit and 32-ch receive
- Single-shot EPI readout, slice-cycled over 10 TR numbers at 10 inversion/delay times
- IR: 12 repetitions (2 references w/o inversion pulse);
- ST: 16 repetitions (4 references w/o saturation pulse);

Acquisition schematic of 1 repetition (10 TRs)



Sequence parameters at 4 fields

B_0	Reso. (mm^3)	SENSE	IR			ST			TE (ms)
			TR (s)	TI (ms)	Time (min)	TR (s)	TD (ms)	Time (min)	
0.55 T	3.3x3.3x3.0	1	4	10~1200	8.0	3	8~900	8.0	29
1.5 T	1.7x1.7x2.0	2	5	10~1400	10.2	4	9~900	10.8	40
3 T	1.7x1.7x2.0	2	6	9~1600	12.2	4	9~900	10.8	30
7 T	1.7x1.7x2.0	2	6	8~2000	12.2	4	7~900	10.8	24

Methods

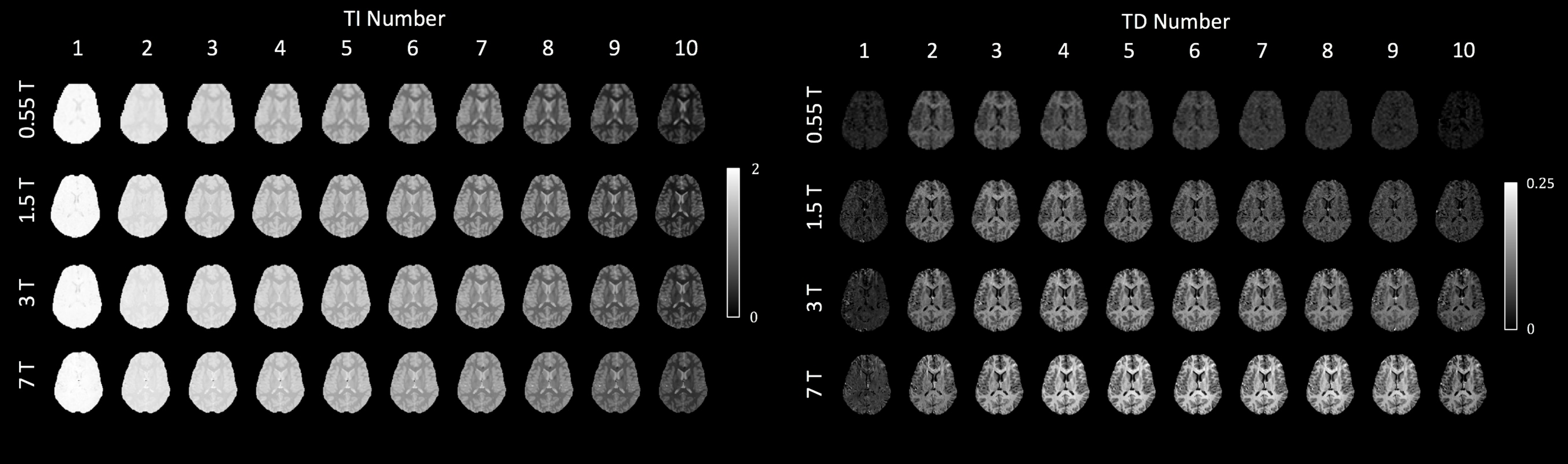
- Data analysis
  - ➢ Voxel-wise analysis for 3 and 7 T data
  - ➢ In a homogeneous white matter structure Splenium of Corpus Callosum (SCC) at all 4 fields
  - ➢ Curve fitting $\begin{cases} S_{w,IR}(t) = a_{s,IR}e^{-\lambda_s t} + a_{f,IR}e^{-\lambda_f t} \\ S_{w,ST}(t) = a_{s,ST}e^{-\lambda_s t} + a_{f,ST}e^{-\lambda_f t} \end{cases}$

    For 0.55 and 1.5 T, $a_{f,IR}$ was assumed to be 0
  - ➢ Independently at 3 and 7 T, calculate two-pool model parameters f, k and R_m assuming $S_{m,ST}(t = 0) = 0.93$ and $R_w = 0.4\ s^{-1}$ *(van Gelderen et al., Neuroimage 2016)*
  - ➢ At 0.55 and 1.5 T, calculate R_m using averaged f and k from 7 T
  - ➢ Fit $R_m = aB_0{}^{-b}$ ($B_0 = 0.55, 1.50, 2.89, 6.98$ T)

