

The anisotropic bias of fractional anisotropy in anisotropically acquired DTI data

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Introduction

For diffusion tensor imaging (DTI), the necessity to acquire a high number of diffusion directions to estimate the tensor orientation robustly [1] means the acquisition time for DTI scans is often long compared to other scans [2]. To shorten the acquisition time, a reduction of spatial resolution is often opted for, with an increase in slice thickness being the most effective option [3-5]. The resulting anisotropic voxel size, however, means that the orientation-dependent diffusion information is sampled in a higher resolution in the acquisition plane (in-plane) than through the acquisition plane (through-plane), which might introduce a bias in diffusion estimates in any subsequent analysis. Fiber bundles with an orientation in-plane will therefore suffer more from the partial volume effect (PVE) than bundles oriented through-plane. Although the inherent shortcoming of anisotropic voxel sizes is common knowledge, the extent of this issue, which may be particularly relevant for longitudinal studies, has not been investigated. In this work, we aim to quantify the effect of varying the anisotropy of the voxel size (while keeping the voxel volume constant) on the estimation of diffusion measures (e.g., fractional anisotropy, FA). Our results show that the bias in FA changes non-linearly with the anisotropy of the voxel size. One can also observe that the FA changes depend on the relation between the bundle (size and position) and the data grid.

Methods

An anterior-posterior (AP) oriented fiber bundle was simulated with 0.025mm isotropic voxel size, FA value of 0.9, with an isotropic background ($3.2 \times 10^{-3} \text{ mm}^2/\text{s}$) [6]. This simulated high-resolution data set was then reconstructed with different anisotropic voxel sizes (but with a constant voxel volume of 2.5^3 mm^3) by decreasing the in-plane voxel size and simultaneously increasing the slice thickness (e.g., with an in-plane resolution of 1.75mm the slice thickness becomes 5.1mm). This procedure was performed separately along the coronal (perpendicular to the bundle) and axial (parallel to the bundle) image planes, reflecting the different acquisition schemes adopted in literature [4,5]. As a reference for the anisotropic voxel sizes, the simulated image was also reconstructed at 2.5mm isotropic voxel size (Fig. 1a). For the coronal slices, increased slice thickness means an anisotropic voxel size with the largest voxel dimension along the main axis of the AP-oriented bundle (Fig. 1b), where the lower voxel size in-plane results in less PVE with surrounding tissue. For the axial slices, on the other hand, increased slice thickness results in an anisotropic voxel size with the long axis perpendicular to the bundle (Fig. 1c), making the PVE with the surroundings more pronounced.



Figure 1: An anterior-posterior oriented fiber bundle is shown. The orientation of the acquisition plane is irrelevant for isotropic voxel sizes (a), but not for anisotropic voxel sizes. In (b) and (c), anisotropic voxel sizes are shown (with equal in-plane resolution and slice thickness), but in (b) the acquisition slice is perpendicular to the bundle (coronal), whereas in (c) the acquisition slice is parallel to the bundle (axial). The resulting difference in partial volume effect with the surroundings can be observed clearly.

Results

Figure 2 shows the FA as a function of slice thickness for both acquisition simulations, i.e., where the image plane is perpendicular (coronal) or parallel (axial) to the bundle. With increasing slice thickness, the in-plane voxel size decreases, and for the coronal slices the reduced PVE results in an increase in FA. Despite the overall increase, the FA oscillates around an increasing value, which is caused by the discrete nature of the grid. Where one maybe would expect the FA to increase monotonously with higher in-plane resolutions, the positioning of the acquisition matrix relative to the fiber bundle ultimately determines the amount of PVE. Consider, for instance, a square bundle of 8mm wide. If this is acquired with an in-plane resolution of 2mm^2 , the bundle fits nicely into an integer number of voxels. Increasing the resolution to 1.5mm^2 , the bundle does not fit into complete voxels, and the outer voxels are partial volume voxels, reducing the average FA of all voxels. The same rationale exists for the oscillation of the observed FA values in axial slices, although an overall FA decrease is observed due to the larger through-plane voxel size perpendicular to the bundle.

Discussion

Several recent DTI studies have opted for larger slice thickness and thus anisotropic voxel sizes (e.g., [3-5]), but, as Figure 2 shows, the FA depends on the interrelation between the anisotropy of the voxel size and the orientation of the fiber bundle. This difference in the anisotropy of the voxel size can even result in FA changes of 15% (depending on the anisotropy of the voxel size), whereas in literature a difference of 5% may already be classified as significant (e.g., [7]). The results presented here for the FA can be generalised to other diffusion measures as well, e.g., mean, axial, or radial diffusivity. Especially with the increasing interest in longitudinal studies [8,9], it is important that any intrasubject morphological changes do not introduce an orientation-dependent bias in diffusion measures. In children, for instance, different brain regions grow in specific stages of development [10,11], which may also result in morphological changes of fiber bundles. Secondly, differences in the positioning of the head at follow-up scans could result in different orientations of the fiber bundle of interest. Given anisotropic voxel sizes, these intrasubject differences in morphology or orientation could bias diffusion measures. By contrast, if the data is acquired isotropically, the diffusion bias is independent of bundle orientation, which would improve the interpretability of DTI data. In summary, we have shown that for data sets acquired with an anisotropic voxel size, the preferential averaging of fiber bundles along a particular axis introduces a significant bias. We therefore believe that in DTI, it is highly desirable to have isotropic voxel size.

References

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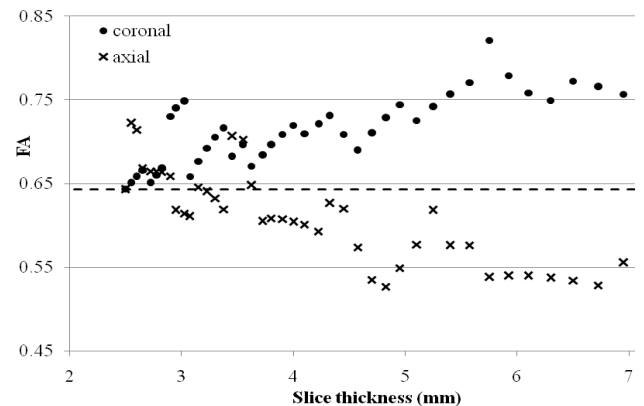


Figure 2: FA as a function of coronal (image plane perpendicular to the fiber bundle) and axial (the axis of the fiber lying in the image plane) slice thickness, while keeping the voxel volume fixed at 2.5^3 mm^3 . The dashed line shows the FA value of the 2.5mm isotropic voxel size.