

Observation of time-dependent transverse relaxation rate due to mesoscopic magnetic structure

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Target Audience: Researchers interested in accessing magnetic tissue structure at the mesoscopic scale using transverse relaxation.

Purpose: To perform the experimental validation of recently developed relation between the transverse relaxation and the structural randomness in magnetically heterogeneous media.

Theory

Transverse relaxation in biological tissues is affected by diffusion of molecules across the magnetic fields induced on the mesoscopic scale of paramagnetic cells, iron clusters, contrast doped extracellular space, etc. This structural complexity is the subject of interest in biological MRI; the first question to answer is which structure properties survive the massive averaging of the signal during measurements with a macroscopic resolution. It was recently proposed that the spatial organization of paramagnetic structures determines a distinct power-law approach of transverse relaxation to its long-time asymptote.¹ This can be visualized by computing $-d^2/dt^2 \ln S(t) = dR_2/dt = \text{const} \cdot t^\nu$, where $S(t)$ is the free induction decay signal, $R_2(t)$ is the instantaneous relaxation rate, t is time, and ν is the structure-defined exponent, which is $\nu=3/2$ for media with short-range (Poissonian) disorder. In the spectrum, this maps onto the proportionality of the so-called self energy part^{2,3}, $\Sigma(\omega)$, to $\omega^{1/2}$ at low ω . The self-energy part can be thought of as a frequency-dependent relaxation rate in the generalized Lorentzian spectrum $S(\omega) = 1/[-i\omega - \Sigma(\omega)]$. This theory is applicable to media with weak magnetic heterogeneity.¹⁻⁵ In this work, we present experimental results obtained in a well-controlled model system of spherical microbeads, representing short-range disorder, and compare them to Monte Carlo simulations and theory^{1,3}.

Methods

Sample Preparation: Several samples were prepared by suspending polystyrene microbeads (volume fraction 30%, diameter=10 μ m, Dynoseed TS10, Microbeads AS, Norway) in a density matched aqueous solution of sodium chloride ($c_{\text{NaCl}}=1.33\text{M}$). The addition of different amounts of Holmium(III) chloride hexahydrate ($\text{HoCl}_3 \cdot 6\text{H}_2\text{O}$) ($c_{\text{HoCl}} = 0 - 5.75 \text{ mM}$) allowed the adjustment of fluids susceptibility relative to the particles.

NMR Measurement: The NMR measurements were performed on a Bruker DPX 200MHz using a standard zg30 sequence (TR=4s, 16 aver., no spinning). Before the measurement acquisition parameters and shims were adjusted on pure D₂O sample and then kept for all the samples. Heated and dried compressed air maintained the sample at $T=309\text{K}$ during the measurement after an initial settling in period of 5 minutes to ensure the preheated sample to reach thermal equilibrium.

Simulations: Similar to Ref. 3, three-dimensional media of non-overlapping impermeable spheres matching the experimental setup in diameter, volume fraction and susceptibility difference were generated and used for Monte Carlo simulations of randomly diffusing spins.

Data analysis: The phase was adjusted for the measured spectra and the reference frequency was set to the peak of the water line to account for the different susceptibilities of the sample. For the comparison with Monte Carlo simulation all spectra were normalized prior to calculations of $\Sigma(\omega)$. Since the simulations do not include the molecular contribution to the transverse relaxation, a monoexponential R_2 was added to the data using a linear dependence on contrast agent concentration, c_{HoCl} , in bulk solution: $R_2(c_{\text{HoCl}}) = R_2^0 + R_2^c \cdot c_{\text{HoCl}}$. The time derivative of $R_2(t)$ was calculated as the second derivative of $-\ln S(t)$ using the Savitzky-Golay method with a linearly increasing kernel size of $0.4 \cdot t$ [cf. Ref. 1].