Results

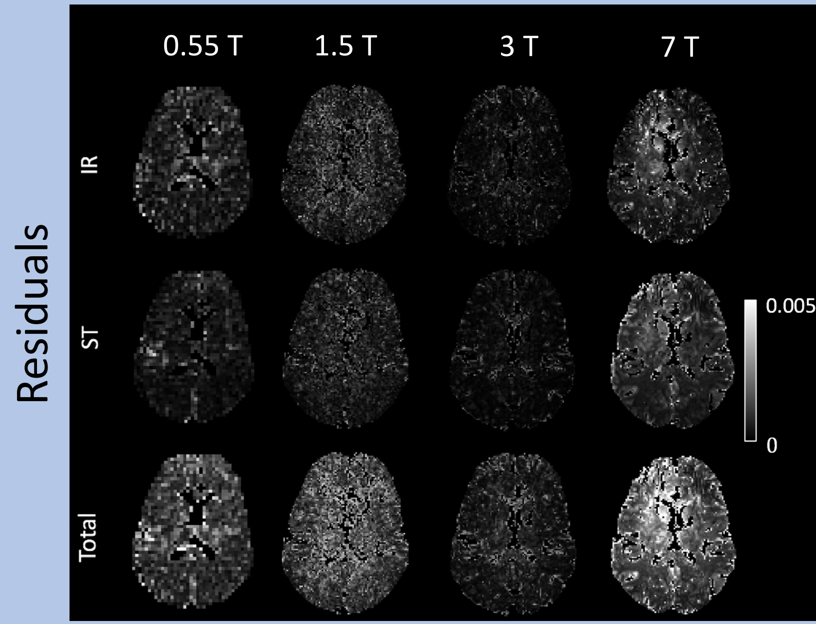
- Saturation images at 10 TI (inversion times) and 10 TD (delay times)

