Dependence of the apparent T_1 on Magnetization Transfer

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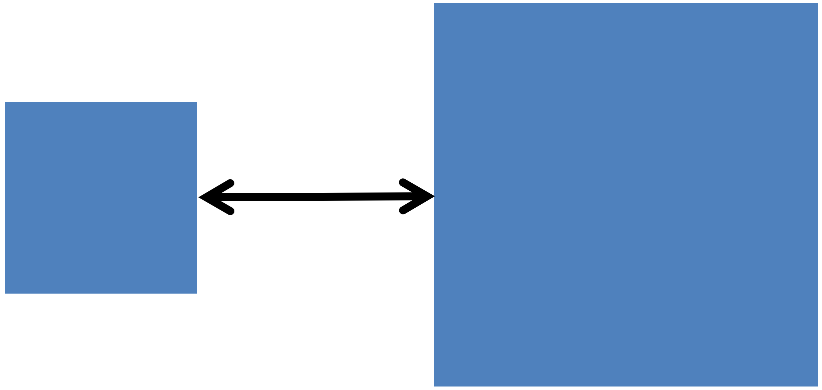
Two-Pool Model

Tissue has two pools of ^{1}H:

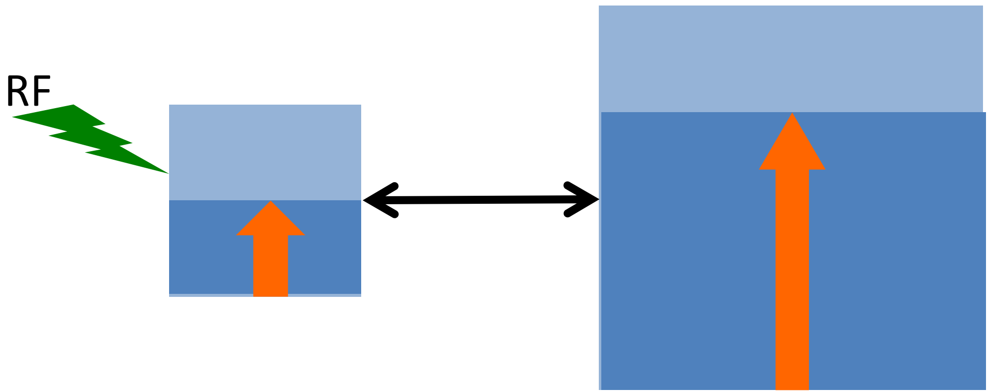
- free ^{1}H in water (visible)

- bound ^{1}H in macro-molecules (not visible)



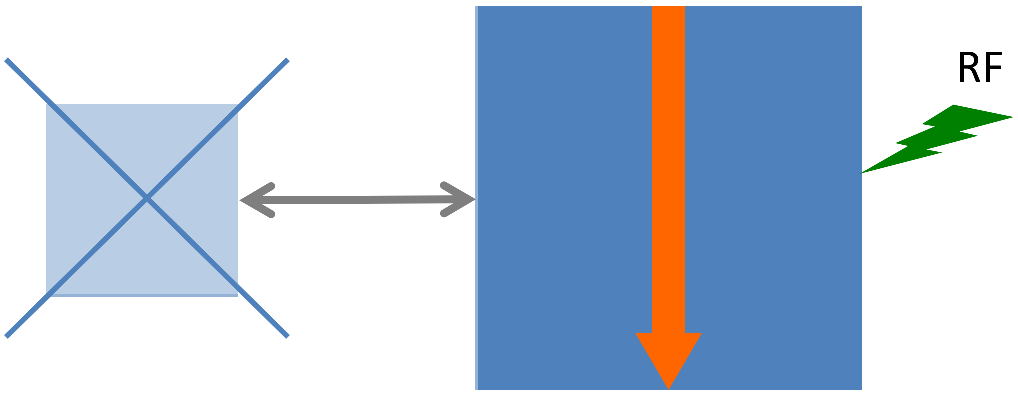
MT

Classic MT experiment: steady state saturation of bound pool, measure level of M_z in free pool



