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Assessment of an iconic-geometric nonlinear registration method for deep brain stimulation (DBS) planning

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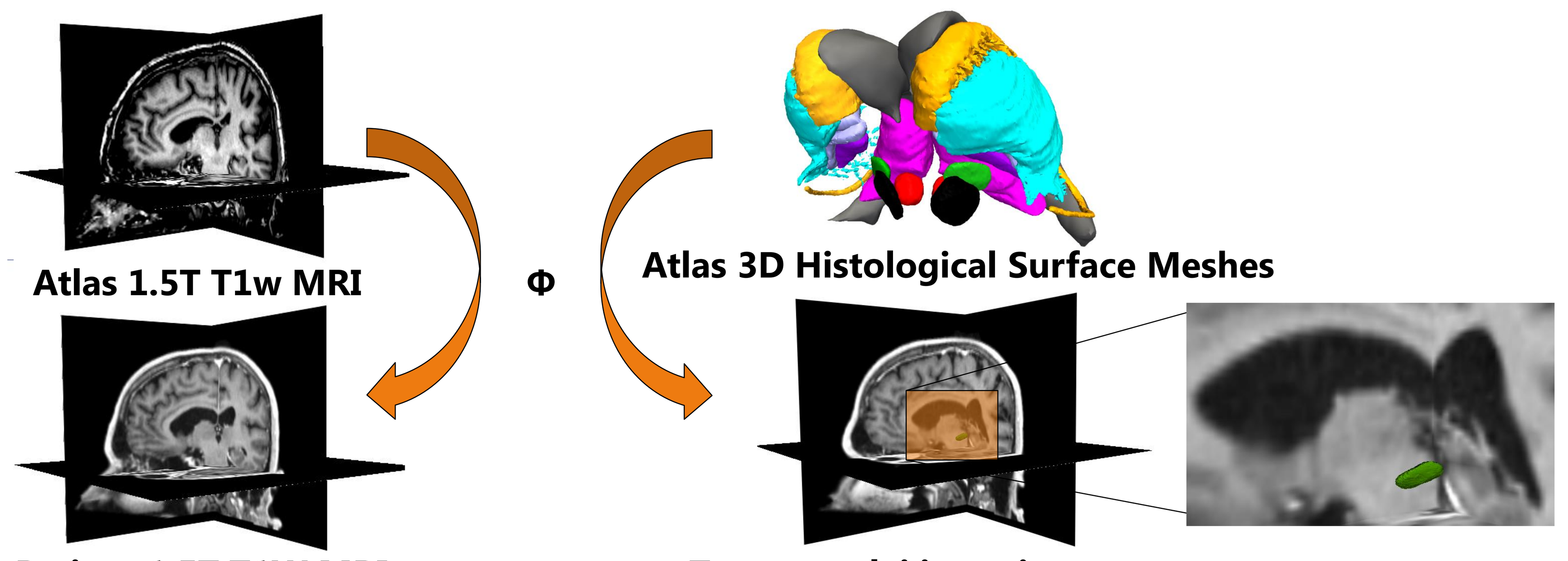
INTRODUCTION

- **Context:** successful DBS surgical outcome depends on precise electrode implantation. To plan the implantation strategy, pre-operative **targeting** is performed to estimate the location of basal ganglia (BG) stimulation nuclei in the patient's brain.
- **Targeting Strategies:** direct visual inspection of the BG nuclei in MRI is not always possible, requiring the use of indirect methods, such as **atlas-based targeting through image registration.**
- **3D Histological Atlas of the Basal Ganglia [1]:** a 3D model of the human BG, obtained from the co-registration of histological and 1.5T T1-weighted (T1w) MRI data of a healthy elder specimen.
- **Deformation Models:** embed different degrees of freedom and desirable properties in the solution of the atlas-to-patient registration (rigid, affine, nonlinear).



- **Challenges:** deform atlas structures of histological precision based on 1.5T T1w MRI data where certain BG nuclei are invisible; respect anatomical shape properties; cope with anatomical variability among patients.
- **Our Solution:** a **nonlinear diffeomorphic** registration algorithm based **simultaneously** on **intensities** (image data) and **geometric** (shape data) constraints.