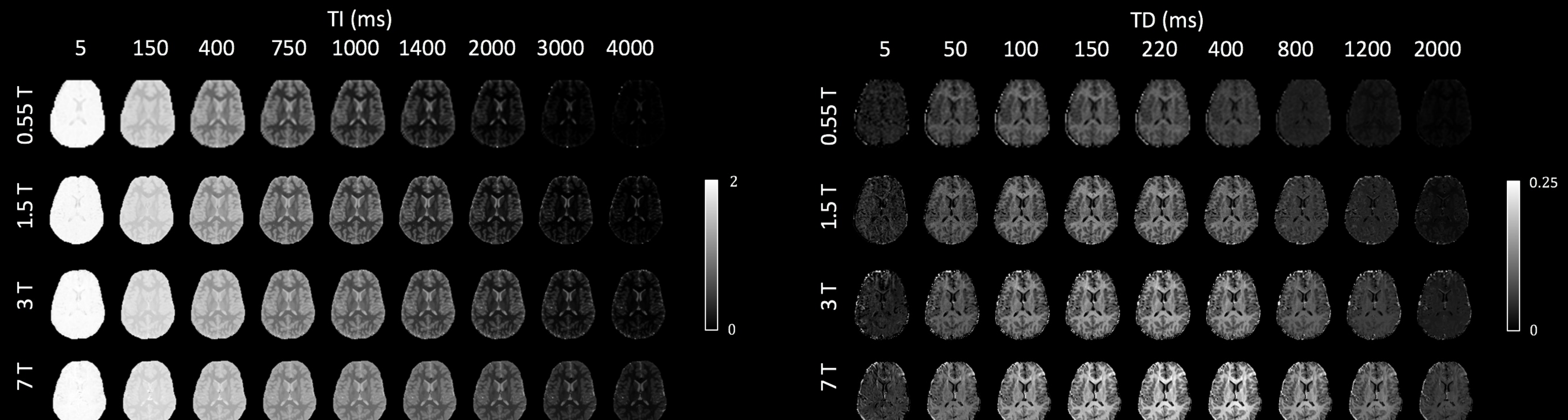
$$S_w(t) = 1 - \frac{M_z(t)}{M_{z0}}$$



Results

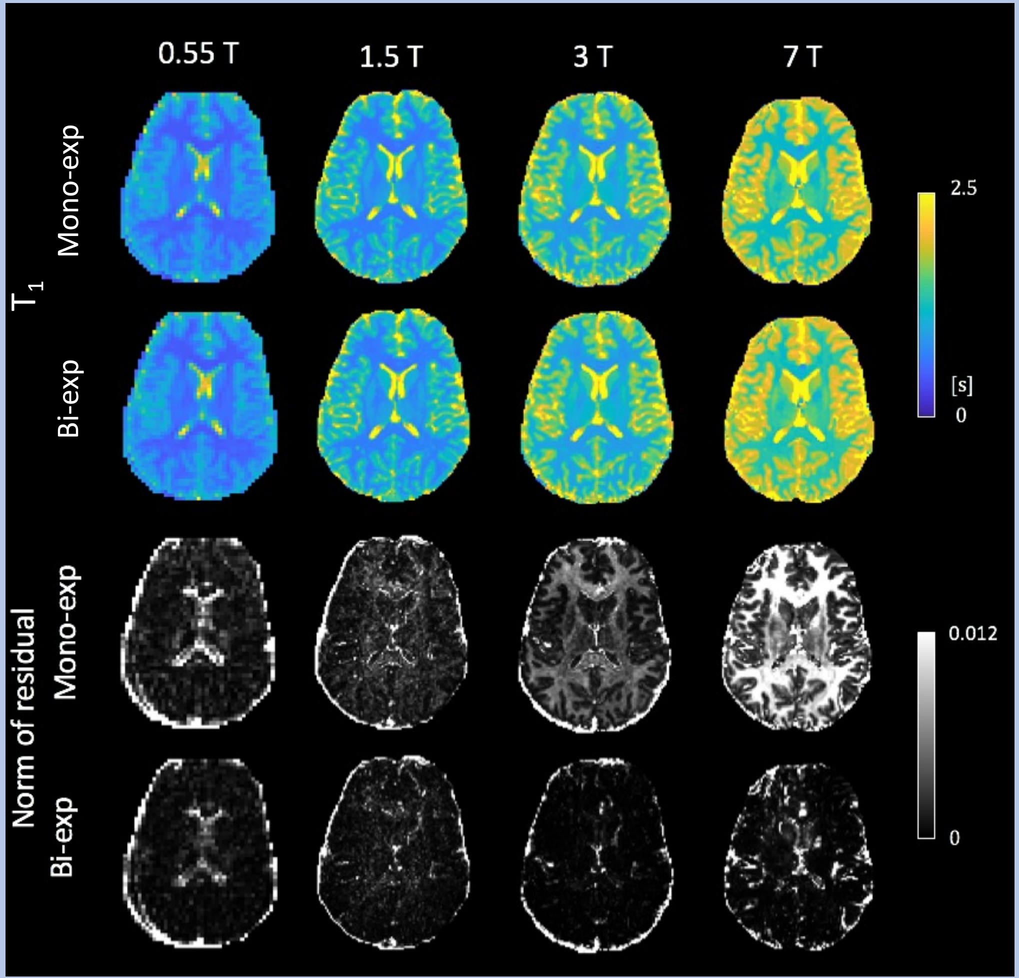
- Saturation images at a fixed set of TI (TD)
  - By voxel-wise temporal interpolation (bi-exponential model)
- T_1 increases with B_0
- Saturation transfer effect increases in magnitude and duration with B_0