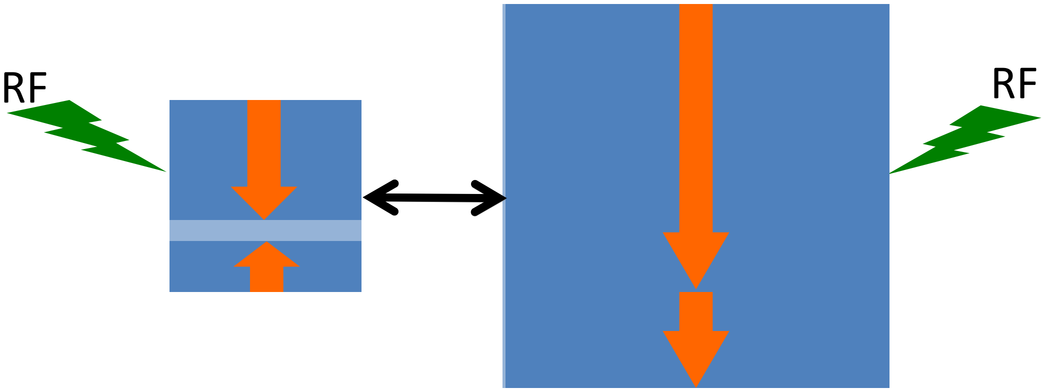
Inversion

Classic T_1 experiments ignore bound pool



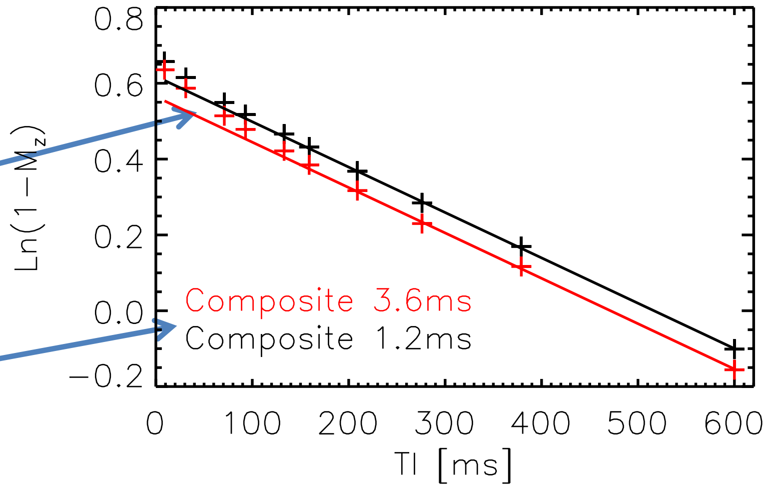
Inversion: 2-pool model

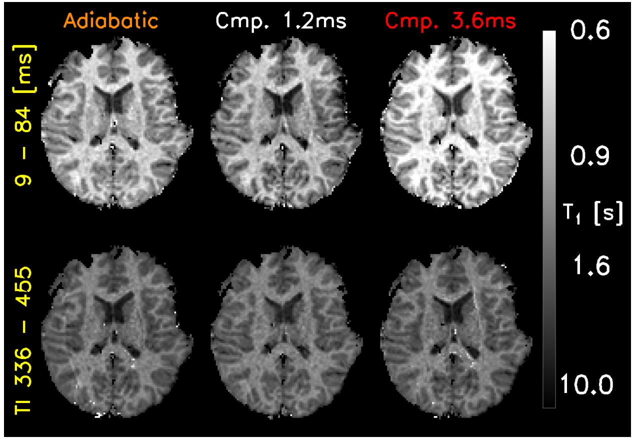
Non-inverted bound pool changes IR-recovery



2-Pool Effects

- Inversion recovery is double exponential
- Shape of IR depends on RF level saturating the bound pool
- Apparent T_1 depends on TI
- Apparent T_1 depends on bound pool size





Poster #0015:

- Dependence of apparent T_1 on TI
- IR data on 11 more subjects
- Comparison 3T and 7T
- Results of two pool analysis
- Relation between T_1 and bound pool size

Poster 0015

Dependence of the apparent T_1 on Magnetization Transfer

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Introduction

In this presentation, we discuss how the less mobile ^1H nuclei in larger molecules influence both the longitudinal relaxation (T_1) properties of water and their measurement. It is shown the inversion recovery signal is bi-exponential, and that the amplitude of the second exponent depends on the parameters of the applied inversion pulses. It is also shown the macro-molecular content may explain most of observable T_1-contrast in the brain.

Background

- Most tissues, in particular brain tissues, have 2 distinct classes of ^1H nuclei: mobile ^1H in water, and less-mobile ^1H in larger molecules (lipids, proteins etc.).
- The mobile atoms, forming the free pool, contribute to the MRI signal; the less mobile ones, making up the bound pool, have a 10-100μs T_2 and so are not directly MRI-visible in most experiments.
- The two pools are coupled by chemical and magnetic exchange processes, the bound pool can therefore still influence the MRI signal generated by the free pool.

Background

- MT (magnetization transfer) experiments aim to saturate the bound pool and characterize this pool by explicit modeling of the exchange with the free pool.

- Most T_1 measurements, based on either Inversion Recovery (IR) or saturation experiments, implicitly assume a single pool model, ignoring effects of the bound pool.

