The impact of fibre orientation on T1-Relaxation in white matter

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Abstract Recent MRI studies have shown that the orientation of nerve fibers relative to the main magnetic field affects the R2 relaxation rate. The physical causes have been discussed in several studies but are still not completely understood. However, understanding this phenomenon in detail is of interest since it might serve as a basis for new diagnostic tools. Therefore, this study investigates the influence of fibre orientation on the R1 relaxation rate and demonstrate a positive correlation between both parameters. This could be helpful for a better description of physical tissue properties.

Zusammenfassung: Neuere MRT Studien konnten einen Zusammenhang zwischen der Nervenfaserausrichtung und der R2* Relaxationsrate nachweisen. Die hierbei zugrunde liegenden Effekte wurden zwar schon in einigen Studien diskutiert, sind aber noch nicht vollständig verstanden. Die vorliegende Arbeit untersucht daher den Zusammenhang zwischen der R1 Relaxationsrate und der Faserorientierung. Die Ergebnisse zeigen dabei eine positive Korrelation zwischen beiden Parametern, was für die Bestimmung von Gewebeeigenschaften auf mikroskopischer Ebene hilfreich sein könnte.

Motivation

The investigation of the human brain microstructure *in vivo* is a field of great interest in the neuroimaging community. In especially T2* mapping using gradient echo acquisitions has become a widely used tool for quantitative brain mapping in many studies. Recently, MRI studies have been convincingly demonstrated that the orientation of nerve bundles towards the main magnetic field (B0) influences the magnitude and phase evolution of the MR signal in white matter (WM) regions [1]. This phenomenon has the potential to serve as basis for the definition of biomarkers to classify the course of neurological diseases or to examine brain tissue properties [2, 3]. It is commonly assumes that the observed R2* contrast originates mainly form the susceptibility shift induced by the myelin sheath surrounding the axons. This assumption is supported by field simulation studies were the underlying physical effects were studied in detail using numerical or analytical models [3, 4]. Even though these model allow for a proper reconstruction of the experimental data, they are simplifying the myelin microstructure by neglecting its laminar structure and assuming a homogeneous object instead (Fig.1). In contrast, more realistic models with regard to the laminar structure underestimate the thickness of the myelin sheath and predict a wrong frequency shift for the myelin-associated compartment [6].

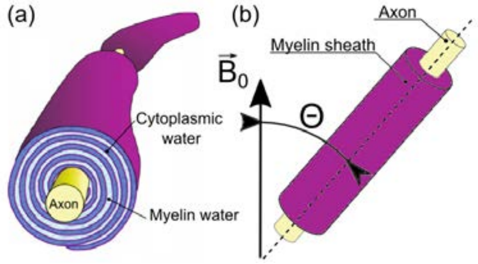

Fig. 1: Schematic of the myelin sheath and the alternating water and cellular compartments (a) as well as the simplistic model at an angle Θ relative to the B0 field (b). Modified from [7].

These discrepancies between a realistic tissue representation and the experimental data indicates an incomplete description of the physical effects. However, a proper model considering the multiple spatial scales could offer a new way to examine the physical properties of the myelin microstructure. Therefore, the aim of the current work was to investigate the relationship between the R1 relaxation rate and the nerve fibre direction relative the main magnetic field. This increases the number of experimental parameters and could be useful for the verification or improvement of biophysical models.

Material and methods

A group of 14 healthy subjects with an average age of 43.1+-11 years was scanned with a 3T System. For each subject, diffusion weighted EPI data [bandwidth=1628Hz/pixel, TE=87ms, TR=9000ms, FOV=220 x 220 x 122 mm^3 and a voxel size of 1.72 x 1.72 x 1.70 mm^2, bvalue=1000 s/mm^2] were acquired to reconstruct the angle (Θ) between the predominate nerve bundle orientation and the B0 field from the main diffusion direction. Furthermore, a series of gradient echo and EPI images were acquired from which quantitative maps of the decay rates R1, R2* and total water content were reconstructed and co-registrated to the diffusion weighted data. Details about the protocol for reconstructing of the quantitative parameters can be found in [7]. For investigating the relationship between the fibre orientation and the decay rates, the respective values were extracted from the corresponding maps (R1, R2* and Θ). Voxels outside purely WM regions and with a fractional anisotropy below 0.4 were ignored. Finally, these data were sorted by increasing angles and averaged within 5° degree intervals. This leads to two (R1 and R2) angular dependent curves for each subject.

Results
The averaged experimentally determined orientation dependence of R2* and R1 are shown in Fig. 2a-2b. As expected, the observed R2* rate in Fig. 2a increases with increasing angle, consistent with previously published findings [1]. More importantly, an orientation dependent behaviour was also observed for R1 as shown in Fig. 2b and 2d. R1 monotonically increases with angle and varies between 1.271 Hz and 1.299 Hz, corresponding to a T1 relaxation time of 786ms for parallel fibre orientation and 769ms for fibres oriented perpendicular to B0. Fig. 2c-2d shows the angular dependence of R2* (c) and R1 (d) for each individual subject scanned. As can be noted, the observed average behaviour (Fig. 2a-2c) clearly reflects the R1 angular dependence in each subject.

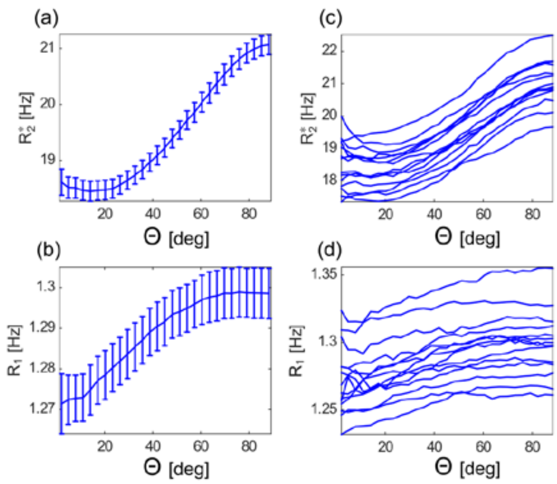

Fig. 2: Angular dependence of R2* and R1 averaged over all subjects (a, b) as well as for each individual subject (c, d). The error bars indicate the standard error of mean.

Discussion
Understanding the physical origin of the observed R1 contrast might be a very helpful step towards a better description of the brain microstructure and its physical properties. Here, the susceptibility shift of the myelin sheath relative to the surrounding tissue might be a potential and obvious source as it already serves as basis to explain the R2* angle dependency. The basic assumption is that this shift induces local field heterogeneities which depend on the fibre orientation towards the main B0 field and accelerate the dephasing process of the spins. In addition to the longitudinal fields, this assumption implies also that the myelin sheath induces orientation related fields in the transverse directions. Diffusing spins experiencing these fields as a time dependent random magnetic field. The field component arround the Larmor frequency could therefore potentially increase the transition rate between the spin eigenstate, thereby affecting the R1 relaxation rate.

Summary
This study has demonstrated a relationship between the R1 rate and the predominant nerve fibre direction with respect to the main magnetic field. This observation could be serve as a starting point for the definition of biomarkers for the classification of brain degeneration or helpful for the improvement of biophysical models. Apart from this, the R1 angle dependency might provide additional information to examine physical tissue properties on a microscopic scale.

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