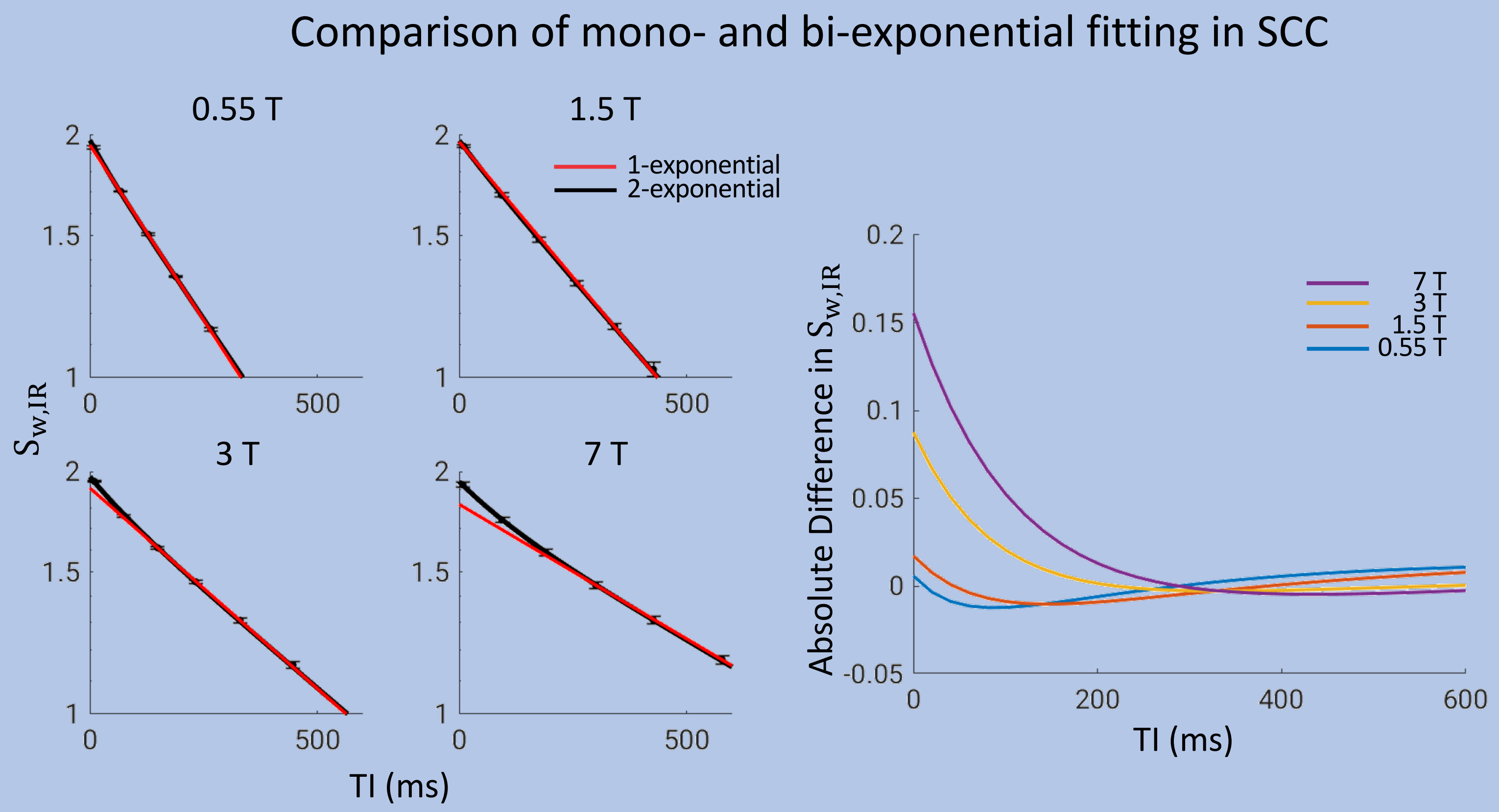




Results

- Looking at IR data alone
- Strong increase of fast component in the white matter with B_0

