An in-plane, mirror-symmetric visualization tool for deep brain stimulation electrodes*

Thomas J. Richner, Bryan T. Klassen, and Kai J. Miller

Abstract—**Deep brain stimulation (DBS) is used to treat a range of neurologic conditions. Determining the anatomic location of the DBS lead and inferring the microelectrode recording track from co-registered pre-operative and post-operative scans is important for stereotactic surgery and neurophysiology research. Reslicing images with the DBS lead in-plane while maintaining mirror symmetry is not possible with current clinical navigation software. Therefore, we developed an open source software tool in Matlab for visualizing DBS lead placement and anatomic segmentation with computed tomography and magnetic resonance images. The code and graphical user interface are available at: github.com/camplaboratory/DBS_reslice**.

Clinical Relevance — **This tool enables assessment of stereotactic accuracy by visualizing the DBS lead in-plane while intuitively maintaining mirror symmetry.**

I. Introduction

Deep brain stimulation (DBS) is used to treat Parkinson, essential tremor, dystonia, obsessive compulsive disorder (OCD), and other conditions. During DBS surgery, a microelectrode is incrementally advanced towards the target to electrophysiologically map the track for sensory or motor modulation. If satisfactory, electrical stimuli are applied through the macroelectrode to assess therapeutic effect and assess for side effects. If satisfied, the DBS lead is implanted. After surgery, a post-operative computed tomography (CT) image is taken, revealing the lead location.

Quantifying DBS lead placement relative to brain anatomy is essential for clinical refinement and neurophysiology research. Neurosurgeons must assess the accuracy of their stereotactic technique by comparing post-operative scans with pre-operative plans. Electrophysiology researchers must determine the anatomic position of each recording and stimulation site. This can be done by co-registering the pre-op magnetic resonance (MR) and post-operative CT images, and then visualizing the DBS contact positions (from CT) at their inferred position in the MRI.

Most intuitively, the structural MRI should be resliced along the with the DBS lead in-plane while maintaining mirror (bilateral) symmetry across the midline of the brain. Current clinical navigation software can reslice along a trajectory, but the resulting orthogonal views are essentially arbitrary (Fig. 1A), do not maintain symmetry, and are difficult to interpret. The goal of this research is to make a software tool that solves this problem available to the community.

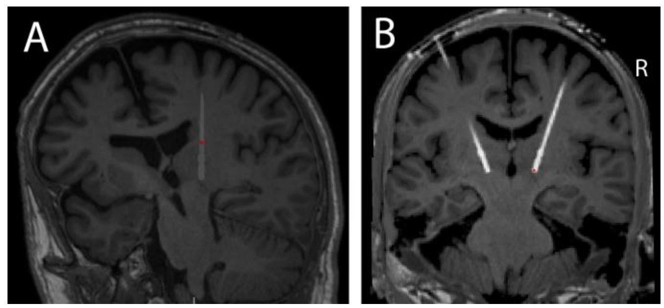

Figure 1. Comparison of in-plane DBS lead visualization with and without mirror symmetry. (A) The trajectory view from commercial DBS planning software does not maintain mirror symmetry. (B) Our visualization tool keeps the right DBS lead in-plan while maintaining symmetry.

II. Methods

To reslice along a DBS lead while maintaining mirror symmetry, the user defines a vector along the DBS lead and the mid-sagittal plane. From this vector and plane, a series of rotations are calculated. Our implementation in Matlab includes two graphical user interfaces (GUIs): the first is used to define these vectors and calculate the transformation and the second is used to review the images and segment the anatomic structures. The code and graphical user interface are available at github.com/camplaboratory/DBS_reslice.

A. Preprocessing & image fusion

In order to define the DBS lead vector and mid-sagittal plane accurately, a single volumetric image containing the DBS lead and brain structure is needed. The DBS lead is visible in the post-operative CT and the soft tissue of the brain are visible in the pre-op T1 MRI. Several software tools are available to fuse these images. Our suggested method is to convert from DICOM to NIfTI with MRIcron [1], and then co-register and reslice the MRI onto the CT image, fusing them with Statistical Parametric Mapping (SPM) [2]. With the fused images in NIfTI format, the data are ready for reslicing with our software tool.

