Double wave vector diffusion weighting in Wallerian degeneration

Martin A. Koch[1,2], and Jürgen Finsterbusch[1]
[1]*Systems Neuroscience, Neuroimage Nord, University Medical Center Hamburg-Eppendorf, Hamburg, Germany,* [2]*Institute of Medical Engineering, University of Lübeck, Lübeck, Germany*

INTRODUCTION

Double wave vector (DWV) diffusion weighting is a new approach for assessing tissue characteristics such as mean pore size and shape. It is based on the phenomenon that for restricted or hindered diffusion the MR signal acquired with two successive diffusion weighting periods (Fig. 1) may depend on the angle between the two applied gradient directions [1]. At short τ_m, the signal difference between parallel and antiparallel gradient orientations can be related to the mean pore size [1–3]. In recent years, experiments have confirmed the existence of this effect in phantoms, excised tissue samples [2,3], and in vivo in the human corticospinal tract [4]. It is investigated if the size estimate derived from the DWV signal difference between parallel and antiparallel gradient orientations is sensitive to pathological changes in the tissue microstructure of the corticospinal tracts.

THEORY AND METHODS

The DWV-weighted (Fig. 1) signal from randomly oriented pores of diameter a depends on the angle θ between the two diffusion gradients of equal amplitude, G, as [1]

$$S(q,\theta)/S_0 \approx 1-\left\langle R^2\right\rangle \frac{1}{3}q^2\left(2+\cos\theta\right), \qquad (1)$$

where S_0 is the signal without diffusion weighting, if $q = \gamma\delta G$ is small compared to $1/a$, if the time delay τ_m between the two weighting periods is negligible, and if $\delta << \tau_D << \Delta$ holds (τ_D mean time required for diffusion across a pore). Previous results [2–6] indicate that these conditions need not strictly be met for some of the modulation to remain. Özarslan and Basser [5] derived an expression for the signal attenuation which accounts for a finite duration of δ, Δ, and τ_m. The mean squared radius of gyration, $\langle R^2\rangle$, scales with the pore size, such that the difference between signals with parallel and antiparallel gradient orientation can provide information about the tissue structure.

A patient (85 y) with a partial infarct of the right middle cerebral artery was investigated 7 months after the insult. At the time of investigation, she suffered from residual partial paresis of the left arm. A normal volunteer (30 y) was scanned as control. A DWV-prepared double spin echo-echo planar imaging sequence (Fig. 1) with short τ_m was applied on a 3 T whole-body MR system (Magnetom Tim Trio, Siemens, Erlangen/Germany) using a receive-only head coil array. 20 transverse slices were acquired with 3×3×3 mm^3 nominal resolution, δ = 7.36 ms, Δ = 62.36 ms, $\tau_m = \delta$ + 0.6 ms, TR = 4 s, TE = 165 ms, averaging over 4 gradient directions (each with parallel and antiparallel gradient orientations) in the x-y plane and 20 repetitions. The spinal cord axis was approximately aligned with the z axis. For a region-of interest analysis both the left and right corticospinal tract (CST) were delineated by probabilistic fibre tracking [7] on data from a separate diffusion tensor imaging acquisition (diffusion-weighted SE-EPI) starting from a seed voxel in the medulla oblongata. Images were acquired for $S(q,0)$, $S(q,\pi)$, and S_0 and motion corrected before analysis.

RESULTS

In the patient, midbrain asymmetry and lower values of the smallest diffusion tensor eigenvalue in the right corticospinal tract suggest the presence of Wallerian degeneration in the right corticospinal tract. The DWV measurement yields a positive signal difference between parallel and antiparallel gradient orientation in the corticospinal tract in both hemispheres. In a segment of the CST, this difference is lower in the right hemisphere (Fig. 2). Figure 3 shows slice averages of $\langle R^2\rangle$ in the region of interest defined by fibre tracking. In slices 10 to 14, the right CST of the patient exhibits lower $\langle R^2\rangle$ values. The reduction in the right hemisphere might be caused by reduced restriction to diffusion in the extracellular space, as some of the densely packed axons in the tract have disintegrated by Wallerian degeneration, inducing a violation of $\tau_D << \Delta$. Another possible explanation would be that mainly large axons have been lost. In more superior slices, the necrotic infarct area in the right hemisphere is characterized by higher values compared to the contralateral side. No considerable left-right difference is observed in the normal volunteer but $\langle R^2\rangle$ tends to be higher than in the patient (Fig. 3). The chosen δ violates the condition $\delta << \tau_D$ for the most frequent axon diameters in the corticospinal tract, which is on the order of 2 µm [8]. For a quantitative evaluation the deviation can be accounted for [5]. More subjects need to be investigated to ascertain the nature of the observed changes.