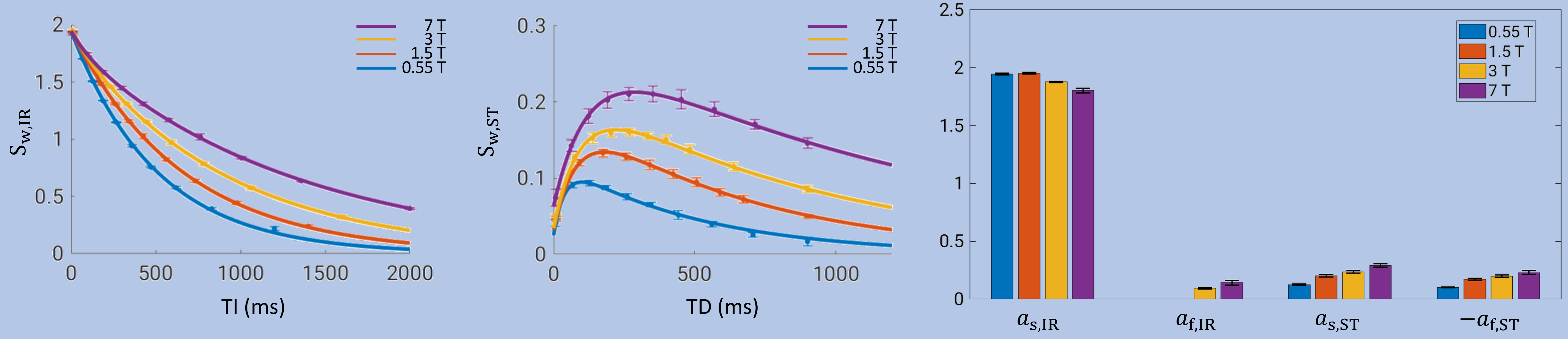




Results

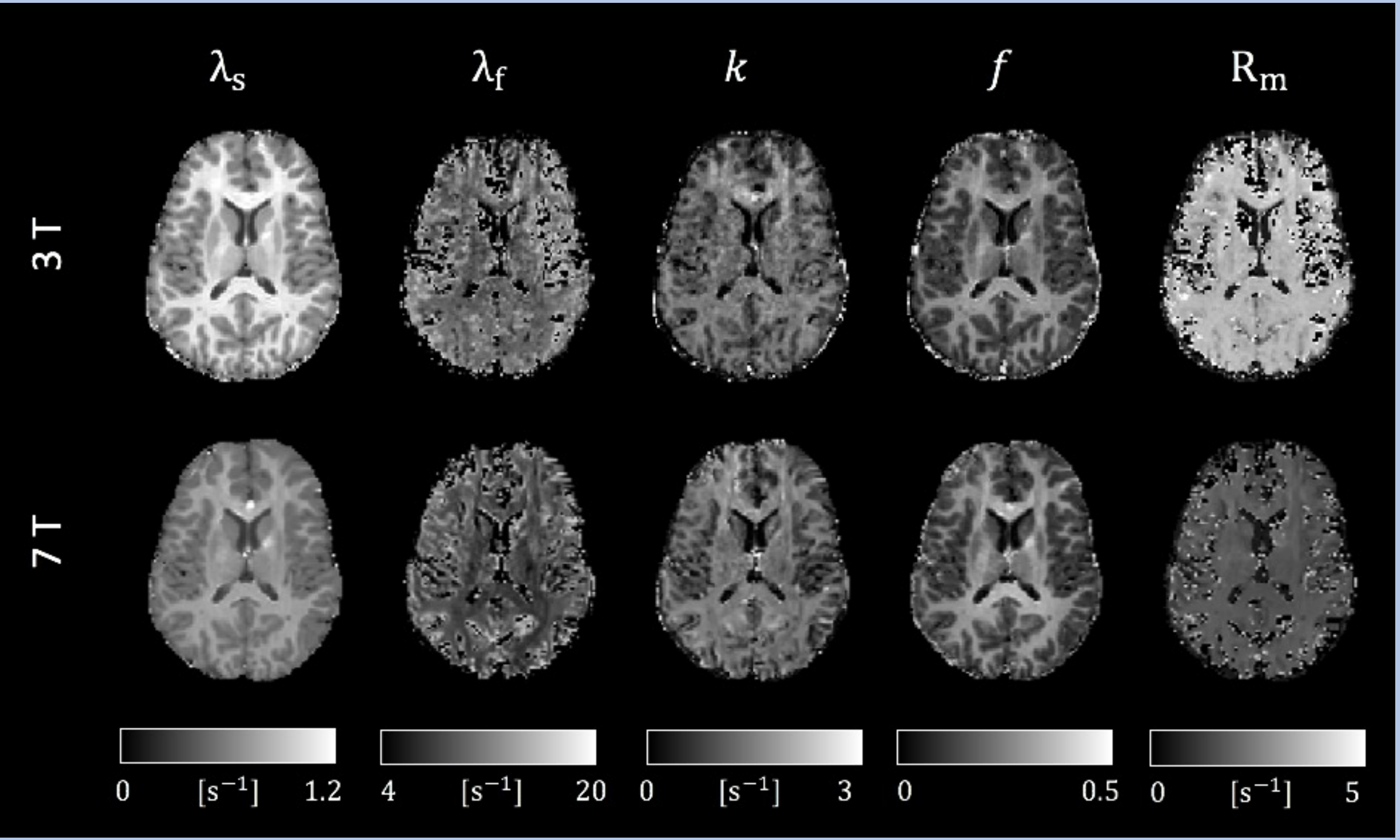
- The bi-exponential model well explained the IR&ST data at 4 fields (R^2>0.999 for all curves)
- Saturation transfer effect reached 20% at 7 T
- Increasing fast component in the white matter with B_0

Fitting results of SCC data over subjects



Results

- Similar 3 and 7 T results for f and k
- Substantial difference (52.4%) in R_m between 3 and 7 T