ICONIC-GEOMETRIC NONLINEAR REGISTRATION

- **Iconic-Geometric Nonlinear Registration Problem [2,3]:** given source data $S=\{S_1,\dots S_n\}$ and corresponding target data $T=\{T_1,\dots,T_n\}$, find a diffeomorphic deformation Φ which minimizes the energy E(Φ) by taking all these constraints into account simultaneously:

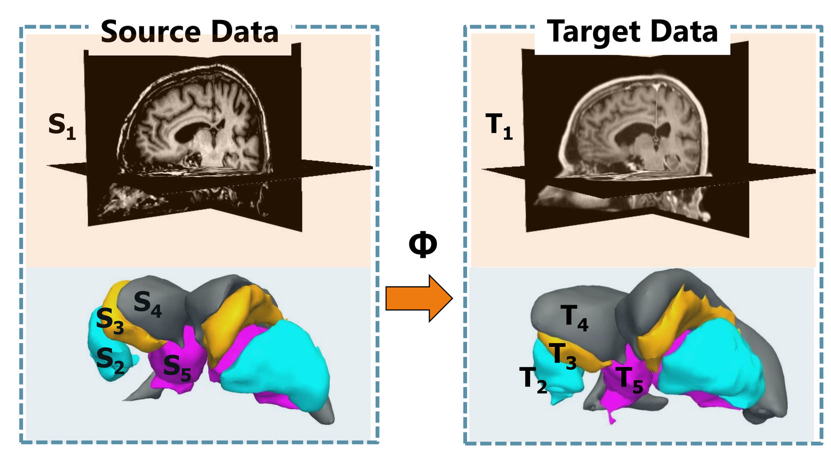
$$E(\Phi) = \underbrace{\sum_i \alpha_i \mathrm{Dist}(T_i, \Phi(S_i))}_{\text{Data-Fidelity Term}} + \underbrace{\mathrm{Reg}(\Phi)}_{\text{Deformation Regularization Term}}$$

α_i **:** weight factor assigned to the *i*-th (source, target) pair of constraints

Iconic Constraints:
- Transmit information about image intensities.
- Evaluated by a similarity distance measure $\mathrm{Dist}(T_i, S_i)$, such as: sum of squared distances, local cross correlation, quadratic error to the local affine model, etc..
- Measures usually dominated by high-contrast image regions.

Geometric Constraints:
- Transmit information about homologous anatomical shapes, represented by geometric entities (points, curves, surfaces).
- Shape relevance to the registration is independent of its contrast in the corresponding image.
- Evaluated by a shape similarity distance measure such as $\mathrm{Dist}(T_i, S_i)$ = varifold distance, which does not require point-to-point correspondences.
- Do not cover the whole data space (constrained to the points of the shape).
- Sensitive to errors of the method used to produce the shape representations.

Iconic-Geometric Constraints:
- Combine the advantages of both individual constraints, while attenuating their drawbacks.
- Iconic data allow the registration of points in the whole data space. They may also compensate for errors in geometrical representations that would impoverish a sought solution Φ.
- Geometric data contribute with prior knowledge about the importance of certain homologous anatomical structures, which should be emphasized in the sought deformation Φ despite their contrast in images.