- Because of their short T_2, the bound pool ^{1}H are not inverted, but only (party) saturated. This difference in M_z state between the two pools becomes MRI visible through exchange between the pools, creating a MT effect in IR measurements.

Theory

Equation for M_z in two pools with exchange and T_1 relaxation [1,2]:

$$\frac{d}{dt}\begin{pmatrix} S_f \\ S_b \end{pmatrix} = \begin{pmatrix} -R_{1f} - k & k \\ k/v & -R_{1b} - k/v \end{pmatrix}\begin{pmatrix} S_f \\ S_b \end{pmatrix}$$

where S_f and S_b are the saturation levels in the two pools ($1\text{-}M_z$), the R_{1f} and R_{1b} their relaxation rates ($1/T_1$), k the exchange rate from free to bound pool, and v the bound pool volume relative to the free pool. The solution for the free pool state is:

$$S_f(t) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$$

ie. the inversion recovery is bi-exponential due to the exchange with the bound pool.

1. Henkelman et.al., MRM **29**:759 (1993). 2 Gochberg, Kennan & Gore, MRM **38**:224 (1997).

Theory

The exponents in the solution are approximately equal to:

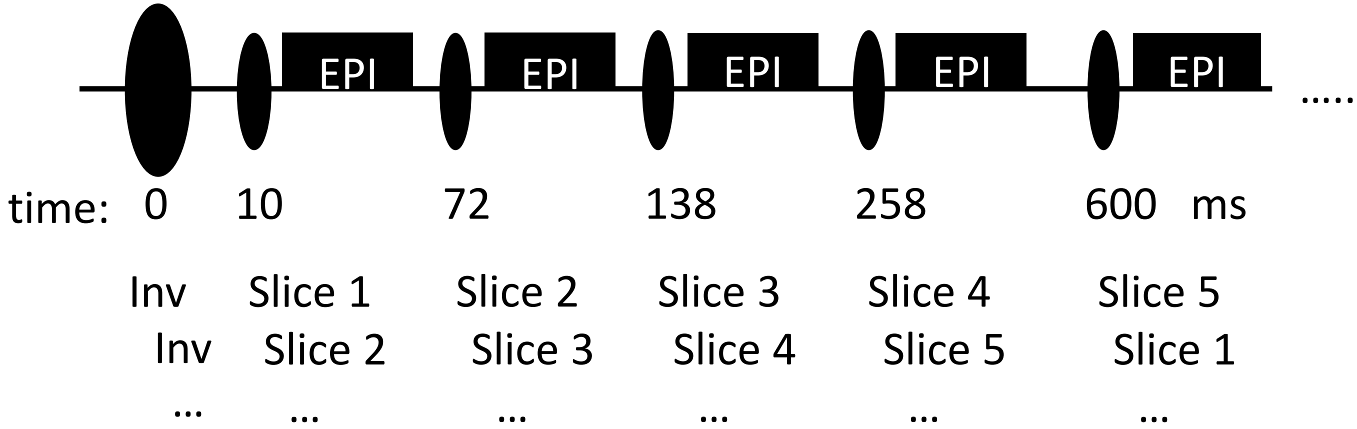
$$\lambda_1 \approx \frac{R_{1f} + vR_{1b}}{1+v}, \lambda_2 \approx \frac{R_{1b} + vR_{1f}}{1+v} + k + \frac{k}{v}$$

This approximation holds if the exchange is fast compared to the difference in relaxation rates between the pool.

The first exponent decays with volume averaged relaxation rates (R_1) of the two pools, the second one is dominated by the sum of the forward (k) and reverse (k/v) exchange rates.

Experiments

All experiments used EPI, with one inversion pulse for 5 slices at 5 different TI times, and shuffling the slice order to acquire all TI's for every slice [1]. Other relevant parameters: TR 4s, TE 30ms, resolution 1.7x1.7x2mm, sense rate 2, 14 averages with inversion, 4 without to serve as reference.



1. Clare & Jezzard, MRM **45**:630 (2001)

Experiments

Four inversion pulses were compared:

1) Hyperbolic secant adiabatic pulse, 830Hz max B_1, 5ms long at 3T, 7ms at 7T.

2-4) A 90_x-180_y-90_x composite hard pulse train, at B_1 levels of
2) 830Hz, 3) 278Hz and 4) 145Hz (total length: 1.2ms, 3.6ms and 6.9ms).