B. Reslicing

A transformation matrix must be calculated from the DBS lead vector and mid-sagittal plane to reslice along the DBS lead while maintaining mirror symmetry. This vector and plane are calculated from points selected along the lead and midline. The fused MRI-CT image is loaded into the DBS Reslice GUI and three orthogonal views are presented. The

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T. J. Richner is with the Neurologic Surgery Department at Mayo Clinic, Rochester, MN 55902 USA (email: richner.thomas@mayo.edu).

B. T. Klassen is with the Neurology Department at Mayo Clinic, Rochester, MN 55902 USA (email: klassen.bryan@mayo.edu).

K. J. Miller is with the Neurologic Surgery Department at the Mayo Clinic, Rochester, MN 55902 USA (e-mail: miller.kai@mayo.edu).

images are not assumed to already be in a standard coordinate space, so arbitrary rotations are expected. Now the user selects several key points within the image. First, the user selects four points along the DBS lead. These points should be near the tip of the lead (typically at each electrode contact) as the brain may have shifted after implantation such that the entire lead is not coplanar, and points near the tip are more important that those near the insertion point. Second, the user selects the anterior commissure (AC) and posterior commissure (PC) points, which are the standard midline anatomic features used to align images to anatomic atlases. Last, the user selects an additional three points along the midline. These points should be well spread out along the sagittal plane to ensure accurate estimation of the mid-sagittal plane. From these points, a set of vectors and rotations will be calculated.

The AC-PC unit vector $\hat{y}$ is calculated from the AC and PC points simply as

$$\hat{y} = \frac{AC - PC}{|AC - PC|}. \quad (1)$$

A vector normal to the mid-sagittal plane is fit from the AC, PC, and three midline points m_1, m_2, and m_3 using principal component analysis (PCA). Five nearly coplanar points would otherwise over define this plane, so a plane of best must be found. The five points are loaded as rows into a matrix and the mean is subtracted to center at zero giving A. The covariance matrix, C is calculated as $C = A^T A$. An eigenvalue decomposition of C yields the eigenvectors $\vec{e}_k$ and eigenvalues λ_k satisfying

$$C\vec{e}_k - \lambda_k \vec{e}_k = 0. \quad (2)$$

The first two eigenvectors (corresponding to the two largest eigenvalues) describe orthogonal directions of greatest variance. They lie in the mid-sagittal plane. The third eigenvector $\vec{e}_3$ is therefore normal to the mid-sagittal plane. This direction $\vec{e}_3/|\vec{e}_3|$ is denoted $\hat{x}$ in neurosurgical AC-PC convention [3]. Crossing $\hat{x}$ and $\hat{y}$ gives an orthonormal vector $\hat{z}$ along the ventral-dorsal axis. The third axis of AC-PC space is defined as $\hat{z} = \hat{x} \times \hat{y}$.

The image volume is then rotated into AC-PC space with three rotation matrices about the three axes. Rotation about the z-axis by angle $\theta = \tan^{-1}(\hat{y}(1)/\hat{y}(2))$ is determined by

$$R_z = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (3)$$

and rotating $\varphi = \tan^{-1}(\hat{y}(3)/(\hat{y}(2)/\cos(\theta)))$ about the x-axis an angle is determined by

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & \sin(\varphi) \\ 0 & -\sin(\varphi) & \cos(\varphi) \end{bmatrix}. \quad (4)$$

After rotating $\hat{z}$ with

$$\hat{a} = R_x R_z \hat{z} \quad (5)$$

we can rotate about the y-axis to maintain mirror symmetry with $\eta = -\tan^{-1}(\hat{a}(1)/\hat{a}(3))$ and

$$R_y = \begin{bmatrix} \cos(\eta) & 0 & \sin(\eta) \\ 0 & 1 & 0 \\ -\sin(\eta) & 0 & \cos(\eta) \end{bmatrix}. \quad (5)$$

