INFLUENCE OF MAXIMAL B-VALUE, FIT POLYNOMIAL AND NUMBER OF DIFFUSION DIRECTIONS ON THE MEASURED KURTOSIS: A PHANTOM STUDY

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Introduction

In contrast to free diffusion, the restrictions present in biological tissue cause the diffusion propagator to deviate from a Gaussian function. Diffusion kurtosis imaging (DKI) [1,2] extends Diffusion Tensor Imaging (DTI) in order to quantify these deviations from Gaussian behaviour yielding additional information about the tissue microstructure. To calculate the kurtosis, diffusion weighted signals with a range of *b*-values must be acquired. The kurtosis can then be determined by a polynomial fit of the logarithmic signal. Unfortunately, it is not trivial to perform this fit correctly and stable. Therefore, the aim of this work was to investigate the dependence of the measured kurtosis on the acquisition parameters maximum *b*-value, order of the fitting polynomial and number of gradient directions under well-defined conditions using recently developed diffusion phantoms [3].

Methods

The kurtosis can be approximately determined using the cumulant expansion (Eq. 1) of the diffusion weighted signal $S(b)$, where D_{app} is the apparent diffusion coefficient and K_{app} is the apparent kurtosis. The expansion is usually terminated after the term quadratic in *b*.

$$\ln[S(b)/S(0)] = -b D_{app} + b^2 D_{app}^2 K_{app} + A b^3 + \ldots \quad (1)$$

The Diffusion Kurtosis Tensor (DKT) W_{ijkl} is used to describe the directional dependence of the kurtosis. The DKT is a fully symmetric tensor with 15 independent elements obtainable from measurements with at least 15 gradient directions [1,2].

The phantom datasets were acquired on a 1.5 T MR scanner (Avanto, Siemens) using a standard twice refocused spin echo EPI diffusion sequence (TR=6 s, TE=165 ms, voxel size 2.5×2.5×5 mm³, FOV 320×190 mm², 16 *b*-values ranging from 0 to 10000 s/mm², 1 direction orthogonal to the fibres and 30 directions, 10 averages). The influence of the echo time was investigated by varying TE in the range from 165 ms to 380 ms using 1 direction. The DTI phantoms consisted of parallel polyester fibres and were constructed as described in [3]. To account for the noise, equation (1) was extended by a noise parameter which was determined in the image background. D_{app} and K_{app} were obtained using the Levenberg-Marquardt fitting algorithm. For the measurement with one gradient direction, the K_{app} values were calculated with different maximum *b*-values using the polynomial in Eq. 1 terminated after the term quadratic and cubic in *b*. To compare the calculation quality of the DKT depending on the number of directions used, the DKT was calculated for each pixel using subsets of the MRI data (30/5 and 15/10 directions/averages).

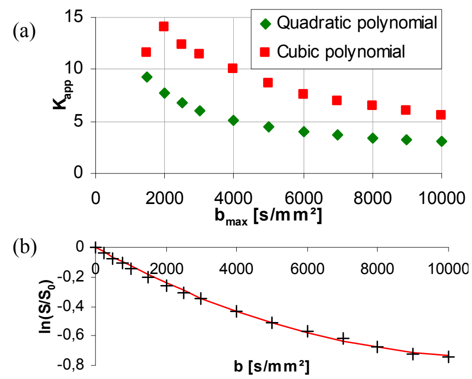

Fig. 1: (a) K_{app} values for a ROI containing the whole phantom, gradient direction orthogonal to the fibres. For the quadratic and the cubic fitting polynomial, b_{max} substantially influences the calculated K_{app} in the whole parameter range. (b) Measured signal in the phantom and fitted quadratic polynomial. The deviations of logarithmic signal from parabolic shape are too small for a stable cubic fit.

Results

Fig. 1a shows the influence of the maximum *b*-value b_{max} on the kurtosis value for a ROI containing the whole fibre area of the phantom with gradient direction orthogonal to the fibres. For all considered b_{max}, the measured kurtosis value substantially changes with b_{max} using the quadratic polynomial. Interestingly, the change of K_{app} is largest for small b_{max}, where small contributions of the higher order terms would be expected. The use of the cubic polynomial does not improve this situation (Fig. 1a), but leads to larger kurtosis values as the cubic term partially compensates the quadratic term at high *b*-values. As shown in Fig. 2, the use of the cubic fit causes a large uncertainty of K_{app} (standard deviation of K_{app} 0.21 for Fig. 2a and 0.67 for 2b). The deviations of the measured logarithmic signal from the parabolic shape are marginal (Fig. 1b). Therefore, the measured signal curve does not contain enough information for a stable cubic fit.

To compare the measurements with 30/5 and 15/10 directions/averages, the DKT was calculated for each phantom voxel. The projected kurtosis $K_{app,y}$ obtained from the tensor is depicted in Fig. 3. Although the measurement time is equal, the calculation of the DKT with the minimally required 15 directions is very unstable (Fig. 3a) while using 30 directions yields reliable results (Fig. 3b). Monte Carlo simulations (not shown) using a constant product of the number of directions and averages confirm that the accuracy of the measured DKT increases with the number of directions. However, employing more than 30 directions does not improve the stability substantially.

The echo time has a strong influence on the measured kurtosis values (Fig. 4).

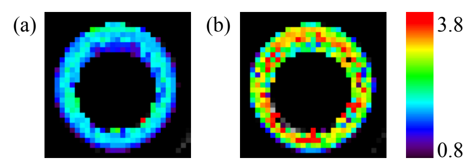

Fig. 2: K_{app} values for the phantom with gradient direction orthogonal to the fibres. While the distribution of the values calculated with the quadratic polynomial is relatively homogeneous (a), the use of the cubic polynomial results in a very inhomogeneous distribution and higher absolute values (b).

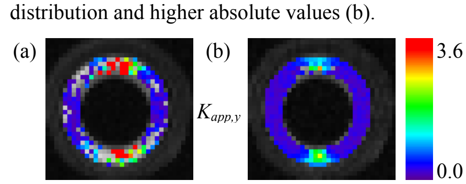

Fig. 3: Kurtosis values projected on the y-axis obtained from the DKT, calculated from a data set with (a) 15/10 and (b) 30/5 directions/averages. The grey pixels inside the fibre ring correspond to negative kurtosis values. In contrast to 30 directions, the calculation using 15 directions is very unstable.

Discussion

The measured kurtosis strongly depends on b_{max} and on the order of the fitting polynomial. Due to the dependence on b_{max} in the entire parameter range, it is not possible to name a b_{max}, where higher orders of the cumulant expansion are completely irrelevant. The use of the cubic fit is not desirable due to the continued dependence on b_{max} and the lack of stability. For comparable results, all the parameters in question have to be maintained constant. For the measurement of the DKT, at least 30 directions should be used. In spite of all these difficulties, the time dependence of the kurtosis (Fig. 4) proves that using a quadratic fit, DKI can yield interesting additional information beyond the Gaussian phase approximation and can be linked with increasing restriction effects at higher diffusion times.

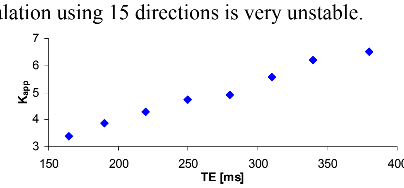

Fig. 4: Dependence of K_{app} on the echo time for a ROI containing the entire phantom using the direction orthogonal to the fibres, b_{max}=10 000 s/mm² and the quadratic polynomial.

References

[1] Jensen et al. MRM 2005; [2] Lu et al. NMR in Biomed. 2006; [3] Laun et al. MRI 2009