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Measuring Anisotropic Diffusion with Rotating Diffusion Gradients

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Introduction: MRI pulse sequences with radial trajectories in k space have been successfully used for diffusion-weighted imaging; these sequences are generally less motion sensitive than conventional ones [1–3]. The diffusion-sensitizing gradients can be applied either in a fixed direction or rotating, e. g., always orthogonal to the readout gradient. The latter alternative has advantages for self-navigating motion correction algorithms as described in [3]. However, the resulting images become more difficult to interpret in the presence of anisotropic diffusion, because different effective diffusion weightings will be applied in different regions of the k space. The purpose of this study was to simulate the acquisition with rotating diffusion gradients for a range of different diffusion anisotropies, in order to learn about potential artifacts due to this method.

Methods: We simulated MR acquisitions with radial k space trajectories using the Matlab software (The MathWork, Inc.). We calculated the Fourier transform of an artificial phantom image, then radially sampled data of this Fourier transform, and regridded these data into a Cartesian grid (averaging oversampled data in the center of k space). Finally, the regridded raw data was Fourier transformed back to image space. This procedure was performed with rotating diffusion gradients and varying degrees of diffusion anisotropy with relative anisotropies between 0 and $\sqrt{2}$. The corresponding two-dimensional diffusion tensor was

$$\mathsf{D} = \begin{pmatrix} 1/(1+a) & 0 \\ 0 & a/(1+a) \end{pmatrix}$$

with a ranging from 0 (complete anisotropy, diffusion only in left–right direction) to 1 (complete isotropic diffusion) in 11 steps. The diffusion attenuation is calculated as

$$A = \exp\left(-\operatorname{tr}(\mathsf{b}(\phi)\mathsf{D})\right)$$

with the b matrix depending on the radial angle ϕ:

$$\mathsf{b}(\phi) = \begin{pmatrix} \sin^2\phi & -\sin\phi\cos\phi \\ -\sin\phi\cos\phi & \cos^2\phi \end{pmatrix}.$$

The effect of varying attenuation in different regions of the k space (different radial angle ϕ) is illustrated in Figure 1.

Parameter maps (ADC maps) of the diffusion coefficients were calculated and compared.

Results: Figure 2 shows diffusion-weighted images (left column) and ADC maps (right column) with relative diffusion anisotropies of 0.707, 0.303, and 0 (from top to bottom). In the case of strongly anisotropic diffusion, the signal attenuation appears more inhomogeneous, especially at the edges of the geometric shapes. The attenuation depends also on the geometric orientation of the image elements: vertical shapes appear brighter than horizontal shapes in the diffusion-weighted image. Consequently, the corresponding ADCs of the vertical shapes appear lower than of the horizontal shapes. Figure 3 shows the signal intensity in the vertical and horizontal bar as a function of the relative anisotropy.

Discussion: The shown results demonstrate that diffusion attenuation by rotating diffusion gradients depends on the geometric shape of the imaged objects. Vertical shapes and especially their edges correspond to areas of the k space left and right of the center. The readout of these areas is performed with vertical diffusion weighting that is orthogonal to the selected diffusion direction in this simulation (left–right). Thus, these shapes appear hyperintense in the diffusion-weighted images.

The observed variation of signal intensity is *not* caused by different diffusion *directions* as observed e. g. in brain imaging with non-isotropic diffusion weightings. In this study, the diffusion direction is always left–right with varying degrees of anisotropy.

Our results indicate that artifacts may be caused by rotating diffusion gradients in tissues with anisotropic diffusion and specific geometric shapes (especially in the presence of sharp edges). In this case, diffusion gradients with fixed direction might be preferable.