Three sets of experiments were executed:

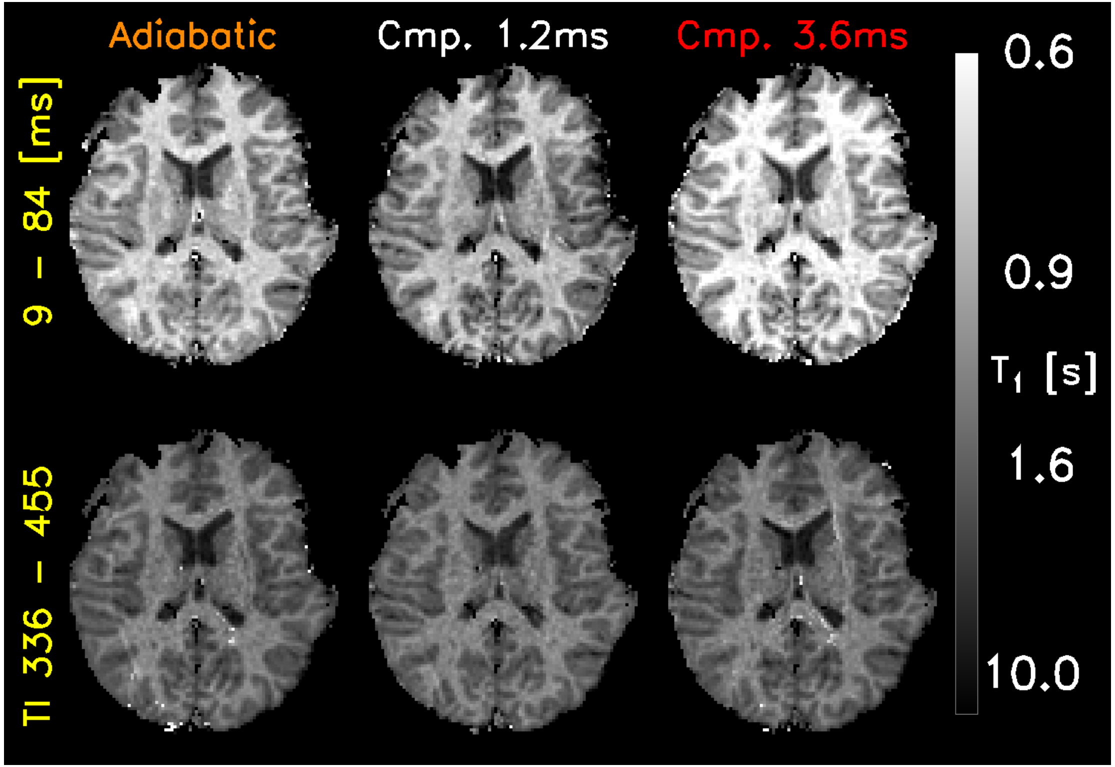
1) 5 subjects at 3T (Siemens Skyra), 10 TI's from 8-600ms (2 sets of 5 acquired in interleaved fashion), with inversion pulses 1-3

2) 11 subjects at 3T (Siemens Skyra), 5 TI's from 8-1200ms, with pulses 1-4

3) the same 11 subjects at 7T (Siemens Magnetom), 5 TI's 8-1200ms, pulses 1-4

Results

The effective T_1, as calculated from the difference between images at two TI's (3T, Exp. 1), showing that the initial part of the IR (top row) is faster than the later times (bottom row). The effect is more pronounced for the lower B_1 inversion pulse (right column), as that pulse results in less bound pool saturation and a therefore a bigger difference between bound and free pool states.