Results

As a first evaluation, the susceptibility match of the particles and fluid was estimated from the dataset to be at $c_{\text{HoCl}}=0.25\text{mM}$. To evaluate the most suitable susceptibility differences only the samples with $c_{\text{HoCl}} > 1\text{mM}$ were included in the further study. From the measured data the two parameters for the monoexponential R_2 were found to be $R_2^0 = 1.6 \text{ s}^{-1}$ and $R_2^c = 6.7 \text{ s}^{-1}\text{mM}^{-1}$.

Figs. 1 and 2 show $\Sigma(\omega)$ of the measured data (solid) and the corresponding Monte Carlo simulations (dotted). For the very good agreement of the amplitude, $\Sigma(0)$, for all samples no further fitting besides the two-parametric fit for $R_2(c_{\text{HoCl}})$ was performed. The shape of measured $\Sigma(\omega)$ agrees with simulations although a systematic deviation is visible. The time-domain counterpart of $\Sigma(\omega)$, dR_2/dt , is shown in Fig. 3. As expected for a short-range disorder¹, the exponent ν of dR_2/dt is $3/2$ (black dashed line), which can be indeed seen on the suitable time scales (over an order of magnitude in time) for both the measured time courses and the simulations.

Discussion

We have obtained a good agreement between the theory^{1,3} and the experiment, especially in the time domain (Fig. 3) and for $\Sigma(0)$ (Figs. 1-2). Currently we believe that the remaining systematic discrepancy in $\Sigma(\omega)$, Figs. 1-2, which needs to be addressed in the on-going studies, such as measuring the ω -dependent CPMG rate⁴, cannot be explained by the surface relaxation, shim failure or distortions of particle packing near the surface of the test tube.

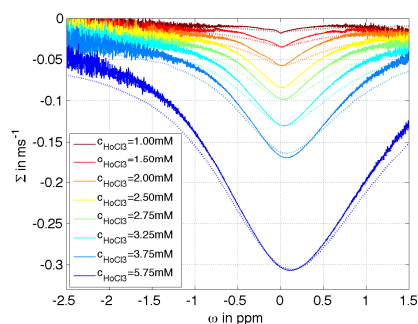


Fig. 1: $\Sigma(\omega)$ of the measured (solid) and simulated (dotted) data. Good agreement of experiment and simulations especially for $\Sigma(0)$.

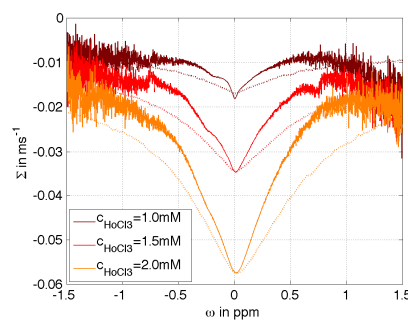


Fig. 2: A closer look at the dataset with small c_{HoCl} from Fig. 1. Clearly visible non-Lorentzian behavior is further examined in Fig. 3.

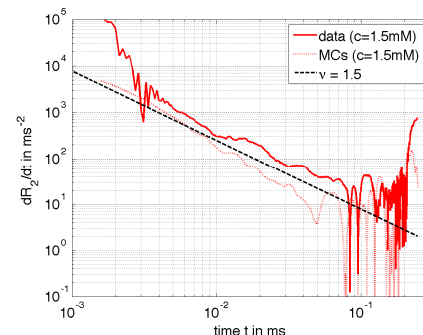


Fig. 3: dR_2/dt of the $c_{\text{HoCl}} = 1.5\text{mM}$ data (red in Figs. 1-2). Measurement (solid) and simulation (dotted) show good agreement with the expected exponent $\nu = 3/2$ (black dashed line).

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References: [1] A. Ruh et al. Proc. ISMRM 21 (2013) 3127; [2] D.S. Novikov, V.G. Kiselev. J Magn Reson 195 (2008) 33; [3] A. Ruh et al. Proc. ISMRM 20 (2012) 460; [4] J.H. Jensen et al., MRM 44 (2000) 144. [5] J.H. Jensen et al., MRM 55 (2006) 1350.