Simultaneous Estimation of Compartment Size and Eccentricity with Double-Wave-Vector Tensor Imaging at Long Mixing Times

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Introduction

Double-wave-vector diffusion-weighting (DWV) experiments [1] have been shown to be a promising tool for the investigation of tissue microstructure by considering the MR signal amplitude vs. the relative angle between the two wave vectors [1-5]. For short mixing times between the two diffusion-weighting periods involved, the signal modulation is proportional to the pore or cell size and, thus, can be used to estimate compartment sizes [2-4]. For long mixing times, the modulation increases with the cell eccentricity which has been used to detect microscopic diffusion anisotropy [5-7]. Based on a tensor model which is valid for arbitrary wave vector directions, cell shapes, and cell orientation distributions, a rotationally invariant measure of the cell eccentricity, the so-called *MA* index, has been derived [8]. In this study, a direction scheme is presented that allows to determine the 42 independent elements of this tensor model. It is shown that from the full tensor information not only the MA but also the cell or compartment size can be estimated. Examples for human brain data *in vivo* are presented. Thus, DWV tensor experiments with long mixing times could be used to determine compartment sizes and cell eccentricities simultaneously.

Methods

The direction combination scheme for the DWV tensor acquisitions (Table 1) is based on a set of 21 non-collinear gradient vectors that involve not only planar but also diagonal directions and different vector lengths, i.e. q values, in order to distinguish 2nd and 4th order contributions. These directions are combined in pairs of orthogonal and parallel vectors for the two wave vectors yielding 42 combinations. Experiments were performed on a 3T whole-body MR system (Siemens TIM Trio) with a 12-channel receive-only head coil. Healthy volunteers were investigated after their informed consent was obtained. An echo-planar imaging sequence was used involving two diffusion weighting periods and a single refocusing RF pulse in-between. A resolution of 3×3×3 mm^3 was chosen to cover a FOV of 210×210 mm^2 in 20 slices (TE / TR = 155 ms / 6 s). The two diffusion-weighting periods were applied with a b value of 500 s mm^{-2} each, the diffusion time Δ, the mixing time τ_m between the two diffusion weightings, and the gradient pulse duration δ were 31 / 48 / 22 ms, respectively. The MR data were fitted to the tensor model [8] using a Levenberg-Marquardt algorithm to determine the 42 tensor elements. In addition to the *MA* index, the compartment size was determined based on the second order terms of the tensor model.

Table 1: Gradient direction combination scheme to determine the full DWV tensor information.

(1 0 0)^T (1 0 0)^T	(0 1 0)^T (0 1 0)^T	(0 0 1)^T (0 0 1)^T	(1 1 0)^T (1 1 0)^T	(1 0 1)^T (1 0 1)^T	(0 1 1)^T (0 1 1)^T
(0 1 1)^T (1 0 0)^T	(0 -1 1)^T (1 0 0)^T	(1 0 1)^T (0 1 0)^T	(1 0 -1)^T (0 1 0)^T	(1 1 0)^T (0 0 1)^T	(-1 1 0)^T (0 0 1)^T
(-1 1 0)^T (1 1 0)^T	(1 0 -1)^T (1 0 1)^T	(0 -1 1)^T (0 1 1)^T	(1 0 1)^T (1 1 0)^T	(0 1 1)^T (1 0 1)^T	(1 1 0)^T (0 1 1)^T
(1 1 0)^T (1 0 0)^T	(1 0 1)^T (1 0 0)^T	(0 1 1)^T (0 1 0)^T	(1 1 0)^T (0 1 0)^T	(1 0 1)^T (0 0 1)^T	(0 1 1)^T (0 0 1)^T
(1 1 ½)^T (1 1 ½)^T	(1 ½ 1)^T (1 ½ 1)^T	(½ 1 1)^T (½ 1 1)^T	(1 1 -½)^T (1 1 ½)^T	(1 -½ 1)^T (1 ½ 1)^T	(-½ 1 1)^T (½ 1 1)^T
(1 -1 ½)^T (1 1 -½)^T	(-1 ½ 1)^T (1 -½ 1)^T	(½ 1 -1)^T (-½ 1 1)^T	(1 -1 ½)^T (1 -1 ½)^T	(-1 -½ 1)^T (-1 ½ 1)^T	(-½ 1 -1)^T (½ 1 -1)^T
(1 1 ½)^T (1 1 0)^T	(1 1 -½)^T (1 1 0)^T	(1 ½ 1)^T (1 0 1)^T	(1 -½ 1)^T (1 0 1)^T	(½ 1 1)^T (0 1 1)^T	(-½ 1 1)^T (0 1 1)^T

