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White matter tractography for neurosurgical planning: A topography-based review of the current state of the art

Walid I. Essayed[a,b,*], Fan Zhang[a], Prashin Unadkat[a], G. Rees Cosgrove[a,b], Alexandra J. Golby[a,b], Lauren J. O'Donnell[a,**]

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

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ABSTRACT

We perform a review of the literature in the field of white matter tractography for neurosurgical planning, focusing on those works where tractography was correlated with clinical information such as patient outcome, clinical functional testing, or electro-cortical stimulation. We organize the review by anatomical location in the brain and by surgical procedure, including both supratentorial and infratentorial pathologies, and excluding spinal cord applications. Where possible, we discuss implications of tractography for clinical care, as well as clinically relevant technical considerations regarding the tractography methods.

We find that tractography is a valuable tool in variable situations in modern neurosurgery. Our survey of recent reports demonstrates multiple potentially successful applications of white matter tractography in neurosurgery, with progress towards overcoming clinical challenges of standardization and interpretation.

1. Introduction

The visualization of the brain's white matter pathways via diffusion magnetic resonance imaging is receiving increasing attention for neurosurgical planning, as these methods can allow preoperative, three-dimensional, non-invasive, in vivo demonstration of the location and trajectory of white matter tracts. White matter tractography (WMT), as a way for spatially analyzing the brain's white matter, can guide surgical planning in different settings, not only directly when important white matter tracts are involved in the vicinity of the resection cavity of a superficial lesion, but also indirectly when targeting a deeply located lesion or functional structure through probable eloquent white matter. However, validity and reliability issues are hindering tractography's widespread implementation. Consequently, the challenge facing precursor "tractography teams" is demonstrating the real clinical value of tractography in a clinical and surgical setting. For a clearer overview of the current state of the art techniques and clinical impact of modern tractography, we propose to critically review existing studies of tractography methods for neurosurgical planning. A high variability of anatomical, technical, and surgical particularities is faced when summarizing the ever-increasing array of challenging conditions to which modern tractography can be applied.

In this review, we propose to classify the cited reports as supratentorial or infratentorial pathologies (Fig. 1). Supratentorial pathologies will be subdivided into neoplastic, vascular, or functional indications, while reports involving infratentorial pathologies will be grouped according to their anatomical location: brainstem, cerebellum, and cranial nerves (Fig. 1). This review process is not exhaustive and will focus on reports analyzing WMT for surgical planning. For each pathology or location, we report the most recent pertinent publications examining the relevant key tracts.

As reproducibility and standardization across the different methods and teams are of high interest in the field of WMT, we report and discuss the different technical challenges described in the cited reports. By providing a longitudinal locations and pathologies based view of new published research, this review is aimed at clinicians, technical researchers generally interested in tractography, and investigators with interest in a specific disease.

2. General technical considerations

It is useful to have some familiarity with the techniques available for performing WMT, both to better appreciate the contents of this review and to assess the potential utility of future advances. We note that

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Abbreviations: DBS, Deep brain stimulation; DES, Direct electrical stimulation; DTT, Direct tract targeting; FA, Fractional anisotropy; FN, Facial nerve; WMT, White matter tractography

* Correspondence to: W. I. Essayed, Brigham and Women's Hospital, Department of Neurosurgery, 75 Francis street, Boston, MA 02215, USA.
** Correspondence to: L. J. O'Donnell, Harvard Medical School, 1249 Boylston St., Room #210, Boston, MA 02215, USA.
E-mail addresses: wibnessayed@bwh.harvard.edu (W.I. Essayed), odonnell@bwh.harvard.edu (L.J. O'Donnell).

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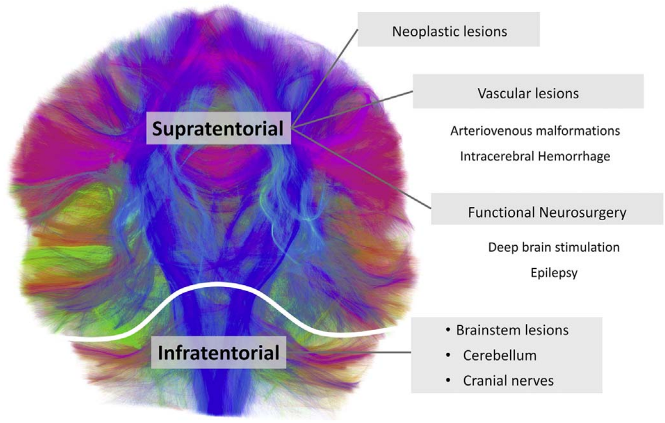

Fig. 1. Illustration of the anatomical subdivision structuring this report.

mathematical modeling of the white matter fibers from diffusion MRI data, development of WMT methods, and testing and validation of these methods are still open areas of research (Pujol et al., 2015). Several in-depth review articles are available (Assaf and Pasternak, 2008; Jones et al., 2013; O'Donnell and Westin, 2011), including recent neurosurgery-specific reviews and commentaries (Bi and Chiocca, 2014; Nimsky et al., 2016a), so here we present a brief overview of the most relevant considerations, which include data acquisition, fiber modeling, fiber reconstruction, and expert interpretation including choices of seed regions and stopping thresholds.