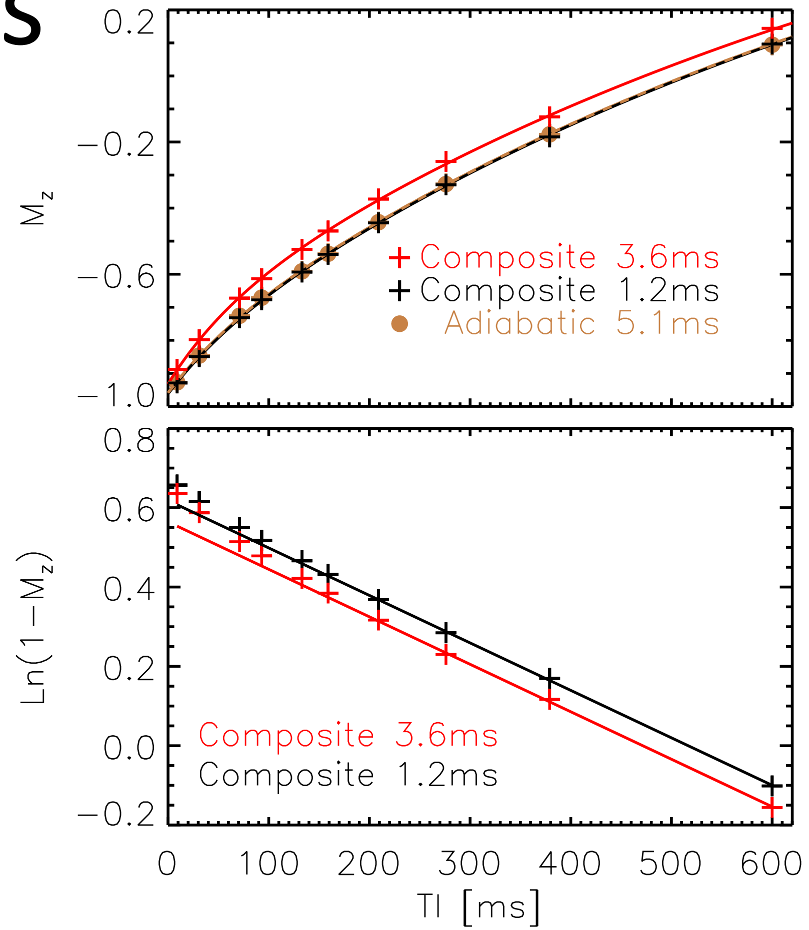
MT dependent T_1

Poster 0015

Results

The IR-curves in an ROI in the splenium of the corpus callosum (SCC), averaged over 5 subjects (3T, Exp. 1). The top graph shows the M_z for the 3 inversion pulses used, with the double exponential fits plotted on top. The short composite pulse and the adiabatic pulse produce nearly identical data.

The bottom graph shows the same data plotted as a log of the saturation, with straight lines fitted to the last three points. This shows a single exponential function is insufficient to fit this data, while the double-exponential fit is nearly perfect (top graph).