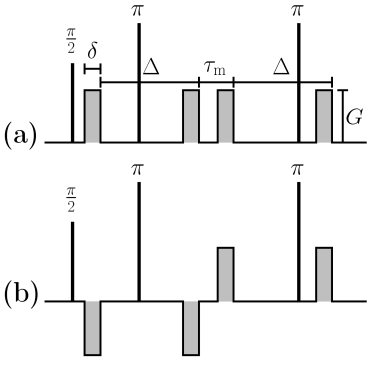

Fig. 1: DWV weighting sequence for θ = 0 (a) and for θ = π (b). Slice select and crusher gradients immediately before and after the refocusing RF pulses, perpendicular to the diffusion gradients (shaded), are not shown. The RF pulses are shaped slice-selective pulses. The preparation shown is followed by an EPI readout sequence.

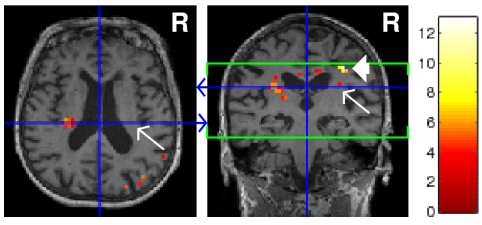

Fig. 2: Patient: t statistic for the signal difference between parallel and antiparallel gradient orientation, $\ln S(q,0) < \ln S(q,\pi)$, superimposed with a T_1-weighted image. CSF spaces were excluded. Horizontal blue lines indicate the relative position of axial (left, slice no. 14) and coronal (right) views. The DWV acquisition slice stack extends between the green lines. In some regions (arrows), the right CST exhibits t values below the arbitrarily chosen threshold (p<0.0001, uncorr.). Regions in the necrotic infarct area (arrowhead) show higher values than on the contralateral side.

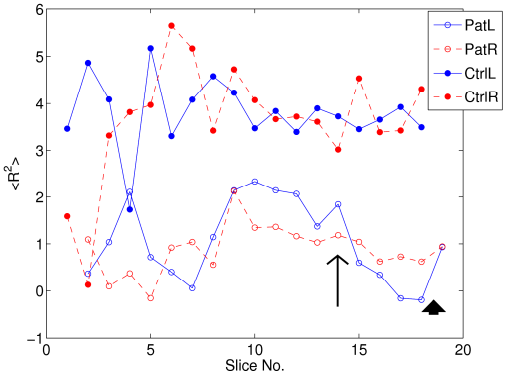

Fig. 3: Pore size estimate $\langle R^2\rangle$ calculated from Eq. (1) for the CST of a patient (85 y) and a normal volunteer (30 y), slice-wise median in the left/right CST as defined from DTI fibre tracking. Slice numbering increases from inferior to superior. The arrow positions correspond approximately to those in Fig. 2.

[1] PP Mitra, *Phys. Rev. B* **51**, 15074 (1995)
[2] MA Koch and J Finsterbusch, *Magn. Reson. Med.* **60**, 90 (2008)
[3] T Weber et al., *Magn. Reson. Med.* **61**, 1001 (2009)
[4] MA Koch, J Finsterbusch, *NMR Biomed.*, in press, DOI 10.1002/nbm.1711
[5] E Özarslan and PJ Basser, *J. Chem. Phys.* **128**, 154511 (2008)
[6] MA Koch and J Finsterbusch, *Magn. Reson. Med.* **64**, 247 (2009)
[7] MA Koch et al., *NeuroImage* **16**, 241 (2002)
[8] S Terao et al., *Acta Neuropathol.* **93**, 1 (1993)