With these rotation matrices the image volumes can be rotated into AC/PC space. One additional rotation brings the DBS lead into plane. PCA is applied to the four user-selected points (as in (2)), with the largest eigenvector corresponding to the axis of the DBS lead. We denote this axis $\vec{d}$. The necessary angle about the x-axis is $\alpha = \tan^{-1}\left(\vec{d}(3)/\hat{y}(2)\right)$ with rotation matrix

$$R_d = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}. \quad (6)$$

Applying the rotation matrices to the brain image *V* (where it is understood that *V* is already rotated into scanner space), yields an image volume V_p with the DBS lead in-plane and mirror-symmetric.

$$V_p = R_d R_y R_x R_z V \quad (7)$$

This process is repeated independently for each DBS lead, as each is likely to be in a different plane.

C. Ride along images

The same rotations can be readily applied to additional images that have been co-registered to the original fused images during the preprocessing step (IIA, above). In our implementation, these are "ride along" images. Ride along images are especially useful when segmentation of anatomic features require comparison of several different sequences (see an example in Fig. 3). After rotating the images, the results are saved in NIfTI format.

D. Review & segmentation

The resulting NIfTI images can be reviewed in our DBS Review GUI to produce trajectory figures, assess DBS placement accuracy, and segment anatomic structures (see Fig. 2B). The DBS lead can be viewed in-plane with ride along images. The microelectrode recording track location, assuming it is coincident with the DBS lead placement, can be inferred on a structural MRI. This enables electrophysiological recordings to be assigned to anatomic structures. Safety margins from vessels can be measured, and regions of interest (ROIs) can be drawn on multiple slices for volumetric measurements.

III. Results

This software tool performs in-plane reslicing of MRI and CT images while maintaining mirror symmetry. The GUIs enable any user to apply this analysis to their pre- and post-operative images without further coding. The mirror-symmetric view gives an intuitive view of the brain, and are more similar to the coronal views we are accustom to. We demonstrate the two GUIs with a DBS lead placement in the subthalamic nucleus (STN) (Fig. 2) and show the utility of this approach for the alignment of electrophysiological signals with anatomic structures in and near the nucleus accumbens (Fig. 3).

