

Fibres at the Magic Angle Generated by Inappropriate Calibration (MAGIC)

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Introduction

Constrained spherical-harmonic deconvolution (CSD [1]) assumes the orientation and contribution of fibres modulating a diffusion weighted signal (the Fibre Orientation Density, FOD) can be derived through deconvolution of an idealised (calibrated) spherical harmonic response from one fit to the target signal, in essence solving the “crossing fibres” problem. During application of CSD to tissue comprising of fibres with low anisotropy, we have observed the appearance of multiple spurious peaks in FOD's – even when it is known there is only a single fibre population (fibres aligned along a single axis). These tend to be oriented at the well known 'magic angles' (55° and 125°). In tissue where anisotropy of constituent fibres is particularly low, the spurious FOD peaks can even have sufficient magnitude to produce 'false positives' in tractography (e.g. tracking through non-existent “magic fibres” Fig. 1). On further analysis, these spurious peaks appear to result from inappropriate calibration – i.e. where there is a large difference between the anisotropy of the 'calibration' and target signals. In this study we characterize the effects of calibration disparity on CSD, formulating methods for both prediction and prevention / removal of peaks in the FOD at the magic angle.

Materials and Methods

Single fibre population diffusion-weighted signal data were simulated according to a 60direction [5], $b=2000$ s/mm² scheme for different fibre types with fixed mean diffusivity (0.7×10^{-3} mm²/s) and fractional anisotropies (FA) varying uniformly from 0.1 to 0.9. For all possible calibration/target (C/T) FA pairings, CSD was used to estimate the FOD ($l_{max} = 8$) and all unique peaks extracted.

Fibre tracking algorithms that employ FOD's commonly employ peak-following/termination criteria based on the amplitude of the FOD peak (low magnitude peaks are more likely to be a result of random noise and therefore should not be followed). Thus, we examine the absolute magnitude of the second largest (artefactual) FOD peak as an indicator of possible negative impact on tractography (as only one large peak should exist following deconvolution of a single population signal). Specifically we employ gradient based edge detection (Canny) to discover region boundaries (i.e. the limits on differences in anisotropy of calibration and target signals) to predict when spurious FOD peaks will have negative impact on tractography results.

Preliminary inspection of data revealed circular banding of artefactual FOD peaks with respect to true fibre orientation (i.e. a consistent elevation with dispersed azimuth). For each C/T pairing, the elevation angles (measured with respect to the largest peak (dot product of vectors)) of peaks with sufficiently large magnitude (FOD > 0.1) were derived and the k-means algorithm applied to identify 5 discrete clusters of FOD peaks. Due to the aforementioned constant azimuthal nature of the clusters, we fitted descriptive models to the clusters (Watson girdle/polar distributions projected to azimuthal angles [2]).

Based on our initial observations that spurious peaks tend to occur at predictable elevations, we hypothesized that it should be possible to distinguish between true and spurious fibre indications within these regions. New crossing and single fibre population signals (3 per C/T pairing) were generated at SNR's of 10, 20 and 50. For each SNR level, C/D pairing and signal type, 500 bootstrap samples [4] were generated (randomly selecting one of the 3 choices for each of the 60 directions with replacement) and FOD's derived. From each FOD, the first and second (ignoring antipodes) largest peaks were extracted and the bootstrap group used to generate a probability density function. If the azimuthal angle of spurious data is random as expected, differences in probability densities of the second orientation should be observable.

Results

Secondary peak magnitudes (Fig. 1) demonstrate two distinct linear boundaries described by the lines $T=0.92C - 0.08$ and $T = 0.50C - 1.3 \times 10^{-5}$ respectively (T – target FA, C – calibration FA) with C/T combinations falling below the second line possessing large (FOD > 0.1) peak magnitudes likely to result in significant errors in tractography. Inspection of elevation angles (Fig. 2) reveals three distinct spurious peak clusters with means of 54.7, 90 and 125.3 degrees. As expected, bootstrap analysis indicated that (provided a minimum SNR is achieved), true crossing fibre produces two distinct maxima in the PDF centred about correct orientations (with dispersal according to discrepancy and SNR), whereas in the spurious case, orientational instability of the second peak results in only a single maxima (about the true fibre orientation).

Conclusion and Discussion

The formation of artefactual peaks at specific elevations does not appear to be accidental. Such peaks coincide with the zero crossings (“the magic angle” θ , for which $3\cos^2\theta - 1 = 0$) and minima ($\pi/2$) of the second order Legendre polynomial, suggesting a systematic error in CSD's ability to describe isotropic diffusion. More specifically, we postulate that zero-crossings constitute a “blind spot” in the descriptive capabilities of the second order polynomial, necessitating the use of higher order polynomials to describe the diffusion-weighted signal. As differences between the transverse diffusivities of target and calibration responses increase, the requisite higher order harmonics increase in power until the iterative constrained deconvolution process no longer suppresses the local maxima – resulting in the observed spurious peaks.

We have shown that it is fairly trivial to predict and avoid the appearance of magic fibre effects (i.e. they occur when the anisotropy of the calibration signal exceeds 200% of that of the target). In the majority of applications of CSD, no effects should be observed – but – there are areas of study in which care must be taken. In child developmental studies, for example, early stage FA of the parietal lobe and posterior limb of the internal capsule are approximately 0.33 and 0.71 respectively [3], while applying a simple threshold calibration approach (extract and average the most anisotropic signals for an image to produce an estimated ideal response as in [1]) would produce an adequate result in the posterior limb, reconstruction of the superior longitudinal fasciculus may be misleading (calibration anisotropy being double that of the target) due to the large (C/T) discrepancy involved. Further examples include imaging of maxillofacial muscle (Fig. 1) and the study of pathologies (e.g. ischemic stroke) known to cause local reduction in fibre anisotropy. To eliminate the issue, one would ideally perform tract-specific calibration, i.e. tailoring multiple response functions to each structure of interest; but in cases where this is not possible, adequate results may be achieved through probabilistic tractography (illustrated by the bootstrap analysis).

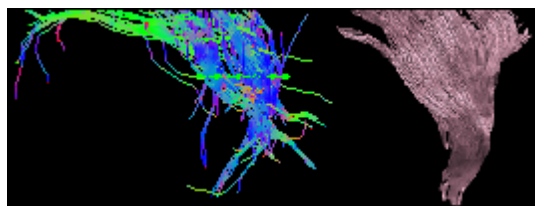


Fig 1: Left: Failed reconstruction of the temporalis muscle due to magic fibre artefacts. Right: Result using appropriate calibration.

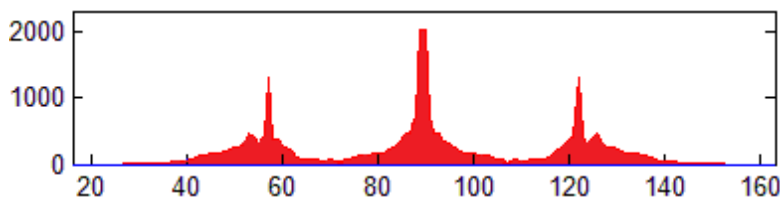


Fig 2: Distribution of high magnitude spurious peaks in relation to Indicated orientation of the true fibre.

[1] Tournier JD *et al* (2004) Neuroimage 23:1176-1185. [2] Fisher *et al*. Statistical analysis of spherical data (1993) Cambridge University Press. [3] Yuji Suzuki *et al*. (2002) NMR in biomedicine. 16:257-260. [4] Tournier *et al* (2007) Neuroimage 35(4):1459-1472 [5] Jones *et al* (1999) MRM 42:515-525