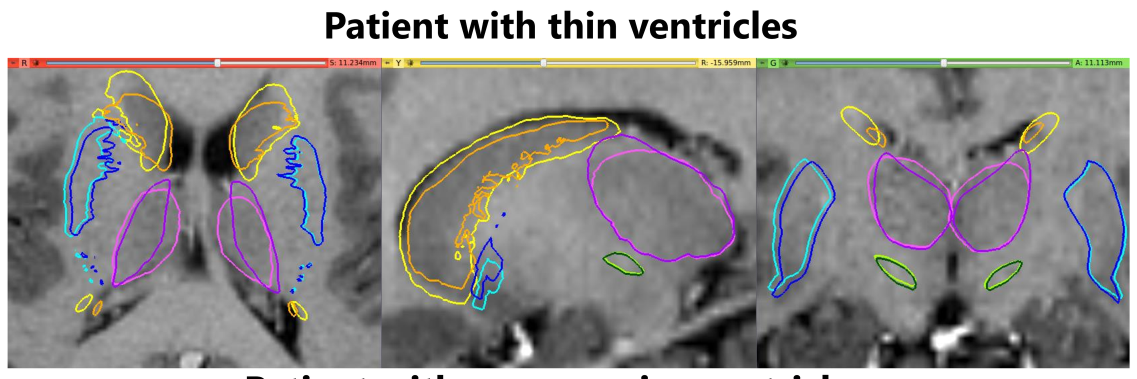


REGISTRATION RESULTS

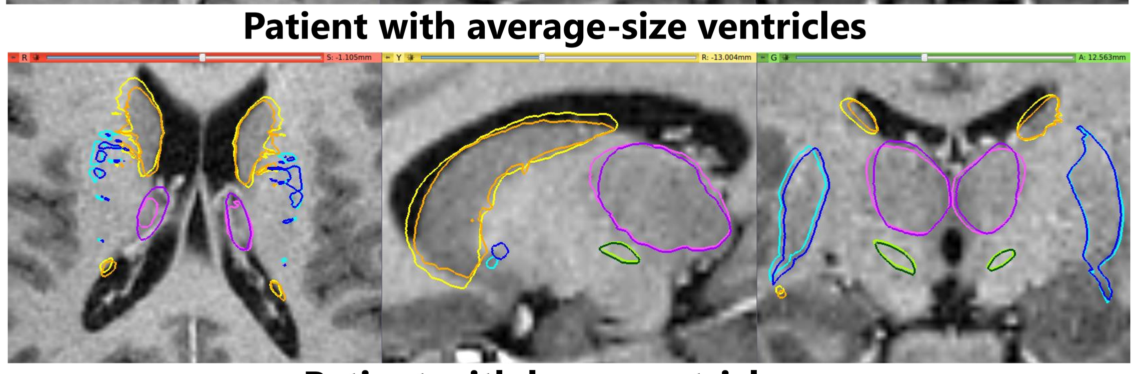
- **Cohort :** 30 Parkinsonian patients undergone bilateral DBS of the subthalamic nucleus (STN).
- **Patient Data:** 1.5T T1w / T2w MRI; patient Freesurfer subcortical meshes; per-operative annotations of microelectrode recording labels (MERL).
- **Evaluated Registration Methods:** piecewise-linear (PL), PL followed by iconic-based nonlinear ANTS (default parameters), PL followed by the iconic-geometric nonlinear method (IG).
- **Iconic-Geometric Registration Data:** 1.5T T1w MRI (atlas/patient); pairs of Freesurfer surface meshes representing the left/right lateral ventricle, caudate nucleus, putamen, and thalamus of the atlas and a patient.