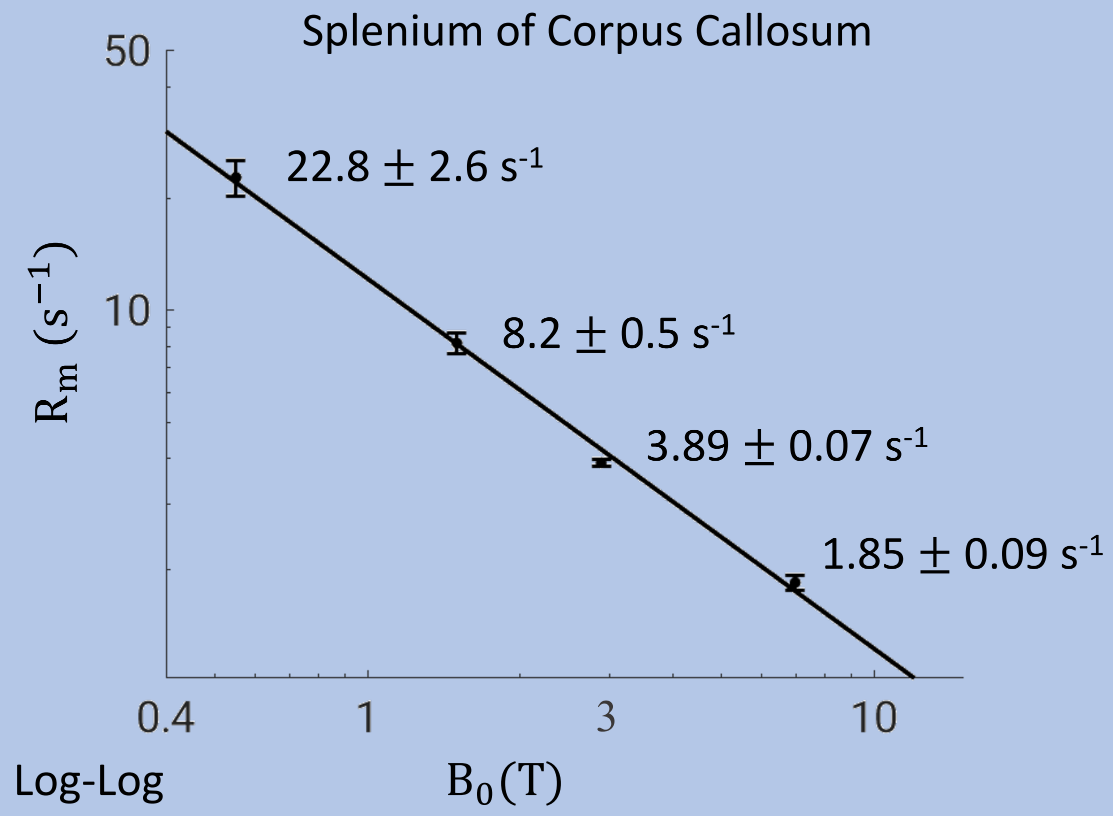


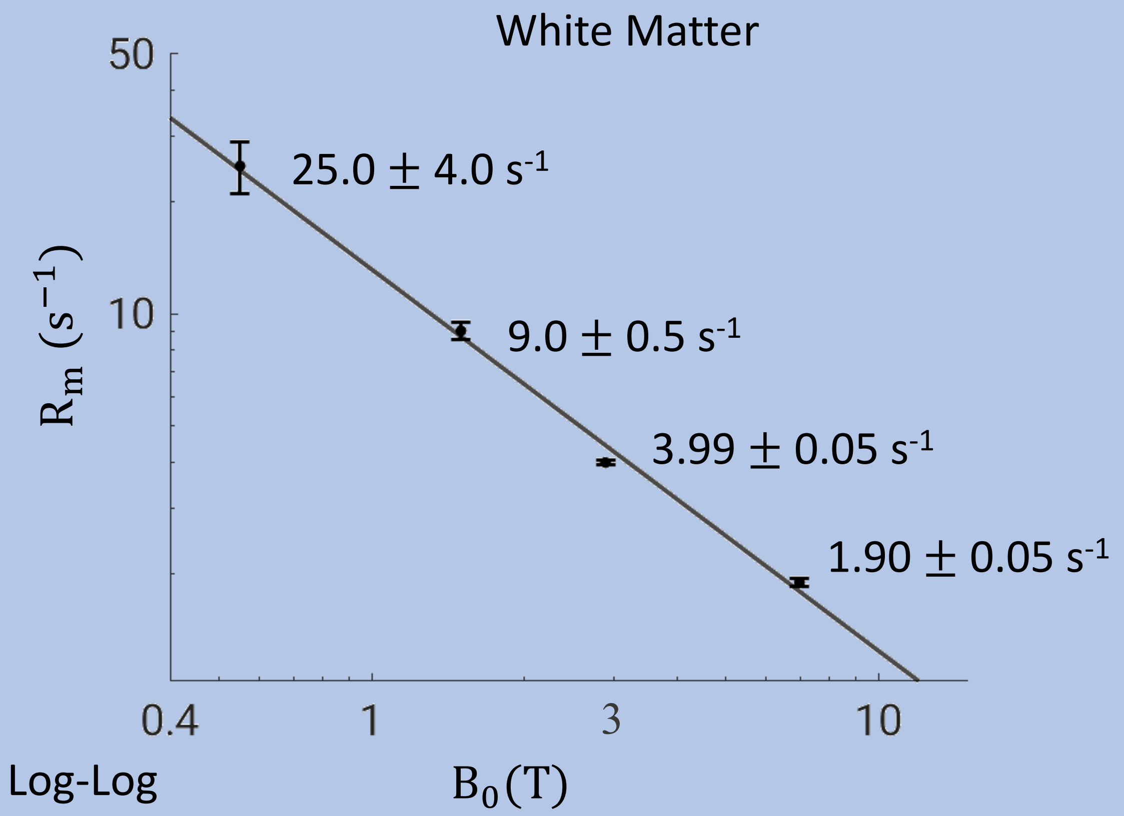
Two-pool results in the SCC over 8 subjects