References:

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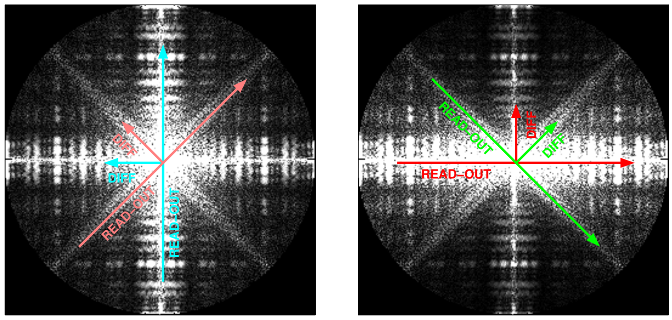

Figure 1: Illustration of effect of rotating diffusion gradients (left hand side: isotropic diffusion, right hand side: anisotropic diffusion in horizontal direction; maximum attenuation with readout gradient in vertical direction and, thus, diffusion gradient in horizontal direction).

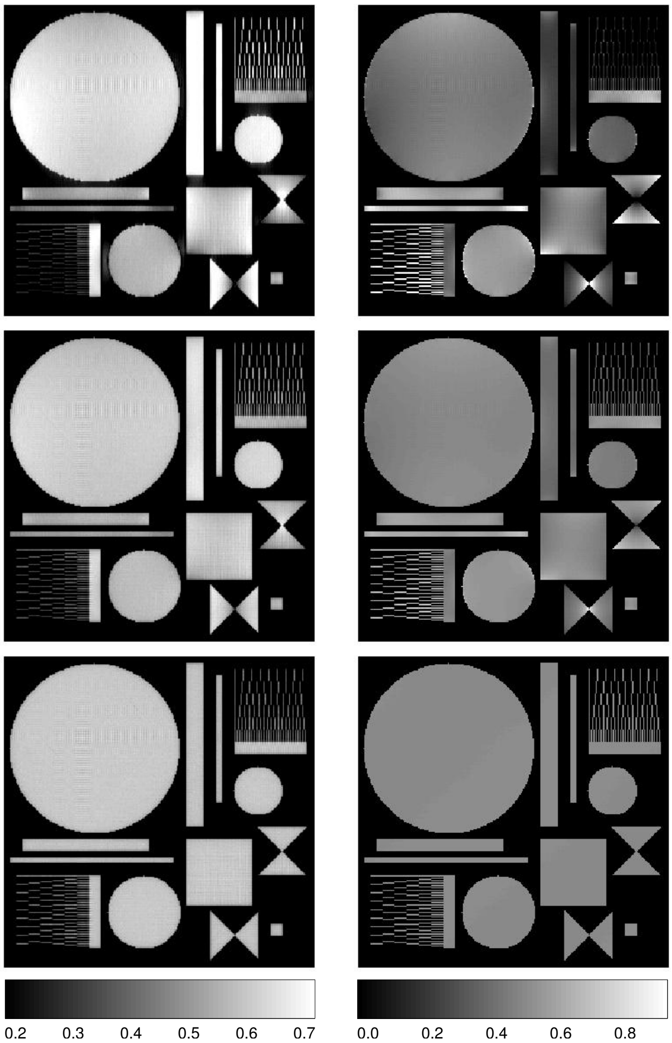

Figure 2: Diffusion-weighted images (left column) and ADC maps (right column) with relative anisotropy of 0.707, 0.303, and 0 and constant mean diffusivity of 0.5.

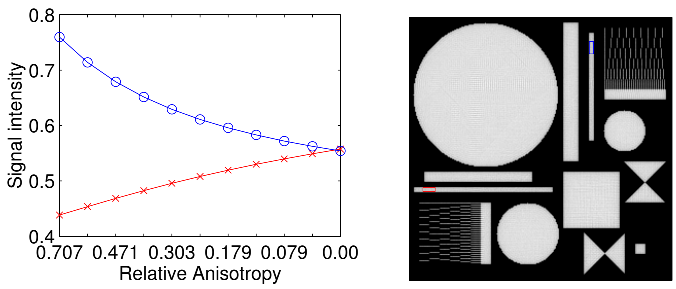

Figure 3: Signal intensities in vertical (blue ○) and horizontal (red ×) bar in diffusion-weighted images.