Performance of deterministic and probabilistic Diffusion Tensor and Q-Ball Corticospinal Tractography in Brain Tumor Patients

M. Bucci[1], M. Mandelli[2], J. I. Berman[3], B. Amirbekian[4,5], C. Nguyen[3], M. S. Berger[6], and R. G. Henry[3]

[1]Radiology and Biomedical Imaging, University of California San Francisco, San Francisco, CA, United States, [2]Department of Neuroradiology, Istituto Neurologico Carlo Besta, Milano, Italy, [3]Radiology and Biomedical Imaging, University of California San Francisco, [4]Radiology and Biomedical Imaging, University of California, San Francisco, [5]UC Berkeley and UCSF Graduate Program in Bioengineering, [6]Department of Neurological Surgery, University of California San Francisco

INTRODUCTION: There has been a tremendous interest in the use of Diffusion MR fiber tracking for presurgical mapping of eloquent regions. Intraoperative electrical stimulation (IES) provides a clinical gold standard for the existence of functional motor pathways that can be used to determine the accuracy and sensitivity of fiber tracking algorithms. Diffusion tensor imaging (DTI) utilizes the tensor model in which white matter tracts are assumed to follow the principal diffusion direction (PDD) defined by the principal eigenvector of the fitted tensor. The Q-Ball reconstruction of high angular resolution diffusion imaging (HARDI) data generates an orientation distribution function (ODF) that can discriminate multiple crossing white matter fiber populations [Hess 2006; Tuch 2003, 2004]. The peaks of the ODF are assumed to point in the direction of white matter tracts. Deterministic fiber tracking methods, including fiber assignment by continuous tracking (FACT), use a linear propagation approach, proceeding according to the principal eigenvector direction [Mori 2002]. Probabilistic streamline fiber tracking methods incorporate the uncertainty of diffusion MR measurements to propagate according to a probability distribution function [Lazar and Alexander 2003, 2005; Jones and Pierpaoli 2005; Parker 2003]. Here we used the residual bootstrap, a non-parametric statistical technique based on data re-sampling that has been showed to accurately estimate the uncertainty in diffusion data [Chung 2006; Berman 2008]. In this work we used IES data as gold standard to evaluate the accuracy and sensitivity of deterministic and probabilistic propagation with DT and Q-Ball fiber tracking.

METHODS: We used preoperative HARDI data (55 directions, b=2000 s/mm^2, sense factor = 2) acquired in a clinically feasible time frame from 13 patients who underwent a craniotomy for resection of a cerebral glioma to obtain corticospinal fiber tracts with both deterministic and probabilistic Diffusion Tensor and Q-Ball fiber tracking methods. We used 21 cortical and 6 subcortical IES sites as a gold standard for the presence and location of functional motor pathways. We tracked from the cerebral peduncle to the cortical stimulation sites from IES and vice versa, thereby determining the false negative rate of connectivity for the various algorithms. For accuracy and precision of the course of the fiber tracts, we measured the distance between the sub-cortical stimulation site and the nearest edge and center of the tractography of corticospinal fiber tract.

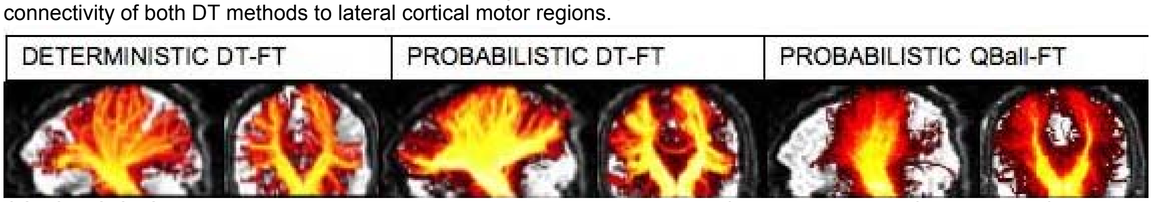
RESULTS: Percent of expected connections found when tracking from the cerebral peduncle to the motor cortex stimulation sites (CP->MC) and from motor cortex stimulation sites (MC->CP) to the cerebral peduncle with the various fiber tracking algorithms. Connectivity was higher with the Q-Ball versus DT fiber tracking and with probabilistic versus deterministic propagation. Lower connectivity was found to the face/mouth regions compared to Hand/Upper Extremities sites for all algorithms.

