Evaluation of diffusion acquisition and tractography methods for neurosurgical planning systems

Jonathan Ashmore[1], Flavio Dell'Acqua[2], Ruth O'Gorman[3], Gareth Barker[2], and Jozef Jarosz[1]

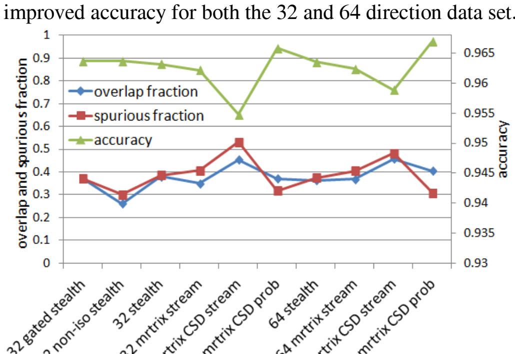
[1]Neuroradiology, Kings College Hospital, London, United Kingdom, [2]Department of Neuroimaging, Kings College London, London, United Kingdom, [3]University Children's Hospital, Zurich, Switzerland

Introduction The use of tractography to inform and guide the surgical resection of space occupying lesions has become increasingly prevalent in recent years. This is partly due to the inclusion of diffusion tensor tractography software into a number of neurosurgical planning systems with regulatory approval for clinical use. Despite being embraced by the neurosurgical community, there are a number of well publicised limitations to the tractography process which can have serious implications with regard to surgical outcome [1]. Considerable research to understand these limitations has been conducted and the resulting studies suggest a number of optimisation strategies for the diffusion acquisition and post processing pipeline. With so many seemingly important refinements to the entire process it can often be difficult for an inexperienced user to know how best to approach initiating a program of tractography for neurosurgical planning. Incorporating all the suggested refinements can lead to long scan times and the requirement for technical expertise for offline processing. To this end, the goal of the work presented here was to investigate some of the well-publicised refinements to both the diffusion acquisition and tractography processing and to assess their importance in reproducing the cortico-spinal tract, a pathway of significant interest to neurosurgeons. Firstly, we investigated changing the number of diffusion encoding directions, acquiring isotropic versus non-isotropic voxels and the effect that cardiac gating has on the resultant tracts. Secondly we compare tracts obtained using a neurosurgical planning system to those from a freely available research tool. Finally we report differences in tract results when more sophisticated methods of post-processing are applied. These include the use of constrained spherical deconvolution (CSD) and probabilistic tractography. The tracts reproduced from each acquisition protocol and postprocessing method are compared to cytoarchitectonic maps of the corticospinal tract which act as a gold standard for its true anatomical location [2].

Methods Diffusion MRI studies were performed on a 1.5T GE HDx MRI scanner, equipped with TwinSpeed gradients (GE Healthcare, Waukesha, WI, USA). The study included 5 volunteers (4 male, age range 23-36 years) who underwent structural and diffusion weighted imaging (DWI). Structural images were acquired with a 3D IR prepared spoiled gradient echo sequence (IRSPGR), TI=300ms, TE=5ms, TR=11.6ms, FA=20, FOV=28cm, 131 slice locations, voxel=1.1x1.1x1.1mm^3, ASSET factor=2. DWI utilized a double refocused spin echo EPI sequence, TR=17s, TE=101ms, FOV=32cm, slices=52, 32 diffusion directions, b-value=1500s/cm^2, 4xb0 images, acquired voxel size 2.5mm^3, reconstructed voxel size 2.5mm^3. This "base" acquisition was subsequently repeated with the following modifications applied separately: (a) 64 diffusion directions with 7xB0 images; (b) peripheral gating to the cardiac cycle with effective TR=15 R-R intervals. (c) reconstructed voxel size, 1.25x1.25x2.5mm^3 (this being the default scanner product sequence). Each diffusion data set was postprocessed using the regulatory approved StealthViz tractography processing software (Medtronic, Colorado, USA) which utilizes a diffusion tensor reconstruction and the FACT streamline tractography algorithm [3]. A seed region was defined within the posterior limb of the internal capsule to only include voxels with diffusion predominantly in an inferior/superior direction as identified on a colour coded fractional anisotropy map. The FA start threshold was 0.2 and stop threshold was 0.1. The 32 and 64 direction datasets with isotropic voxels and no cardiac gating were subsequently re-processed using the mrtrix software package ((http://www.brain.org.au/software/) and tracts were produced using the diffusion tensor and the CSD techniques for both streamline and probabilistic tractography. Probabilistic tractography results were intensity thresholded at 0.5% and all tractograms were converted to nifti format then binarised. Each subject's raw DWI's were aligned to their corresponding structural images using an affine registration (www.fmrib.ox.ac.uk/fsl/FLIRT). The same linear transformation parameters were applied to the corresponding tractography images. Each subject's structural images were then aligned using nonlinear registration (www.fmrib.ox.ac.uk/fsl/FNIRT) to the colin27T1 atlas, the standard space in which the cytoarchitectonic corticospinal tracts are defined. The same nonlinear transformation parameters were applied to the tract images which were previously aligned to the subject's structural image space. In standard space frequency maps were created where the binary tract images were summed across all subjects. The fraction of voxels in the cytoarchitectonic corticospinal tract which overlapped with each tract was calculated and defined as the overlap fraction. The fraction of spurious voxels in each tract which did not overlap with the cytoarchitectonic corticospinal tract were calculated and defined as the spurious fraction. An accuracy score was also calculated, defined as [# true positives + true negatives]/[# true positives + true negatives + false positives + false negatives]