The most important parameters during the data acquisition are the number of gradient directions and the b-value. The number of gradient directions is the number of magnetic field gradients used to encode diffusion-weighted images, and the b-value is a factor representing the amount of diffusion weighting, which relates to the strength and timing of the gradients (Hagmann et al., 2006). The most common and widely used diffusion model, diffusion tensor imaging (DTI) (Basser et al., 1994), typically employs 30 or fewer gradient directions at a b-value near 1000 s/mm^2. Larger numbers of gradient directions and higher or multiple b-values can increase angular resolution and provide information about multiple diffusion compartments to improve the accuracy of fiber tracking estimation (Alexander et al., 2007; Jones, 2004). The field of diffusion imaging is rapidly evolving. Current advanced acquisitions may include high angular resolution (HARDI) (Tuch et al., 2002), which generally has a higher number of gradient directions than DTI and may have b-values over 1000, diffusion spectrum imaging (DSI) (Wedeen et al., 2008), which uses multiple b-values up to 7000 s/mm^2 or higher to sample q-space in a grid fashion, and multi-shell acquisitions that acquire multiple b-values (sampling spherical shells in q-space). Another consideration during acquisition is the possible presence of spatial distortions in the echo-planar imaging (EPI) diffusion MRI scan on the order of 2 mm (Treiber et al., 2016), which can affect WMT (Jones and Cercignani, 2010). Regions near air-bone interfaces, such as the orbitofrontal cortex, temporal poles, and brain stem, were the regions most affected by DWI distortion in a recent study of 250 brain tumor patients (Treiber et al., 2016). Advanced acquisitions using phase encoding gradients of opposite polarity are designed to address this but are not yet widely used clinically (Irfanoglu et al., 2015; Van Essen et al., 2013).

Another technical consideration is the type of mathematical modeling used for fiber reconstruction. DTI enables single-fiber reconstruction, which accounts for one fiber tract per voxel, an anatomically implausible scenario (Duffau, 2014; Jeurissen et al., 2013; Nimsky, 2014). In contrast, multi-fiber reconstruction can enable tracking though crossing fiber regions. Multi-fiber models, such as q-ball (Fernandez-Miranda et al., 2012; Tuch, 2004) (also called high-definition fiber tractography (Fernandez-Miranda et al., 2012)), constrained spherical deconvolution (CSD) (Descoteaux et al., 2009; Farquharson et al., 2013; Mormina et al., 2015; Smith et al., 2013; Tournier et al., 2011), and multi-tensor models (Chen et al., 2015; Chen et al., 2016a; Malcolm et al., 2010), can be beneficial for neurosurgical planning with the potential of an accurate reconstruction of white matter fiber tracts. Note that the more complex models have MRI acquisition requirements, and it is important to use a model that is appropriate for the available data (Ning et al., 2015).

The next technical concern is the choice of a method to compute the tractography. While multiple computational tracking methods are available, the most popular can be categorized as either deterministic or probabilistic. Both methods can start from a point in the brain and trace connections. However, in general, deterministic methods generate a single fiber connection from the start point (Basser et al., 2000), while probabilistic methods aim to detect many possible connections from the start point (Behrens et al., 2007). Often, deterministic methods are visualized as curved lines (streamlines), while probabilistic methods may output a map of connection probabilities. New research in tractography, including microstructure-informed (Daducci et al., 2016), global (Mangin et al., 2013), and machine learning tractography (Neher et al., 2015), has promise for the future.

A final important consideration is the expert processing and interpretation of tractography. Many choices must be made at this step, including tract seeding, tract selection, stopping thresholds, and final interpretation of results. These choices have a large effect on the final tractography output.

Tract seeding (initiation of tractography) and selection (choosing fibers from already-created tractography data) have been studied extensively. For deterministic tractography, it has long been known that the most robust, reproducible seeding method is the “brute-force” or “holistic” approach that seeds tractography in the entire brain and then employs multiple expert regions of interest (ROIs) to select tractography (Huang et al., 2004; Wakana et al., 2007). However, whole-brain seeding may not always be practical clinically, and therefore smaller seeding ROIs or fast interactive seeding may be useful (Chamberland et al., 2014; Golby et al., 2011). Of note is the fact that an optimal seeding region will depend not only on the neuroanatomy, but also on the tractography method. For example in the corticospinal tract of patients with brain tumors, deterministic methods are generally best seeded in a large region of white matter and not in the cortex where diffusion anisotropy is low (Radmanesh et al., 2015), while probabilistic methods are often seeded many times within specific regions in the brainstem and cortex (Farquharson et al., 2013; Niu et al., 2016). Many studies have provided guidelines for ROI placement or anatomical atlas usage to define fiber tracts (Catani and Thiebaut de Schotten, 2008; Lawes et al., 2008; Wakana et al., 2004; Wassermann et al., 2016), though methods that rely on normal neuroanatomy may not produce sufficient results in patients with tract displacement due to mass lesions (Schonberg et al., 2006). Specifically in patients with brain tumors, several groups have investigated optimal structural and functional ROIs for tract seeding and selection of the corticospinal tract (Holodny et al., 2001a; Niu et al., 2016; Radmanesh et al., 2015; Schonberg et al., 2006; Weiss et al., 2015). However, even when the ROIs are held constant, there is known variability in tract selection across expert raters and across tractography methods (Burgel et al., 2009; Colon-Perez et al., 2016). This has led to neurosurgical planning research into standardization using automated placement of ROIs and automated identification of key tracts based on their trajectories (O'Donnell et al., 2017; Tunc et al., 2015; Zhang et al., 2008).

In addition to the seeding and selection regions, the thresholds for starting and stopping WMT are important choices. Early investigations demonstrated that lowering the fractional anisotropy (FA) threshold could enable increased tracking in edema and tumors (Akai et al., 2005; Schonberg et al., 2006). Today, each state-of-the-art multi-fiber WMT method relies on a different threshold, which is necessarily specific to the fiber model and tractography framework (e.g. fiber orientation distribution (FOD) based thresholds, apparent fiber density, generalized