TIME TO MOVE ON: AN FOD-BASED DEC MAP TO REPLACE DTI'S TRADEMARK DEC FA

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Introduction: The directionally-encoded colour (DEC) fractional anisotropy (FA) map is arguably the most iconic and heavily relied upon tool for fast global inspection of anatomical structures in diffusion weighted imaging (DWI) datasets. Originally proposed in 1997[1], the map's 3 DEC vector elements are simply defined as the absolute value of the individual elements of the first eigenvector (FEV)[1,2] of the tensor model obtained from diffusion tensor imaging (DTI). This allows for intuitive interpretation of the map through direct association of red and mediolateral, green and anteroposterior, blue and superoinferior. The map's FA intensity results in a white matter (WM)-like "segmentation" that highlights regions where a single preferred orientation is better defined. Both DEC and FA components, however, are a possible source of misinterpretation. The orientation of the FEV is flawed in regions of crossing fibres, causing misleading DEC cues for individual voxels/regions and "false edges" in the overall map (Fig.1). The FA shows naturally low values in these regions as well[3], causing further confusion when (inadequately) used as a cue to identify, e.g., pathologies. Both of these DTI-specific issues have already been tackled for a long time by higher order strategies; e.g., obtaining the fibre orientation distribution (FOD) from constrained spherical deconvolution (CSD)[4]. We hereby propose an FOD-based DEC map that exploits the FOD's rich angular information.

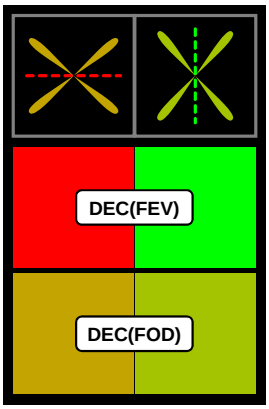

Fig.1: FODs in neighbouring voxels with slightly different angles between FOD lobes (FEV shown as dashed line), and the resulting DEC(FEV) and DEC(FOD) contrasts.

Theory: In what follows, $\mathrm{DEC}(u)$ evaluates to the unit DEC vector of orientation u (as per the established elementwise absolute value colour convention[1,2]). Hence, the DEC component of the DEC FA map is simply obtained by $\mathrm{DEC}(\mathrm{FEV})$. Rather than just obtaining the DEC from a single orientation, we define $\mathrm{DEC}(\mathrm{FOD})$ as an FOD amplitude weighted mix of colours for *all* orientations:

$$\mathrm{DEC}(\mathrm{FOD}) = \oint \mathrm{FOD}(u) \cdot \mathrm{DEC}(u) \cdot \mathrm{d}u \Big/ \left\| \oint \mathrm{FOD}(u) \cdot \mathrm{DEC}(u) \cdot \mathrm{d}u \right\|$$

Note that the "average" DEC resulting from this definition may significantly differ from the single DEC derived from the "average", yet ill-defined, FEV (Fig.1). Instead of weighting the final DEC by an anisotropy measure, we directly employ the FOD's total integral; i.e., we propose $\mathrm{DEC}(\mathrm{FOD}) \cdot \oint \mathrm{FOD}(u) \cdot \mathrm{d}u$ for the final map. Note that this particular weighting does not simply cancel out the denominator of $\mathrm{DEC}(\mathrm{FOD})$, as the triangle inequality applies to this case, yielding $\left\| \oint \mathrm{FOD}(u) \cdot \mathrm{DEC}(u) \cdot \mathrm{d}u \right\| \leq \oint \mathrm{FOD}(u) \cdot \mathrm{d}u$.

Data & processing: DWI data of a single subject were acquired on a Siemens 3T scanner, with a voxel size of 2.5×2.5×2.5 mm³, and using a multi-shell acquisition scheme by applying diffusion weightings of b = 0, 1000, 2000, 3000 s/mm² respectively for 5, 17, 31, 50 directions. An additional b = 0 volume was acquired with reversed phase encoding. The DWI data was preprocessed using a state-of-the-art pipeline, including susceptibility-induced distortion correction using the reversed phase encoding volume[5], combined eddy-current induced distortion and head motion correction[6], and N3 bias-field correction[7]. WM FODs were obtained by applying multi-shell multi-tissue (MSMT) CSD[8] to the DWI data. The normalised $\mathrm{DEC}(\mathrm{FOD})$, as defined above, was calculated using discrete samples of the FODs evaluated for a set of 1281 directions (4th order icosahedral tessellation). This computation only takes a few seconds for the whole dataset. Finally, the normalised $\mathrm{DEC}(\mathrm{FOD})$ was weighted by the total FOD integral. For comparison, we also calculated the $\mathrm{DEC}(\mathrm{FEV})$ map from the tensor model and weighted it by the FA map, resulting in the traditional DEC FA map.