Piecewise-linear (bright colors) and iconic-geometric (dark colors) results

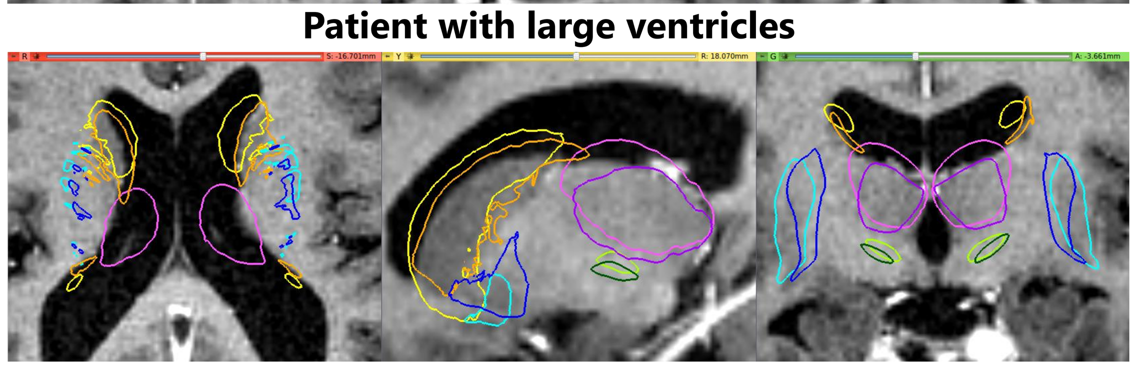
Patient with thin ventricles



Patient with average-size ventricles

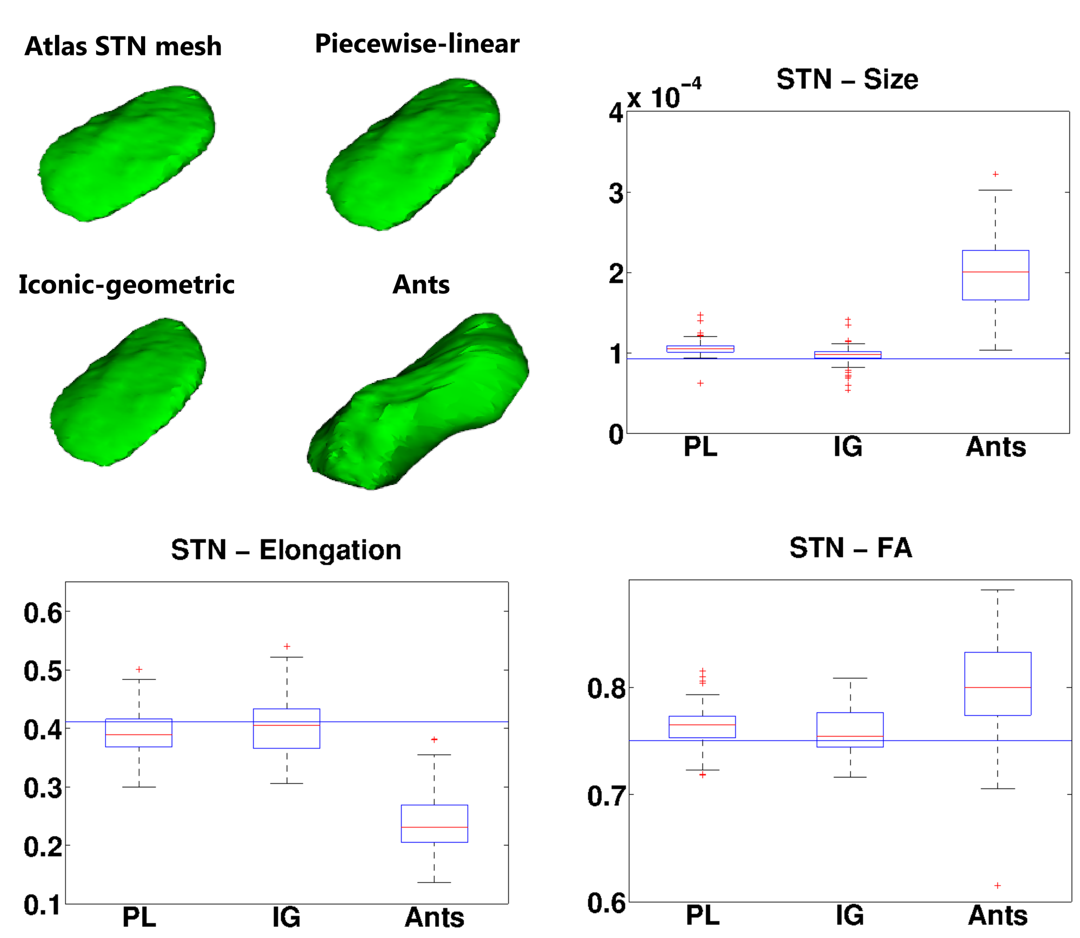


Patient with large ventricles

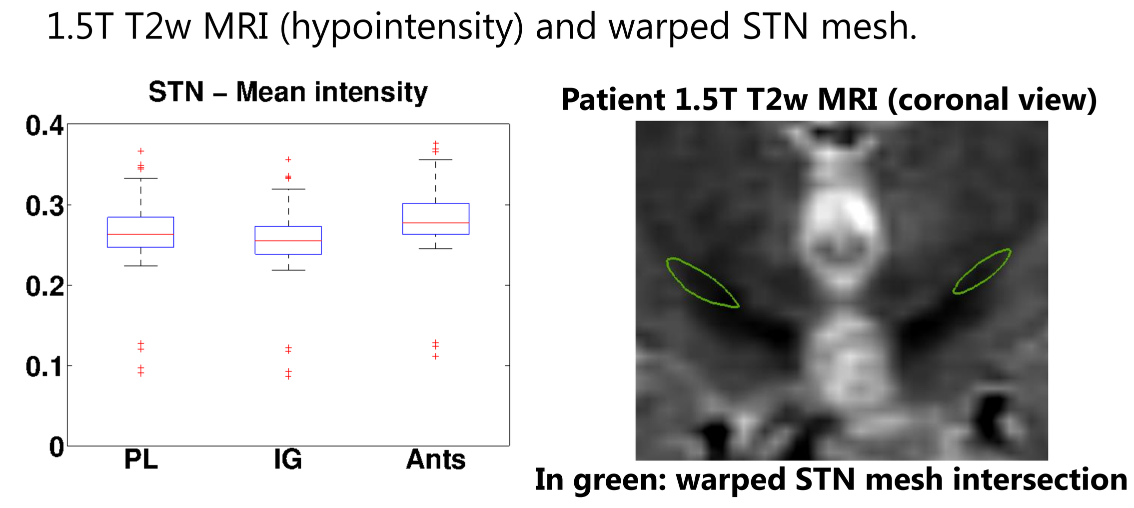


QUANTITATIVE EVALUATION

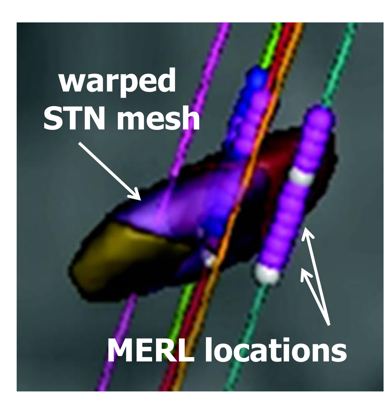
- **Shape measures** (size, elongation, and fractional anisotropy or ``sphericity") from warped STN meshes.



