Double wave vector diffusion weighting in the human corticospinal tract in vivo

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INTRODUCTION

Recently, experiments have gained new interest where two successive gradient pulse pairs of different direction are used for diffusion weighting (double wave vector diffusion weighting, DWV) [1-5]. DWV measurements might provide a means to acquire detailed information on the tissue structure, such as cell size and shape. In samples characterized by restricted diffusion, a difference between parallel and anti-parallel orientation of the gradients was predicted by theory [1] and numerical simulation [4, 5], and was observed in biological samples [3, 5]. Here, this effect is demonstrated in human brain tissue *in vivo*, using a clinical MR system.

METHODS

The DWV-weighted (Fig. 1) signal from randomly oriented pores should depend on the angle θ subtended by the two diffusion gradients as $S(q,\theta) \propto p[1 - \langle R^2\rangle(q^2/3)(2+\cos\theta)] + (1-p)[1-q^2 2\Delta D]$ if $q = \gamma\delta G$ is small and if the time lag τ_m between the two weighting periods is negligible. The mean squared radius of gyration $\langle R^2\rangle$ increases with pore size. D is the free diffusion coefficient, p the volume fraction of restricted diffusion. The term proportional to $(1-p)$ represents contributions from spins not experiencing significant restriction during Δ and is an extension of the description in [1]. It is also assumed that $\delta \ll \tau_D \ll \Delta$ holds, with τ_D being the mean time required for diffusion across a pore. For complete restriction, the diffusion-induced signal loss should vary by a factor of 3 between parallel and anti-parallel gradient orientations.

DWV measurements were performed at 3 T magnetic field strength on a whole-body MR system (Magnetom Trio, Siemens, Erlangen, Germany). For two healthy volunteers axial slices of the brain were imaged, using spin-echo echo planar imaging with a multiple spin-echo diffusion preparation (Fig. 1, $\tau_m = \delta + 0.56$ ms) which was designed to suppress cross terms between applied diffusion gradients and background gradients. Two experiments were performed. In experiment A the dependence of the signal amplitude on θ was measured, averaged over a region of 20 voxels in the left and right corticospinal tracts (CST). $\mathbf{G}^{(1)}$ was rotated in a plane perpendicular to the z axis, $\mathbf{G}^{(2)}$ was parallel to x (x: left-right, y: anterior-posterior, z: head-feet direction). On the observation time scale the protons in the CST will experience significant restriction along the gradient directions (4 slices, 3×3×10 mm^3 nominal resolution, $\delta = 14$ ms, $\Delta = 89$ ms, $q_1 = 94.1\cdot10^3\ \text{m}^{-1}$ and $q_2 = 133.1\cdot10^3\ \text{m}^{-1}$, TE = 283 ms, 4 averages). Experiment B was a DWV measurement with parallel and anti-parallel diffusion gradients only, averaging the results over 4 different absolute gradient directions with $G_z = 0$ and $G_x = G_y$ (20 slices, 3×3×3 mm^3 resolution, $\delta = 10$ ms, $\Delta = 67$ ms, $q_1 = 97.0\cdot10^3\ \text{m}^{-1}$ and $q_2 = 137.2\cdot10^3\ \text{m}^{-1}$, TE = 213 ms, 15 averages).

RESULTS

Within expected accuracy, experiment A yielded the predicted shape of the signal dependence on θ in the CST (Fig. 2). Most of the $\langle R^2\rangle$ values derived from experiment B after applying a noise threshold (Fig. 3) are positive and on the order of 10 μm² (using $D = 2\cdot10^{-9}\ \text{m}^2\text{s}^{-1}$), supporting the validity of the equation given above. Deviations from real compartment sizes are to be expected due to violation of the conditions τ_m, $\delta \ll \tau_D \ll \Delta$. The results suggest that it is possible to develop a DWV-based method to estimate compartment sizes *in vivo*.

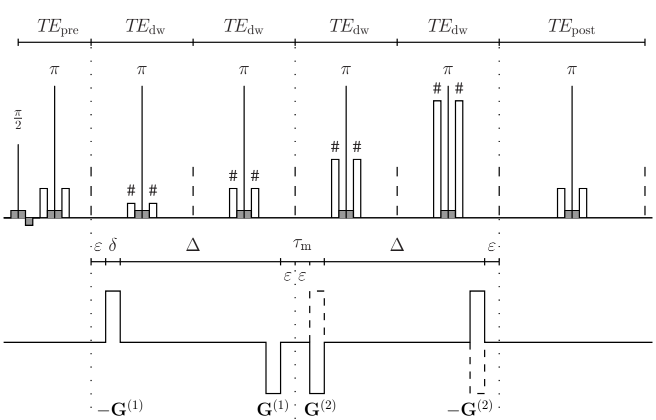

Fig. 1: DWV preparation used in the experiments. Slice-select gradients are shaded. Spoiler gradients marked with "#" were perpendicular to $\mathbf{G}^{(1)}$ and $\mathbf{G}^{(2)}$. Vertical dashed lines mark spin echo positions. The echo at the last shown position was acquired. $|\mathbf{G}^{(1)}| = |\mathbf{G}^{(2)}|$. For $\mathbf{G}^{(i)}$, the solid line corresponds to θ = 0.

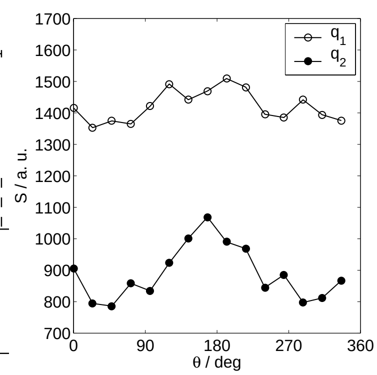

Fig. 2: Experiment A: DWV signal amplitude in CST versus the angle between gradients, θ, for two different gradient amplitudes.

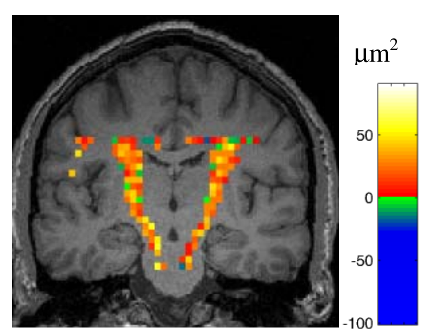

Fig. 3: Experiment B: color-coded value of $\langle R^2\rangle$, overlaid on a corresponding T1-weighted image. Color suppressed where $S(q_2,\pi) < 30$. The top and bottom row of colored voxels represent the edges of the measured slice stack.

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