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# Comparing Voxel- and Streamline-Based Paradigms In Clinical Tractography

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## ABSTRACT

Tractography has become more widely used in neurosurgical planning, yet traditional voxel-based Region of Interest (ROI) segmentation often includes anatomically implausible fibers and becomes challenging with distorted anatomy near lesions. This study evaluates the paradigm shift from voxel- to streamline-based tractography for reconstructing the Arcuate Fasciculus (AF) and Inferior Fronto-Occipital Fasciculus (IFOF), using Constrained Spherical Deconvolution (CSD) with both deterministic and probabilistic tracking. Both approaches are evaluated for robust, clinically meaningful bundle reconstructions.

Tractograms were generated using deterministic and probabilistic CSD methods, with 0.5 to 8M streamlines, from ten patients diffusion MRI data. Bundles were segmented using BundleSeg with a voxel-wise and a streamline-based atlas. Morphological fidelity was assessed using volume, shape descriptors (elongation, diameter, fractal dimension, irregularity), and Bundle Shape Similarity (BSS).

Streamline-based atlas produced compact, coherent bundles, while voxel-wise atlas generated larger volumes with less anatomically constrained fibers. Trunk volumes are approximately stable across streamlines number except for probabilistic voxel-wise atlas. Shape metrics confirm the intrinsic difference of the two atlases, with lower surface irregularity and fractional dimension for the streamline-based approach, emphasized by higher average length and elongation, then enhanced continuity. Deterministic CSD achieved higher shape fidelity with clinical references (BSS ≈0.6–0.8) compared to probabilistic methods (BSS ≈0.2–0.4). Shape and volume metrics stabilized ~2M streamlines. Voxel- and streamline-based segmentations seem to be complementary: volume for safety, streamlines for tract geometry.

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## INTRODUCTION

Tractography has become an important tool in clinical practice for preoperative neurosurgical planning. A wide range of tools is currently available: some of them are fully automated –enabling faster and smoother workflow- whereas others have been developed by individual research groups integrating libraries and packages widely available online.
The design and optimization of a tractography pipeline involve several aspects, that may substantially influence the reconstruction, from image processing to streamline reconstruction and tracts segmentation.
Streamline generation and segmentation plays a crucial role in tract reconstruction, as they shapes the morphology and the extent of reconstructed tracts, as well as their underlying anatomical representation. Different segmentation paradigms reflect distinct clinical approaches and are based on different topological assumptions underlying tract reconstruction.
This study investigates the shift **from voxel-wise to streamline-based segmentation** and evaluates its clinical impact on the reconstruction of two major tract: the **arcuate fasciculus** (AF) and the **inferior fronto-occipital fasciculus** (IFOF) in healty brain region. Resulting tracts are quantitatively compared varying both the number of generated streamlines and the tracking deterministic or probabilistic approach within a CSD reconstruction framework.

## METHODS AND MATERIALS

Tractograms were generate using a CSD algorithm (Mrtrix) with a streamlines number of 0.5, 1, 2, 4 and 8 Million, on 10 patient MRI diffusion data. Bundles were segmented using the BundleSeg algorithm which supports different atlases. The two atlases compared are one derived from TractSeg data (voxel-wise) and the Yeh atlas (streamline-based).
Reconstruced bundles were compared using the Scilpy *shape measure* function, that provide volumetric and shapes descriptor for each tract.
Among all the metrics provided, the analysis focused primarly on volume (**total and trunk volume**) as well as shape descriptors related to tract morphology and structural complexity as **elongation**, **fractal dimension** and **irregularity**.
Resulting metrics are compared with those obtained from **manual** segmentation performed by an experienced neurosurgeon, which is used as a **reference** standard and also provide as a normalization factor.