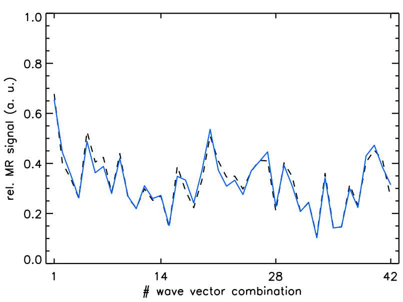

Fig. 1: MR signal amplitude (dashed) vs. the direction combinations of the tensor scheme (see Table 1) in a single voxel and corresponding fit with the tensor model of Ref. 8 (solid).

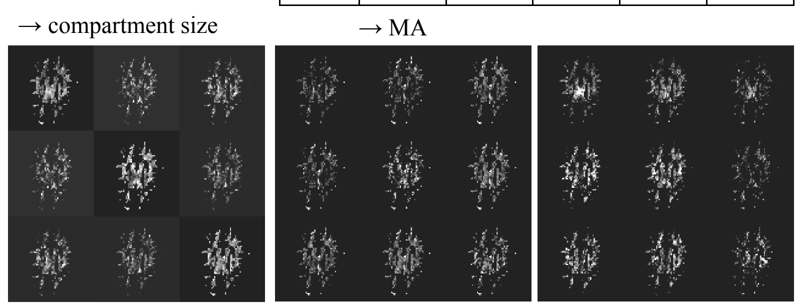

Fig. 2: Maps of 27 of the 42 tensor elements in a white matter section of the centrum semiovale derived from a fit to the tensor equation of Ref. 8. The left set shows the second order contributions R_{ii} and R_{ij}, from which the compartment size can be estimated, the two other present the fourth order tensor components R_{iiii} and R_{iiij} which are required for the *MA* index and F_{iiii} and F_{iiij}, respectively.

Results and Discussion

Results of the DWV acquisition and the fitting procedure to the tensor equation are shown in Fig. 1. The fit to the tensor equation is in a good agreement with the data, minor deviations arise possibly due to a reduced signal damping in some directional combinations. Maps of 27 of the 42 tensor elements, both 2nd and 4th order elements, are shown in Fig. 2 for a white matter section within the centrum semiovale. From these tensor elements, the cell eccentricity measure *MA* and a compartment size estimate can be calculated. The results of the compartment size estimation, slice-wise averaged diameters of all 20 slices investigated are shown in Fig. 3. Typical values are around 10.2 µm which is comparable to values obtained *in vivo* with dedicated DWV experiments and short mixing times [9].
Thus, DWV tensor imaging at long mixing times may provide an alternative approach to assess compartment sizes in the living human brain. In particular, compartment size and cell eccentricity information can be obtained in a single experiment.

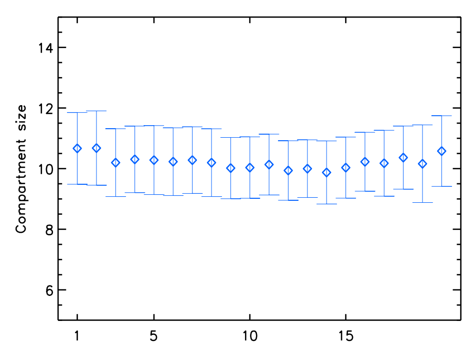

Fig. 3: Slice-wise averaged compartment sizes in the brain of a healthy volunteer.

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