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Comparison of seeding methods for visualization of the corticospinal tracts using single tensor tractography

Alireza Radmanesh [a,*], Amir A. Zamani [a], Stephen Whalen [b], Yanmei Tie [b], Ralph O. Suarez [b], Alexandra J. Golby [b]

[a] Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston 02115, USA
[b] Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, Boston 02115, USA

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ABSTRACT

Objectives: To compare five different seeding methods to delineate hand, foot, and lip components of the corticospinal tract (CST) using single tensor tractography.
Methods: We studied five healthy subjects and 10 brain tumor patients. For each subject, we used five different seeding methods, from (1) cerebral peduncle (CP), (2) posterior limb of the internal capsule (PLIC), (3) white matter subjacent to functional MRI activations (fMRI), (4) whole brain and then selecting the fibers that pass through both fMRI and CP (WBF-CP), and (5) whole brain and then selecting the fibers that pass through both fMRI and PLIC (WBF-PLIC). Two blinded neuroradiologists rated delineations as anatomically successful or unsuccessful tractography. The proportions of successful trials from different methods were compared by Fisher's exact test.
Results: To delineate hand motor tract, seeding through fMRI activation areas was more effective than through CP ($p < 0.01$), but not significantly different from PLIC ($p > 0.1$). WBF-CP delineated hand motor tracts in a larger proportion of trials than CP alone ($p < 0.05$). Similarly, WBF-PLIC depicted hand motor tracts in a larger proportion of trials than PLIC alone ($p < 0.01$). Foot motor tracts were delineated in all trials by either PLIC or whole brain seeding (WBF-CP and WBF-PLIC). Seeding from CP or fMRI activation resulted in foot motor tract visualization in 87% of the trials (95% confidence interval: 60–98%). The lip motor tracts were delineated only by WBF-PLIC and in 36% of trials (95% confidence interval: 11–69%).
Conclusions: Whole brain seeding and then selecting the tracts that pass through two anatomically relevant ROIs can delineate more plausible hand and lip motor tracts than seeding from a single ROI. Foot motor tracts can be successfully delineated regardless of the seeding method used.

1. Introduction

Diffusion-tensor imaging (DTI), despite its limitations and critics [1], has proven useful for preoperative planning and intra-operative guidance in neurosurgery [2,3], especially in combination with neurophysiological subcortical mapping [4,5]. Diffusion tensor remains the most commonly used model in streamline tractography in commercially available neuronavigational platforms.

Delineation of the corticospinal tracts (CSTs) by Diffusion tensor tractography is a useful tool in preoperative planning for surgical lesions that are located close to the pyramidal tract to avoid or predict postoperative motor deficits [6,7]. Such delineation is of utmost importance considering the pivotal functional role of the motor tracts. However, hand and face components of the CST are known to be technically challenging to delineate using conventional tractography methods [8,9].

A wide range of methods, including the "gold standard" intraoperative neurophysiologic techniques, have been used for functional motor mapping of the human cortex and depicting a "motor homunculus" [10,11]. Based on the anatomic motor homunculus, foot, hand, and face components of the CST are expected to originate from different areas of the precentral gyrus. These cortical areas can be determined noninvasively by functional magnetic resonance imaging (fMRI). In order to seed the CST, the cerebral peduncle (CP) has been commonly used as the anatomic region of interest (ROI) [12,13]. However, seeding from the CP and using the conventional single-tensor tractography often results in depicting only a subset of CST that propagates vertically to

* Corresponding author. Present address: Department of Radiology & Biomedical Imaging, University of California, San Francisco, USA. Tel.: +1 4155702353; fax: +1 415 353 8593.
E-mail address: alireza.radmanesh@ucsf.edu (A. Radmanesh).

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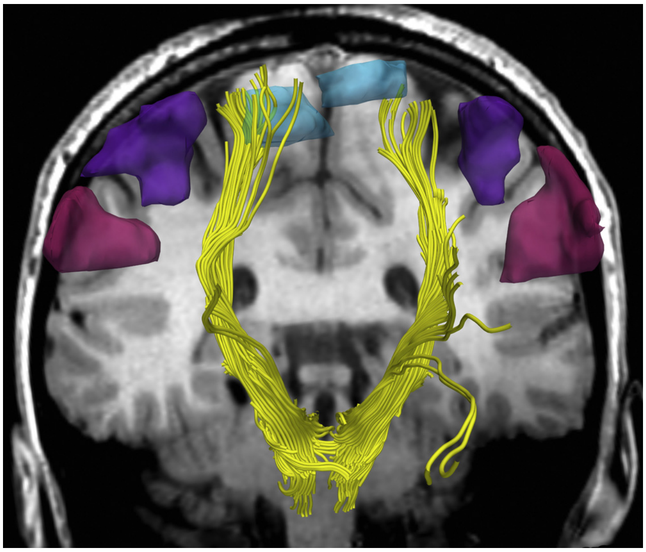

Fig. 1. Tractography of the corticospinal tract in a healthy subject determined from seeding in the cerebral peduncle. FMRI was used to define primary motor cortex for the foot (blue), hand (purple), and lip (magenta). This seeding region resulted in delineation of the portions of the CST linking to the motor cortex subserving the lower extremity. However, the hand and lip portions of the CST were not delineated.

the parasagittal cortex, and according to the motor homunculus, mainly serves lower extremity motor function. This can be visually confirmed by aligning the fMRI activation areas (obtained during hand clenching, foot tapping, or lip pursing) with the anatomical image that contains tracked fibers (Fig. 1). Depicted CSTs by other authors using streamline deterministic approach show the same issue [2,3,9].