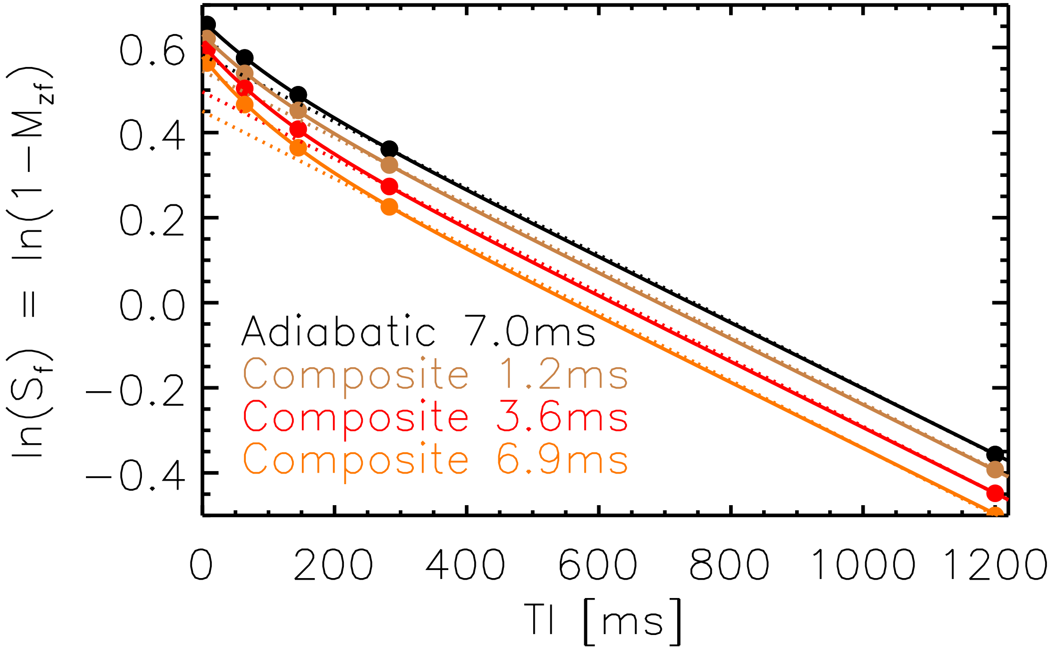


MT dependent T_1

Poster 0015

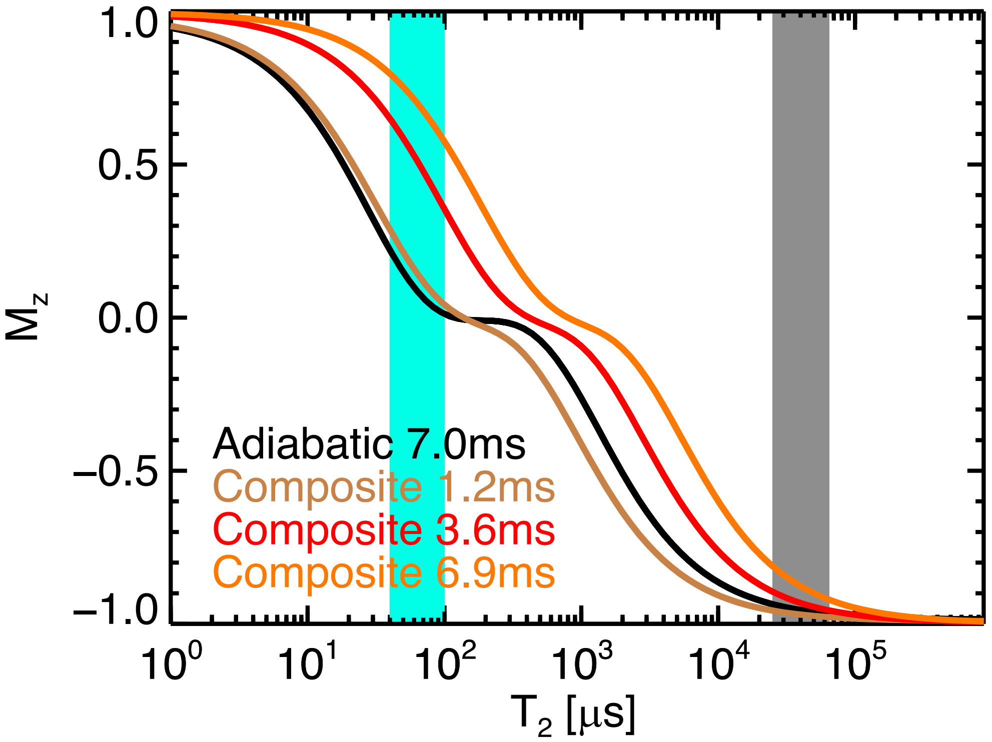
Results

Average data of SCC-ROI's on 11 subjects scanned at 7T (Exp. 3). The log of the 1-M_z is plotted as function of TI, for 4 inversion pulses, with the double exponential fit in solid and a single exponential fit in dotted lines. Confirming the 3T results, the IR is not mono-exponential and the deviation depends on the RF amplitude. The overall vertical shift of the lines is due to the decreasing inversion efficiency with longer pulses.



Results

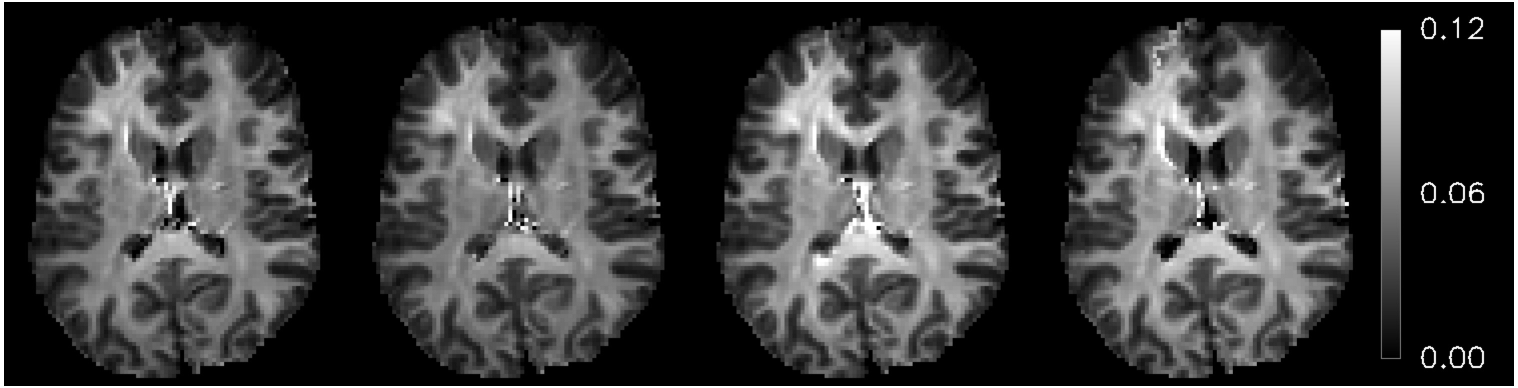
Simulation of M_z as function of $T_2^{(*)}$. The bound pool, with a T_2 in the range indicated by the turquois bar, will be saturated to a varying level, due to the different levels of RF energy in the pulses applied. The longer pulse also shows less inversion efficiency for the free pool (gray band); especially relevant for 7T, where the T_2^* will be shorter.