Results & discussion: Fig.2 shows a comparison between the intensity and colour components of the DEC FA and FOD-based DEC map, as well as both weighted DEC maps. Intensity-wise, the main differences are found in crossing fibre regions; e.g., certain regions in the centrum semiovale and a huge part of the cerebellum. Note that the FOD integral is also more meaningful from a microstructural point of view, as it incorporates the apparent fibre density (AFD) interpretation[9] that relates to the total intra-axonal volume in each voxel. Colour-wise, the $\mathrm{DEC}(\mathrm{FEV})$ appears higher contrast, but this is often a false contrast: e.g., the corticospinal tract seems to "cut" through the corpus callosum. The average purple colour of the $\mathrm{DEC}(\mathrm{FOD})$ indicates that they are merely interdigitating. Fig.3 shows a situation akin to Fig.1, where the DEC FA map's colours are misleading and do not match the individual FODs, as well as their spatial continuum. Fig.4 presents an example where the DEC FA (accidentally) matches individual FOD lobe's colours in a crossing region, but "neglects" others, leading to sharp yet false edges. Note that in a clinical setting, these false positive DEC FA features may not only lead to false positive conclusions, but also to false negative ones in case they mask out or otherwise distract the observer's attention from real pathological features. Even when using the FOD-based DEC map, we of course still advise inspection of the FODs for tract-specific information.

Conclusion: The DEC FA map is a fundamental feature of DTI, and is thus affected by its inherent flaws. We propose an FOD-based DEC map that builds on the intuitive "absolute value" colour scheme[1,2], yet fixes major issues of both the DEC FA's colour and intensity by incorporating the FOD's rich angular information.

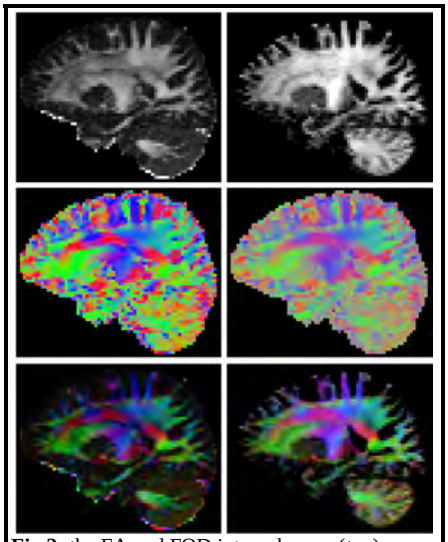

Fig.2: the FA and FOD integral maps (*top*); the $\mathrm{DEC}(\mathrm{FEV})$ and $\mathrm{DEC}(\mathrm{FOD})$ contrasts (*middle*); the DEC FA and FOD-based DEC maps (*bottom*)

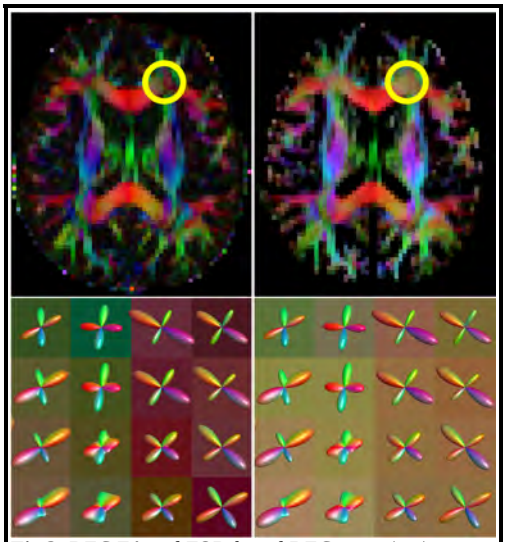

Fig.3: DEC FA and FOD-based DEC maps (*top*); zoomed region of the maps with FOD overlay (*bottom*). Note the misleading colours in the DEC FA map.

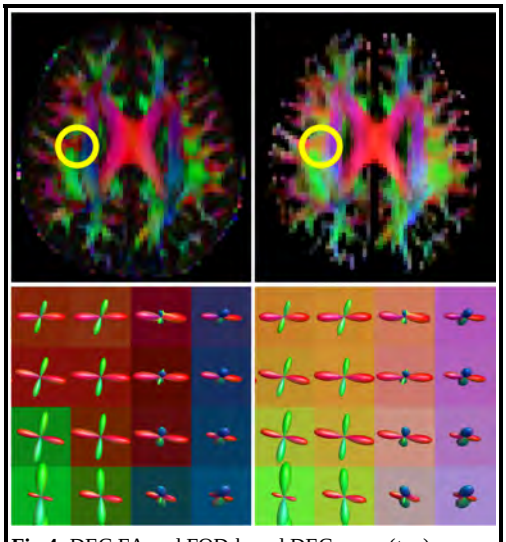

Fig.4: DEC FA and FOD-based DEC maps (*top*); zoomed region of the maps with FOD overlay (*bottom*). Note the false discontinuities in the DEC FA map.

References: [1] Pierpaoli C, Proc. ISMRM 5, 1741 (1997), **[2]** Pajevic S and Pierpaoli C, MRM 42(3), 526-540 (1999), **[3]** Jones DK et al., NeuroImage 73, 239-254 (2013), **[4]** Tournier JD et al., NeuroImage 35(4), 1459-1472 (2007), **[5]** Andersson JLR et al., NeuroImage 20(2), 870-888 (2003), **[6]** Andersson JLR et al., Proc. ISMRM 20, 2426 (2012), **[7]** Tustison NJ et al., IEEE TMI 29(6), 1310-1320 (2010), **[8]** Jeurissen B et al., NeuroImage 103, 411-426 (2014), **[9]** Raffelt D et al., NeuroImage 59(4), 3976-3994 (2012).