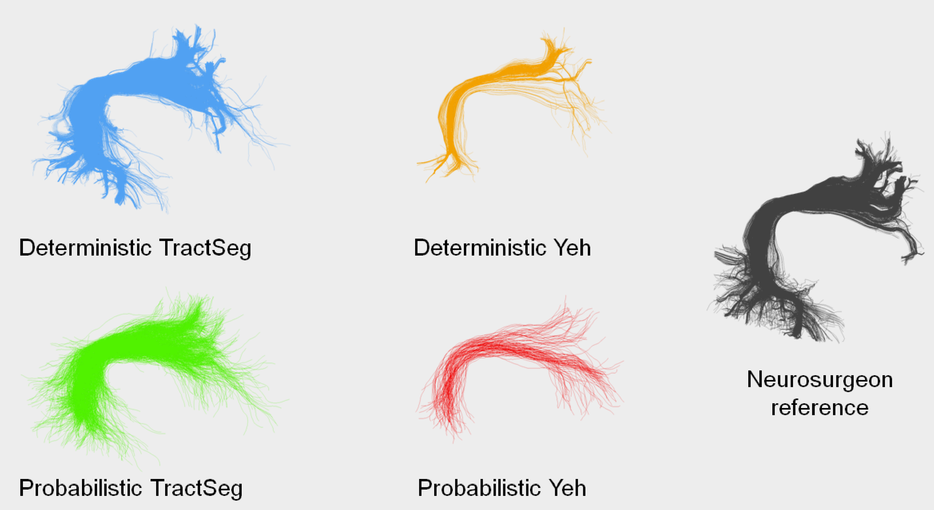


**Figure 1.** Different AF reconstruction @2M streamlines

## RESULTS

**Streamline-based** atlas shaped more **compact, coherent** bundles, with a morphology more consistent with the expected anatomy, due to streamline continuity constraints inherent to this approach. In contrast **voxel-wise** segmentation consistently generated bundles with **larger volumes**, both in the trunk and in the endpoints, regardless the number of streamlines in the tractogram. Shape analysis confirm the intrinsic difference of these approaches, showing a lower surface irregularity and fractal dimension for the streamline-based segmentation, but higher average length and elongation.
Analysis is performed across different number of streamlines, suggesting that increasing tractogram size beyond 2M results only in a modest increase in trunk volume (except for probabilistic voxel-wise) whereas the endpoint volume increases substantially particularly when using probabilistic CSD algorithm.

