Track density imaging (TDI): validation of super-resolution property

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Introduction: Super-resolution track-density imaging (TDI) has been recently introduced as a means to achieve high-quality white matter images, with very high spatial-resolution and anatomical contrast (1). This method achieves super-resolution by using the long-range information contained in the diffusion MRI fibre-tracks; the density of a large number of streamlines provides intra-voxel information to generate an image with higher resolution than that of the acquired source diffusion-weighted imaging (DWI) data (1). Super-resolution MRI methods have been used previously, including controversial applications to DWI (2). All previous methods are based on the more commonly used super-resolution principle: combining images acquired with relative sub-voxel shifts, which is generally accepted can only achieve super-resolution in the slice direction (3). This limitation does not apply to super-resolution TDI since it relies on a different principle. As with any new technique offering super-resolution, the question arises as to the validity of the extra information generated: are the structures that appear following the super-resolution processing an artefact of the previously published ZOOPPA acquisition protocol (5) (1 mm isotropic resolution, 0.8 mm isotropic). This also applies to the 'low resolution' (LR) TDI data (2.4 mm isotropic). For the phantom, the directionally-encoded colour (DIC) version of the TDI maps (1) was used.

Methods: In vivo data: High-resolution DWI data were acquired from a healthy volunteer at 7T (Siemens) using the previously published ZOOPPA acquisition protocol (5) (1 mm isotropic resolution, 60 DW-directions, 6 repeats, acquisition time = 69 min). For anatomical reference, a conventional T1-weighted image (0.8 mm isotropic) was also acquired. In vivo data pre-processing: T1-weighted images were co-registered to T1 data, DWI data were motion-corrected and registered to T1 data. Data were interpolated to the new reference frame with 0.8 mm isotropic resolution; this 0.8 mm DWI data-set will be our reference data-set and referred to as the 'gold-standard' (GS). This GS data-set was down-sampled by a factor of 3 to simulate a DWI data-set that would have been acquired at a lower 2.4 mm isotropic resolution (Fig. 1); this 2.4 mm data-set will be referred to as the ‘low resolution’ (LR) data. In silico data: The numerical Phantom A from the NFG software package (4,6) was used for this study, and DWI data were simulated with b=3000s/mm², 60 DW-directions, 2mm voxel-size, and SNR=17.

Fibre-tracking: Whole brain (or phantom) fibre-tracking was performed using in-house software based on MRtrix (6), including CSD (7) to model multiple fibre orientations, and probabilistic tracking using 2nd order integration over fibre orientation distributions (ifOD2) (8): 1mm step-size, 3 FOD samples/segment, termination criteria: exit the brain/phantom or when FOD amplitude < 0.1. Two million tracks were generated (randomly seeded) for each data-set.

Track-density imaging: TDI maps were generated by counting the number of tracks in each grid-element (Note: grid-elements can be smaller than voxel-size of source data (1)). For the LR in vivo data-set, a 0.8 mm isotropic grid was used with super-resolution TDI (super-TDI<sub>L</sub>), (i.e. 2.4 mm source LR DWI data super-resolved to 0.8 mm TDI map); for comparison, a TDI map without super-resolution (2.4 mm grid) was also created (TDI<sub>L</sub>). For the GS in vivo data-set, the same 0.8 mm grid was used for TDI without super-resolution (TDI<sub>LS</sub> map). Therefore, super-TDI<sub>L</sub> and TDI<sub>LS</sub> have the same resolution, but only the super-TDI<sub>L</sub> map was constructed using super-resolution; by comparing these maps, the effect of super-resolution can be evaluated. A similar analysis was performed for the in silico data (with 0.2 mm grid to generate super-resolution TDI, and 2 mm grid without super-resolution); for the phantom, the gold-standard is given by the known simulated structure (4). Due to the lack of TDI contrast in the phantom, the directionally-encoded colour (DEC) version of the TDI maps (1) was used.

Results: As can be seen in the in vivo (Fig. 2) and in silico examples (Fig. 3), the structures generated by the super-resolution method are consistent with those observed in the gold-standard TDI maps. Note also that these structures are not apparent in the low resolution maps, emphasising the power of the super-resolution TDI. It should be noted that short fibre-bundles tend to have fewer tracks (less seed-points), which leads to reduced TDI intensity (e.g. see relatively low intensity of peripheral short bundles in the phantom).

Discussion: This study validates the super-resolution property of the TDI method. Both the in vivo and in silico data show that the structures that could be identified in the TDI map only after using super-resolution were consistent with the corresponding structures identified in the reference maps. This supports the claim that the structures generated by the super-resolution step are accurate and not an artefact of the super-resolution process itself. This provides further evidence for the important potential role of the super-resolution TDI methodology in neuroscience.