MT dependent T_1

Poster 0015

Results



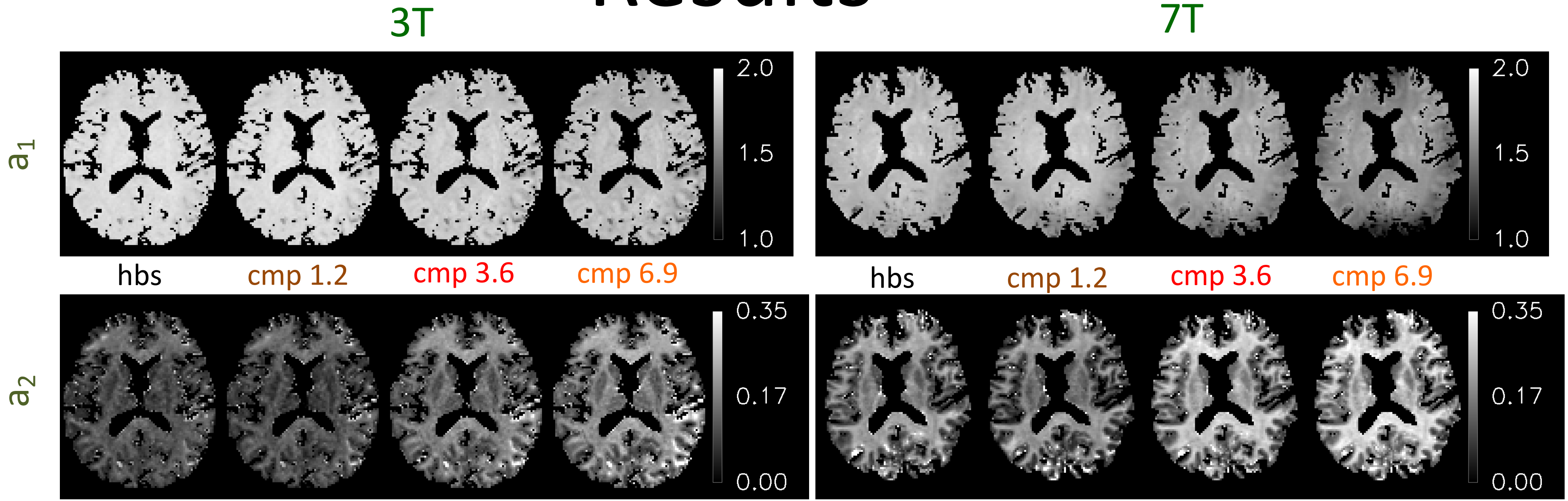
Pulse: hbs cmp 1.2 cmp 3.6 cmp 6.9

The deviation of the images at T_i=8ms compared to a single exponential fit to the last two T_i'2 (258 & 1200ms), one slice for four inversion pulses at 7T. The deviation is bigger for the inversion pulses with a lower amplitude, resulting in less bound pool saturation. White matter shows a bigger effect than grey matter, as that has a higher concentration of non-mobile ^{1}H.

MT dependent T_1

Poster 0015

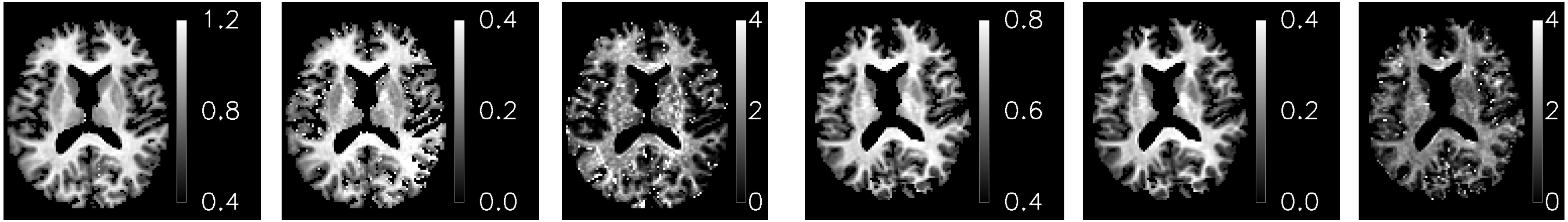
Results



Example of fitting results for one subject, scanned at 3T and 7T, showing the amplitude of both components (top:a_1 and bottom:a_2) for one slice for the four inversion pulses. The normalized signal is converted to saturation ($S= 1- M_z$), for complete inversion the sum of the components would be 2. The increase of the shorter component (bottom row) with decreasing MT saturation is clear, especially at 7T. The decreasing in amplitude (at 7T) anterior and posterior in the brain is due to RF inhomogeneity.