B_0	λ_s (s^{-1})	λ_f(s^{-1})	k(s^{-1})	f	R_m(s^{-1})
3 T	1.112 ± 0.025	10.60 ± 0.40	1.50 ± 0.05	0.281 ± 0.014	3.89 ± 0.07
7 T	0.760 ± 0.008	8.19 ± 0.37	1.38 ± 0.09	0.289 ± 0.017	1.85 ± 0.09

Results

- R_m fitting result in SCC: $R_m = 12.2{B_0}^{-1.00}$ (R^2=0.997)
- In the entire white matter: $R_m = 13.2{B_0}^{-1.03}$ (R^2=0.996)





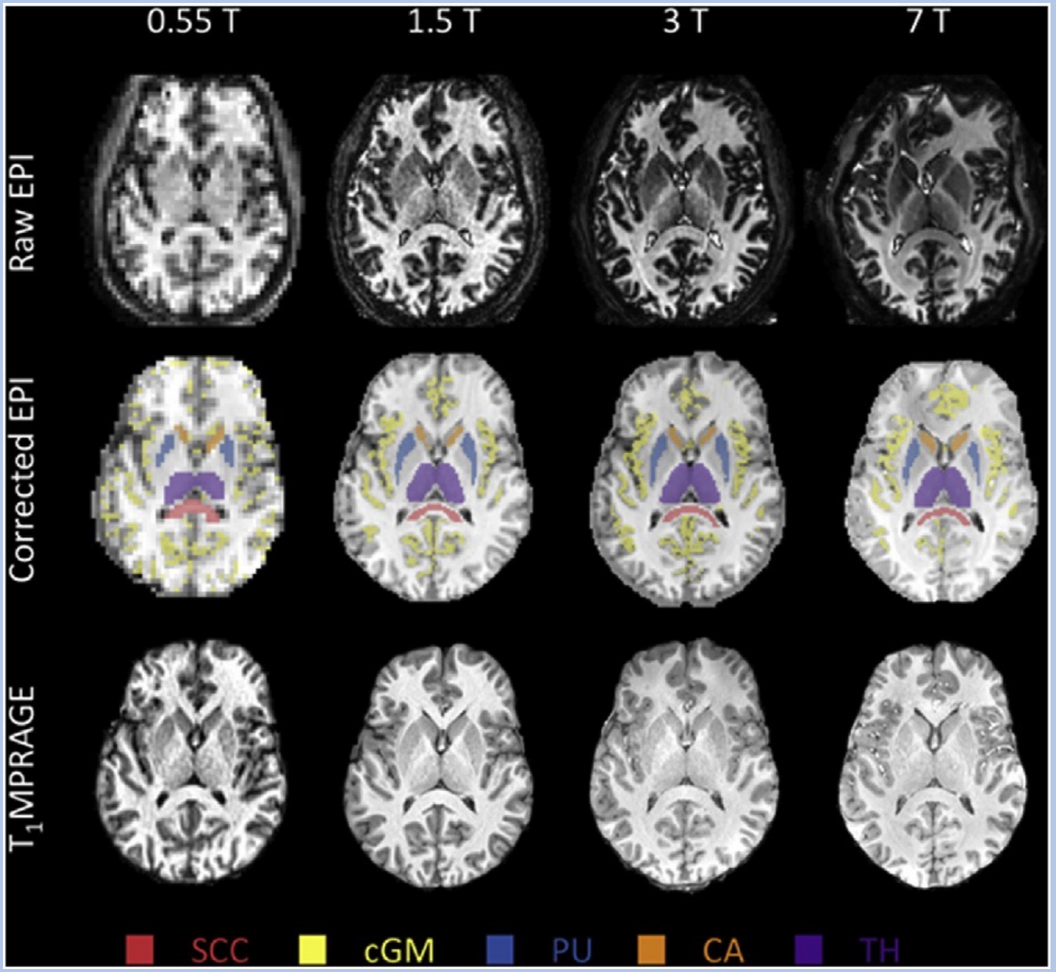
Conclusions and Discussions

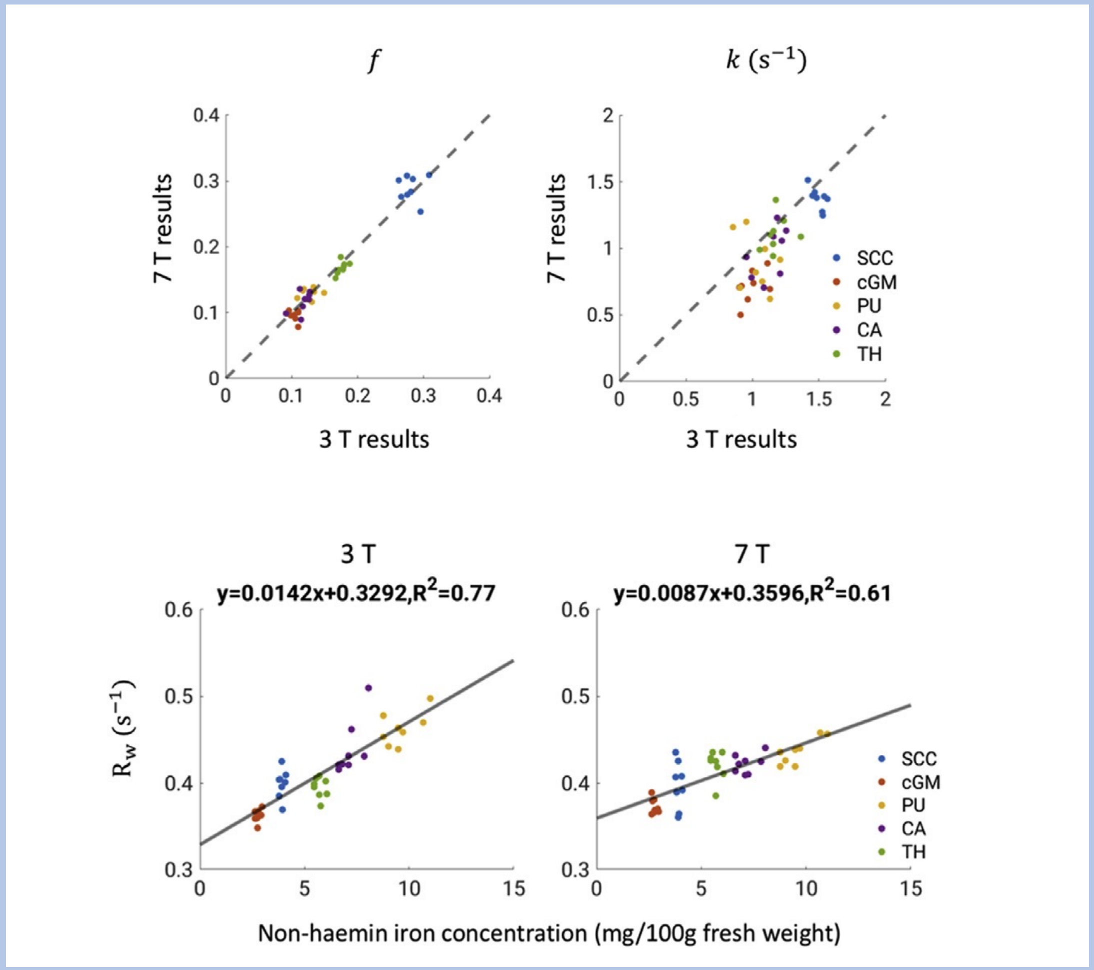
- Joint analysis of IR and ST data in white matter suggests dependence of T_1 on B_0 through macromolecule proton relaxation rate $\mathrm{R_m}$ and magnetization transfer effect
- $\mathrm{R_m}$ was measured to be 2-20 s^{-1} in the B_0 range of 0.55-7 T, in agreement with early NMR studies on lipids *(Lee et al., 1972; McLaughlin et al., 1973; Ellena et al., 1985)*
- $\mathrm{R_m}$ follows a simple inverse linear dependence on $\mathrm{B_0}$ as $\mathrm{R_m} = 12.2/\mathrm{B_0}$, a special case of the generally applied power-law dependence

- Despite its capability to explain the IR-ST data in a wide range of $\mathrm{B_0}$, two-pool model is over-simplistic for the chemically and structurally complex white matter
- The two-pool parameter assumptions and the inverse linear dependence may not hold below 0.55 T and/or beyond 7 T
- Nevertheless, the study furthers understanding of B_0 dependence of T_1 and demonstrates the close relation between T_1 and MT

Please also check out our recent publication for analysis in gray matter structures:

Wang Y, van Gelderen P, de Zwart JA, Duyn JH. B0-field dependence of MRI T1 relaxation in human brain. NeuroImage 2020;213:116700





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- Anonymous reviewers for Wang et al., NeuroImage 2020;213:116700

Thank you for your attention!

Please direct comments to
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