Results Quantitative results are provided in figure 1 and selected tract frequency maps are shown in figure 2. The results indicate that the number of diffusion directions and the use of cardiac gating had little impact on the tractography generated using StealthViz. The use of non-isotropic voxels appeared to moderately decrease the overlap and spurious fractions. This result is verified in figure 2(a) where the blue pathway is visibly thinner with fewer spurious posterior/anterior projections. The quantitative results in figure 1 appear to suggest there is little difference between StealthViz and diffusion tensor streamline tractography from mrtrix. Furthermore there was little difference between 32 and 64 direction data when processed with StealthViz. For the more sophisticated post processing methods streamline tractography with CSD produces the greatest overlap fraction but correspondingly the greatest spurious fraction. The accuracy score in figure 2, indicated that CSD with probabilistic tractography has an improved accuracy for both the 32 and 64 direction data set.

Figure 1. Overlap fraction, spurious fraction and accuracy for the various acquisition and tractography methods



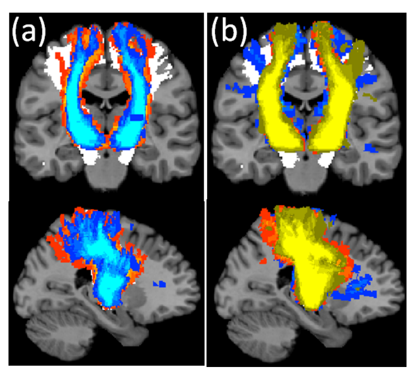


Figure 2. Tract frequency maps in standard space comparing (a) isotropic voxels (red) vs non-isotropic voxel (blue). (b) mrtrix DTI streamline tractography (red), mrtrix CSD streamline tractography (blue) and mrtrix CSD probabilistic tractography (yellow). Cytoarchitectonic maps of the corticospinal tract are shown in white

Discussion We report initial results for the validation of tractography against cytoarchitectonic maps of the corticospinal tract. Our results suggest the neurosurgical planning tool StealthViz provides similar tract results to mrtrix DTI streamline tractography, neither though fully depicts the complete extent of the corticospinal tract compared to the cytoarchitectonic maps. When comparing different acquisition protocols we found that tractography generated from DWI with isotropic voxels had an improved overlap with the cytoarchitectonic maps compared to non-isotropic voxels. Our in-vivo results agree with software models which similarly indicate that non isotropic voxels lead to a bias in tractography of the corticospinal tract [4]. Applying cardiac gating did not exhibit a significant effect on the accuracy of tractography, however cardiac gating may be more significant for tracts affected by the pulsatility of blood or CSF (e.g. corpus callosum). CSD based streamline tractography from mrtrix provided the largest overlap fraction with a corresponding high number of spurious pathways, a result in agreement with published studies [5]. We found that CSD based probabilistic tractography provided the best compromise between overlap and spurious fractions leading to the highest accuracy. This tractography technique is not available in any regulatory approved neurosurgical packages and hence the results from this study may provide justification for the clinical use of non-CE marked software within the EU.

References [1] Kinoshita M. et.al. NeuroImage 25:424 (2005) [2]. Burgel U. et.al. NeuroImage 29:1092 (2006) [3] Burgel U. et.al. Cent. Eur. Neurosurg 70:27 (2009) [4] Neher P.F. ISMRM 3166 (2013) [5] Farquharson S. et.al. J Neurosurg 18:1367 (2013)