Results

3T | 7T



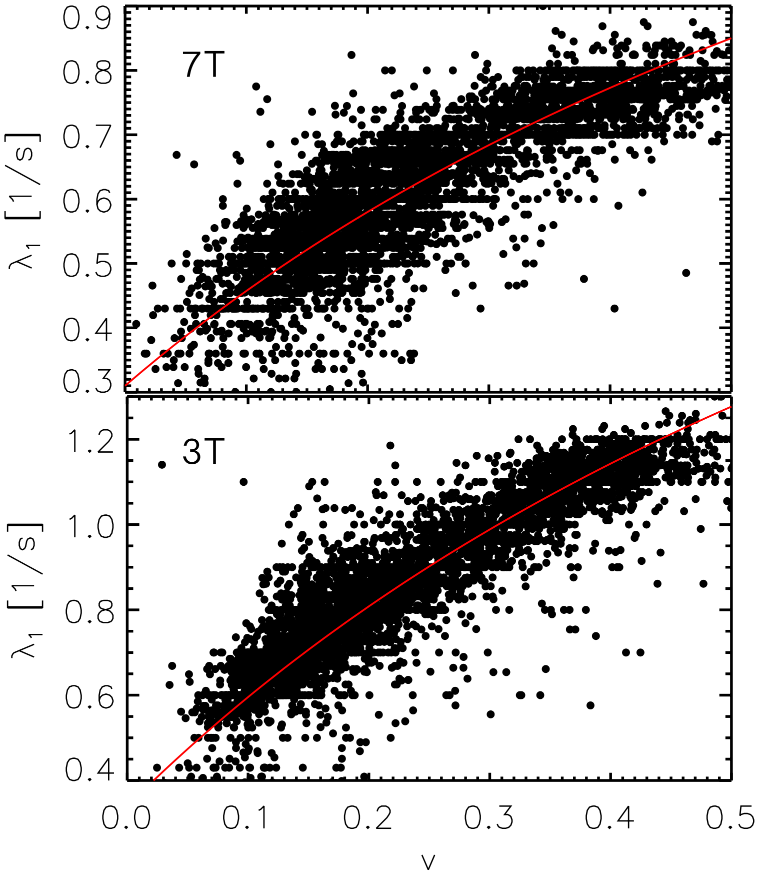
λ_1 | v | k | λ_1 | v | k

Example fit results from one subject (continued from previous slide). Shown are the slower decay rate (λ_1) and the derived relative bound pool size (v) and exchange rate (this rate is water->bound); all rates are in 1/s. Although the decay is field dependent (note the scale difference), both λ_1-maps show similar contrast, and both are similar to the derived bound pool size. The calculated pool size and exchange rates are also similar for the two field strength, although the 3T k-values are slightly higher and have more noise.

Results

Further illustration of relation between the bound pool size (v) and the apparent R_1-rate (the slow component, λ_1), for all voxels for one subject at two field strength. The red lines are the predicted models based on a fixed R_{1f} of 0.4/s (both fields) and a R_{1b} of 2/s for 7T and 3.8/s for 3T.

The plots confirm the notion that exchange with the bound pool may be the dominant contribution to T_1 contrast in the brain [1].



1. Rooney et.al., MRM **57**:308 (2007)

Results

Average results of SCC-ROI in 11 subjects at 3 & 7T (Exp. 2 and 3). Top table shows the fitted amplitudes of the slow and fast components and the derived saturation levels for the two pools. The bottom table shows the fitted decay rates, the assumed bound pool relaxation rate and the derived exchange rate and relative bound pool size (all rates are in 1/s). The fitted parameters (a's and λ's) and S_f follow directly from the data, S_b depends on R_{1b} and v which were derived in conjunction with further MT experiments not described here. The amplitude of the fast component (a_2) clearly depends on the RF amplitude of the inversion, reflecting the differences in bound pool saturation.

B_0	Inv-RF	a_1	a_2	S_f	S_b
7T	HBS	1.77	0.17	1.94	0.87
	Cmp 1.2	1.70	0.18	1.88	0.81
	Cmp 3.6	1.61	0.22	1.84	0.58
	Cmp 6.9	1.54	0.24	1.78	0.44
3T	HBS	1.85	0.12	1.97	0.86
	Cmp 1.2	1.86	0.11	1.97	0.88
	Cmp 3.6	1.78	0.17	1.95	0.60
	Cmp 6.9	1.72	0.19	1.92	0.47

B_0	λ_1	λ_2	R_{1b}	k	v
7T	0.77	9.24	2.0	2.03	0.37
3T	1.10	12.14	3.8	2.39	0.36

Conclusion

- Inversion recovery in brain tissue appears to be bi-exponential, which can be explained by a 2-pool exchange model for T_1 (and MT) effects, confirming earlier reports (e.g. [1,2]).
- In white matter, exchange with the bound pool contributes a fast component to the IR signal with a relative amplitude of 0.08 and 0.29 at 3T, and from 0.16 to 0.40 at 7T, depending on the level of saturation.
- Ignoring exchange with the bound pool results in a dependency of the calculated T_1 on the experimental parameters (RF amplitude, TI's, TR).
- Exchange with the bound pool is likely the dominant source of T_1-contrast in the brain.

1. Pranter et.al., MRM **60** 555 (2008). 2. Labadie et.al., MRM **71**:375 (2014).