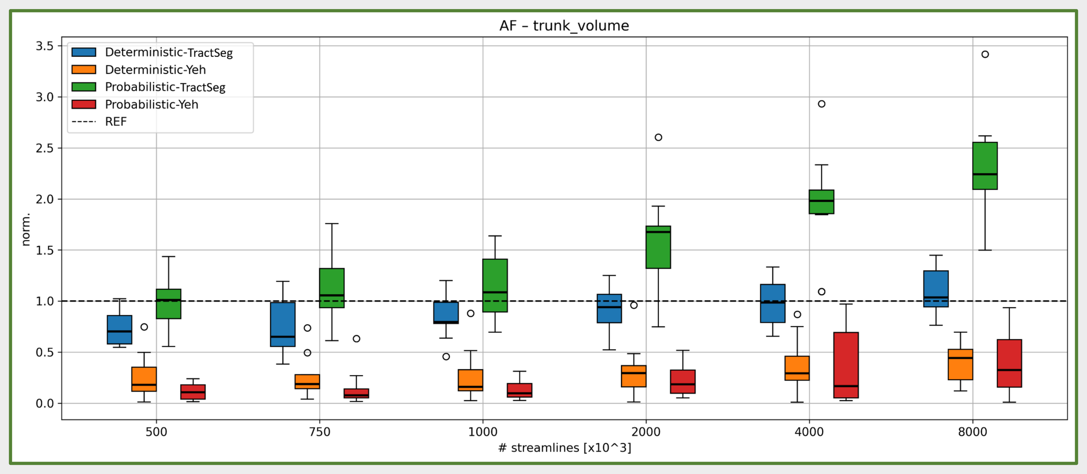


**Figure 2** AF **trunk volume** across number of streamlines, normalized to reference.

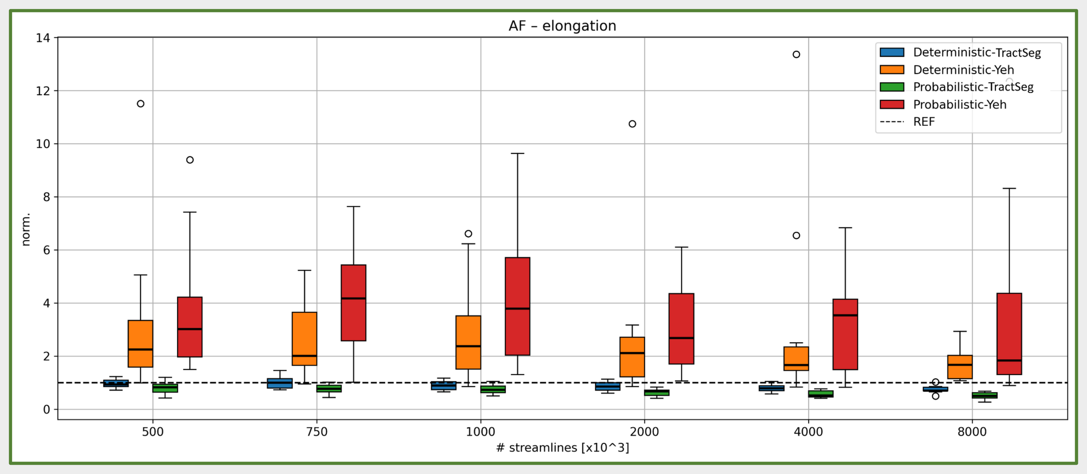


**Figure 3.** AF **elongation** across number of streamlines, normalized to reference.

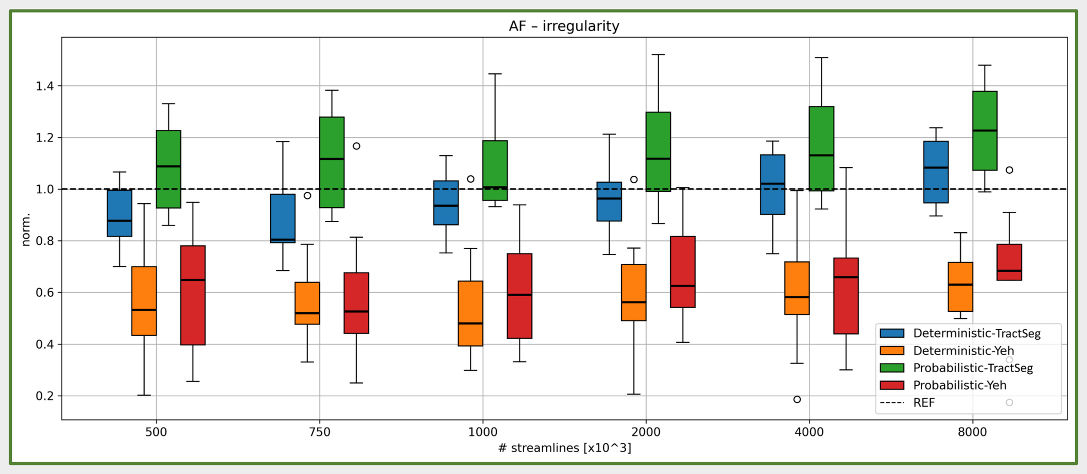


**Figure 4.** AF **irregularity** in deterministic CSD across number of streamlines, normalized to reference.

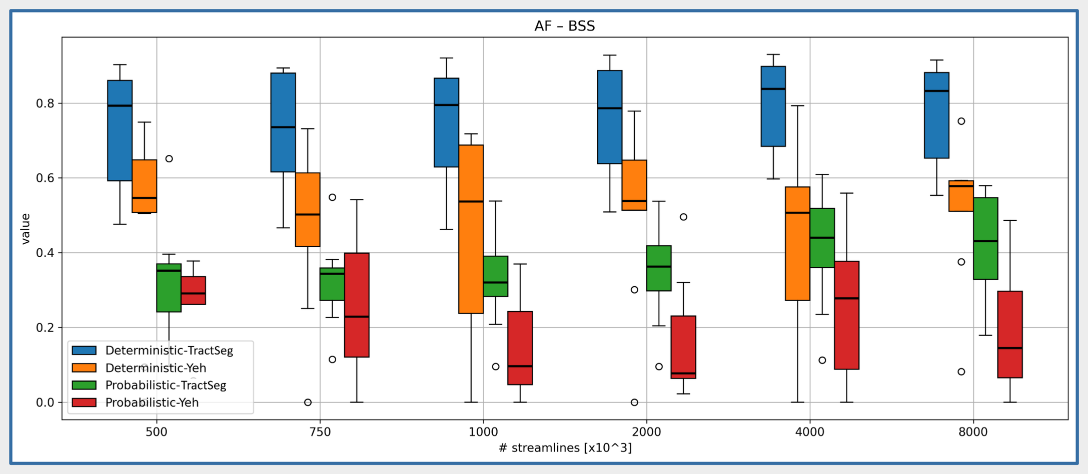


**Figure 5.** AF **Bundle Shape Similarity** with clinical reference, across the number of streamlines.

## DISCUSSION

Volume and shape parameters analysis suggests that differences in atlas paradigm reflects largely on bundle structures. **Streamline-based** atlas, segment preferentially bundles with **greater continuity**, resulting in **lower morphological complexity** and higher mean streamline length, at the expense of smaller reconstructed volumes. In contrast, **voxel-wise** atlas yields to **larger** segmented **volumes** which may reflect the incorporation of anatomically **less plausible trajectories**.

These results suggest that the two segmentations strategy should be adopted by the specific clinical application rather than a-priori assumption.

Furthermore, the comparison of segmented bundles with the clinical reference using the **Bundle Shape Similarity** (BSS) metric, strongly suggests that **deterministic reconstructions better preserves bundle morphology** and consistently achieve higher BSS, despite the substantial differences in volume for the two atlases.

Deterministic tractography was more consistent with the clinical reference standard, supporting its use for preoperative neurosurgical planning. Based on this analysis, a tractogram of 2M streamlines seems to provide a good balance between anatomical coverage and the inclusion of spurious streamlines due to the marginal anatomical information gain compared with the noise incorporation. For probabilistic tractography, this threshold could be lowered to approximately 1M.

## CONCLUSIONS

In preoperative neurosurgical planning, tractography serves as a safety margin to help preserve critical white matter pathways.
The possibility given by the combined **use of both atlases** may offer greater flexibility, allowing tract reconstructions to be tailored to different clinical scenarios.
Using both voxel- and streamline-based atlases allows case-by-case selection: tight reconstructions for restricted surgical spaces, larger bundles for small lesions' safety.
A **quantitative, physics-based approach** to develop clinically validated tractography reconstructions improves surgical safety and preserves critical neural connections.

## REFERENCES

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