Probabilistic tracking algorithm and q-ball diffusion models have been shown to offer better sensitivity in delineating CST compared to the deterministic DTI fiber tracking approach [14]. While significant advantage of such methods in clinical applications require further validation using larger case studies, most commercially available neuronavigational platforms still use the deterministic DTI approach. Therefore, optimizing modifications of this method remain desirable for patient care at least for the years to come.

Researchers have used two different approaches to optimize deterministic DTI method. One is to use alternative tractography methods such as two-tensor model instead of conventional single-tensor tractography [15,16]. Despite suggested advantages of such models, they are difficult to implement and are computationally intensive. The second approach involves optimization of the seeding method for the single-tensor tractography, as we investigate here. Ideally these two approaches could be combined.

To seed the CST, some authors have used the PLIC as an ROI [3]. Others have used fMRI activation and its subjacent white matter as an ROI for tractography and reported promising preliminary results [17–21]. Another possible approach involves seeding in the whole brain and then selecting the fibers that pass through relevant ROIs [22–24]. Although two-ROI approach, also known as Brute-Force, has been shown to increase the validity of tractography in animal model [25], to the best of our knowledge, within subject comparison between multiple different seeding methods for delineation of the CST has not previously been published. In this study we tested five different seeding approaches for delineating the hand, foot, and lip (perioral) motor fibers, and empirically determined which method provided more comprehensive delineation of the motor tracts.

Table 1
Gender/age (in years), tumor type, and tumor location in participating patients.

	Gender/Age	Tumor type	Tumor location
1	M/35	Oligoastrocytoma (II)	Right frontal
2	M/38	Metastasis	Right frontal
3	M/38	Metastasis	Right frontal
4	F/64	Meningioma	Left frontoparietal
5	M/33	Metastasis	Left parietal
6	M/25	GBM	Right parietal
7	F/67	Glioma (low grade)	Right frontal
8	M/22	Oligodendroglioma (II)	Left frontal
9	F/37	Astrocytoma (II)	Left parietal
10	F/54	GBM	Left frontal

2. Materials and methods

Fifteen subjects were studied, including five healthy volunteers and ten brain tumor patients. This study was approved by the Institutional Review Board of the Partners Healthcare System. Written informed consent was obtained from all participants.

Gender/age (in years) for the healthy subjects 1–5 were M/38, F/29, M/28, F/26, and F/25, respectively. Gender, age, tumor type, and tumor location for the patients are listed in Table 1. The patients were scanned prior to undergoing surgical resection of solitary intracranial lesions. These lesions included nine intra-axial tumors and one left frontoparietal meningioma. In the case of meningioma, fMRI and tractography were considered relevant given the location of the tumor and mass effect on the cortical/subcortical portions of the motor pathway.

2.1. Data acquisition and analysis

MR imaging was performed with a 3T scanner (Signa system with Excite 14.0; General Electric, Milwaukee, WI).

a) *Anatomical imaging:* Whole brain T1-weighted axial spoiled gradient-recalled (SPGR) images were acquired with an eight-channel head coil (TR/TE 7500/30 ms; matrix 256×256; field of view (FOV) 25.6 cm; flip angle 20°; 124 contiguous sections).

b) *Functional imaging:* Blood oxygen-level-dependent (BOLD) functional imaging was performed using a quadrature head coil with a T2*-weighted echo-planar imaging (EPI) sequence (in-plane spatial resolution $2 \times 2\,\text{mm}^2$; TR/TE 2000/40 ms; matrix 128×128; FOV 25.6; flip angle 90°; slice thickness 4 mm; 27 interleaved slices). For mapping motor areas, the tasks were self-paced at each subject's comfort level. However, when we explained the tasks to the subjects prior to scanning, we described them as about 1 hand clench, toe wiggle, or lip purse per second for all healthy subjects and patients. The fMRI paradigm consisted of a blocked design of alternating task blocks (hand clenching, foot tapping, and lip pursing) and rest blocks. In each motor task, four task blocks (30-s duration) were interleaved with three rest blocks (10-s duration). For healthy subjects, the tasks were performed for both left and right hand and foot. For patients, depending on the tumor location and clinical suspicion of motor involvement, the tasks were selectively performed for body parts and lateralization corresponding to the lesion location. After image reconstruction, Statistical Parametric Mapping software (SPM2) (Wellcome Centre, London, UK) was used for motion correction to preprocess the data and single subject fMRI analysis. Individually determined threshold was used for each subject, such that BOLD activation was observed within the primary motor cortex. We used an extent threshold of 10 voxels, and smoothing was 6 mm. Both the mean functional image and the anatomical high resolution 3D-SPGR were subsequently registered to the baseline diffusion-weighted imaging (DWI) scan using mutual information rigid registration [26] implemented in 3D-Slicer version 3.6 (www.slicer.org). For all subjects a