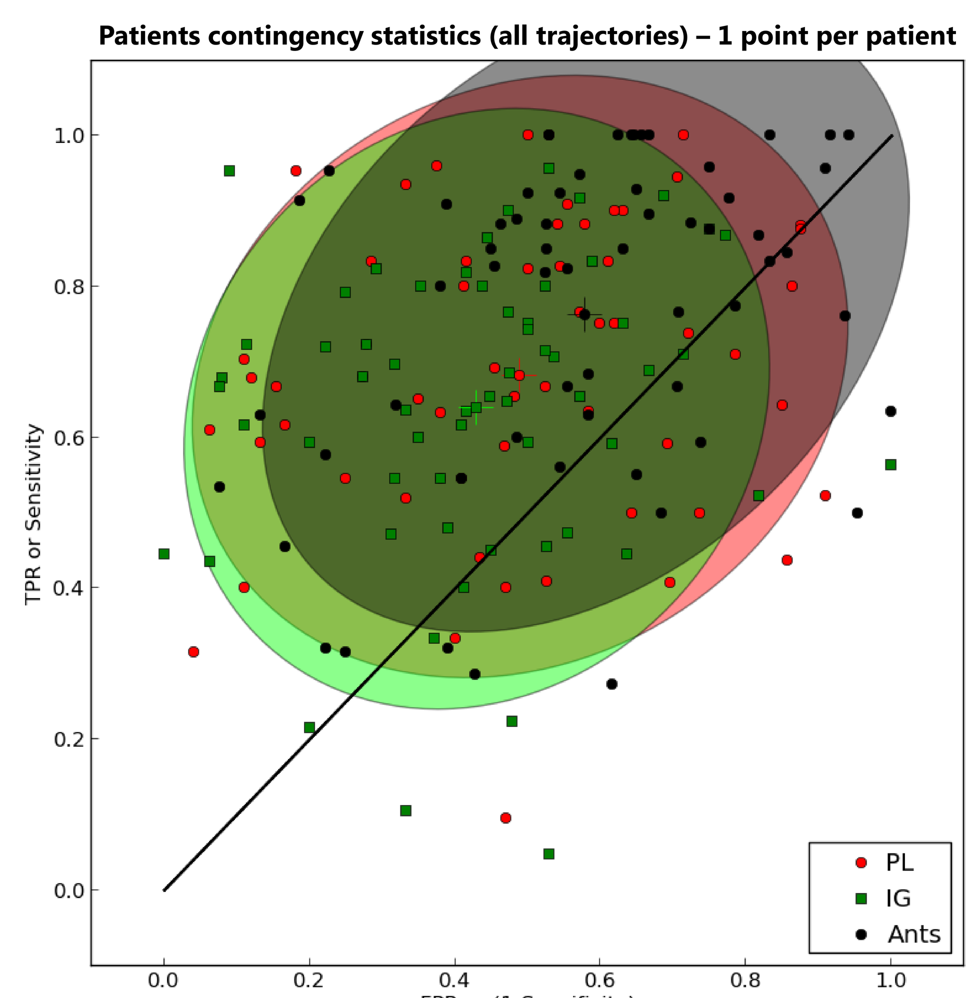
- **Mean intensity,** computed from the overlap between a patient's 1.5T T2w MRI (hypointensity) and warped STN mesh.



- **Retrospective cross-validation with microelectrode recording labels (MERL)** to assess the agreement between the predicted STN location (warped meshes) and per-operative electrophysiological annotations about the STN location. Confusion matrices were computed to assess sensitivity and specificity of each method.



- At each MERL location (electrode contact per explored trajectory), neuronal activity is recorded and labeled according to the electrophysiological signature (e.g. STN).
- The agreement between points labeled as the STN inside/outside warped meshes is evaluated.



CONCLUSIONS

Iconic-Geometric Registration Model:
- More precise atlas-to-patient registration, even for considerably different anatomies.
- Anatomically-robust deformations of the STN and other BG target nuclei that are invisible in 1.5T T1w MRI (globus pallidus, red nucleus, substantia nigra).
- Higher specificity (smaller rate of false positive STN regions) than competitive methods according to the retrospective analysis using electrophysiological data.

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