	Probabilistic Q-Ball-FT CP->MC / MC->CP	Deterministic Q-Ball-FT CP->MC / MC->CP	Probabilistic DT-FT CP->MC / MC->CP	Deterministic DT-FT CP->MC / MC->CP
Face/Mouth	63% / 75%	38% / 62%	38% / 62%	0% / 0%
Hand/Upper Extremities	92% / 85%	62% / 38%	38% / 31%	15% / 23%
All Motor Sites	81% / 81%	52% / 48%	38% / 43%	10% / 14%

Probabilistic Q-Ball fiber tracks were the closest to the subcortical stimulation sites and also had the best precision as indicated by the standard deviation across subjects. Probabilistic DT fiber tracking had the poorest precision especially for detection of the edge of the predicted fiber track and compared to deterministic DT fiber tracking seems to result in a less reliable spread of the fiber track. While the track widths were larger for the Q-Ball methods, these gave consistent results across subjects and therefore have good predictive power for locating the CST intraoperatively.

	Probabilistic Q-Ball-FT edge / center	Deterministic Q-Ball-FT edge / center	Probabilistic DT-FT edge / center	Deterministic DT-FT edge / center
Mean displacement	4mm / 15mm	6mm / 14mm	5mm / 14mm	8mm / 12mm
Standard deviation	3mm / 4mm	4mm / 4mm	5mm / 4mm	3mm / 4mm
Track Width mean (sd)	10 (3) mm	8 (3) mm	7 (6) mm	4 (2) mm

DISCUSSION: Currently, there are different methods available for fiber tracking but only with few methods it is possible to quantify the accuracy and precision in clinical applications. This study highlights the importance of the validation and quantification of preoperative fiber tracking methods, with the aid of electrophysiological data during the surgery, in adverse pathological conditions where the normal architecture of the fibers can be altered. In our study, using cortical and subcortical stimulation sites from IES as a gold standard, we compared deterministic and probabilistic DT-FT and Q-Ball algorithms. The knowledge of known functioning cortical motor sites allows determination of the false negative rate of connectivity, which reflects the accuracy of the tractograms. The subcortical stimulation sites enable determination of the accuracy and precision of the subcortical course of the predicted CST. In particular the precision of these predictions determines the predictive power about the location of the CST intraoperatively. Similar quantitative methods need to be developed to evaluate the specificity of these algorithms. Even though probabilistic DT-FT has shown improved sensitivity over deterministic DT tractography, the relative specificity of both DT based algorithms tends to be much worse than the better Q-Ball model. This is illustrated below in the maximum intensity projections for fiber tracking from the cerebral peduncle without targeting. Both DT methods show erroneous tracks to frontal and parieto-occipital regions while the probabilistic Q-Ball does not. Furthermore, these figures illustrates the lack of connectivity of both DT methods to lateral cortical motor regions.



CONCLUSIONS: Intraoperative stimulation data provide a valuable tool for determination of sensitivity of preoperative fiber tracking methods by indicating the presence and location of functioning pathways. There is significant improvement in the ability to delineate corticospinal tracts preoperatively in brain tumor subjects with Q-Ball compared to DT fiber tracking. The gain is particularly significant for lateral pathways connecting the upper extremities and face/mouth regions, as we have studied here. Probabilistic implementations of these algorithms further boost the sensitivity of these methods, but with a potential increase in false positive connections. This is especially true for probabilistic DT fiber tracking where the inadequacies of the diffusion tensor model result in widely varying and unrealistic propagation directions.