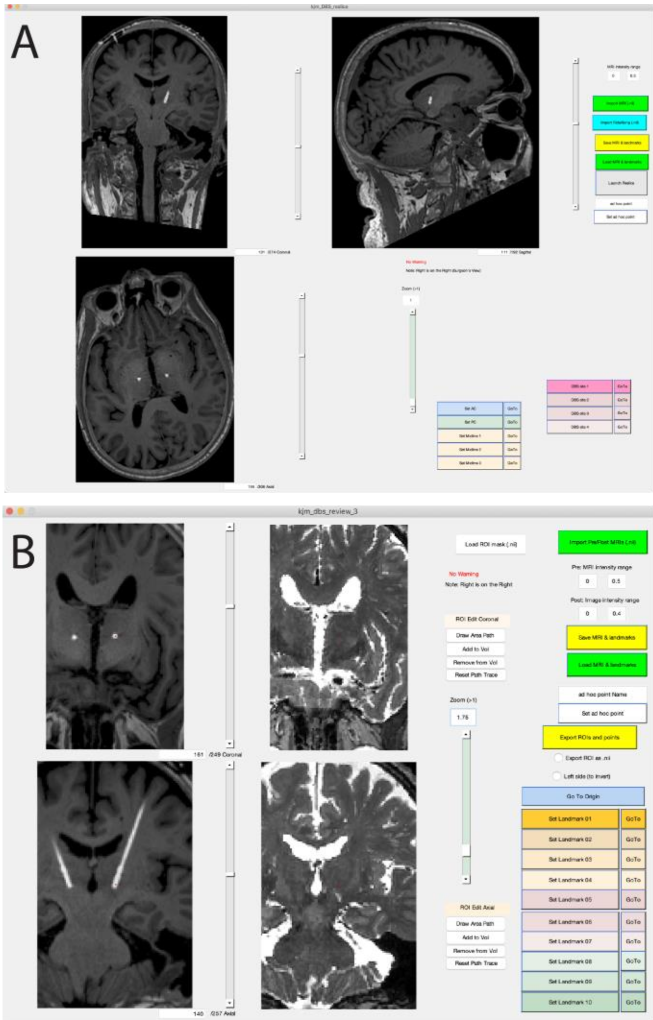

Figure 2. Visualizing an STN DBS lead with our in-plane, mirror-symmetric visualization tool. (A) The DBS Reslicing GUI presents three orthogonal views of the fused CT-MRI. The brain has not yet been rotated and only a small fragment of the DBS lead can be seen. The user selects points along the DBS lead and along the mid-sagittal plane to enable the necessary rotations (sees IIB). The rotated fused image and ride along images are output in NIfTI format. (B) The DBS Review GUI displays the resulting fused image with the right DBS lead in-plane. The T2 MRI was included as a ride along image, receiving the same rotations. Further segmentation of anatomic structures is possible with this GUI.

A. In-plane reslicing & symmetry

The DBS Reslice GUI reslices the images such that the DBS lead is in-plane. The user selects manually nine points and the software automatically rotates the images. Figure 2A shows the DBS Reslice GUI in a patient with DBS leads implanted into STN (images used with written consent from the patient). The initial orthogonal views contain arbitrary rotations due to alignment in the scanner. The DBS lead enters the frame from an angle such that a small segment of the lead is visible. Note that there is no need to manually rotate the image prior to defining the DBS lead vector and mid-sagittal plane. In this example, a T2 image was imported as a ride along image to undergo the same set of rotations.

The resliced CT-T1 merge and T2 images are shown with mirror symmetry in figures 1B and 2B. Nearly the entire right DBS lead is visible with only the insertion point out of plane due to post-operative brain shift. In comparison to clinical navigation software which imposes an arbitrary rotation around the DBS lead (Fig. 1A), the image resliced with our method (Fig. 1B) appears more similar to a standard coronal slice. Mirror-symmetric images readily facilitate within subject visual comparisons of anatomy and identification of brain structures.

B. Localization of electrophysiological recordings

This software tool is useful for preparing figures that incorporate measurements along stereotactic trajectories onto MRI and CT images. In figure 3 we show an example where microelectrode recordings were made in 1 mm increments while approaching the nucleus accumbens in a patient with obsessive compulsive disorder (images used with written consent from the patient). Three MR images and the CT were resliced and segmented using our software tool.

Comparison of several MR images was necessary to segment the structures in figure 3 because no single MR image sufficiently delineated the structures. The image ride along feature enabled several images, which were initially registered to the fused image, to be rotated into the same space with the DBS lead in-plane. By comparing the three MR images, the nucleus accumbens and surrounding structures were segmented. In this example, electrophysiological features specific to nucleus accumbens were found [3], a finding made possible by this visualization tool.

IV. Discussion

This visualization tool for DBS trajectories is intended to be a practical tool for clinicians and researchers.

A. Clinical utility

When planning DBS surgery and when reviewing post-operative images, viewing the DBS trajectory in-plane is a more complete practice than viewing a projection onto a coronal, sagittal or axial plane. Additionally, most neurologists and neurosurgeons are used to looking at mirror-symmetric coronal slices, not those with an arbitrary rotation about the DBS lead. Standardizing the view of the DBS lead to ensure mirror symmetry is a natural approach. We hope this feature, described in detail in this paper, will be integrated into existing clinical DBS planning and navigation software at some future date.

B. Research utility

The ability to recording neural signals from deep structures in awake human subjects undergoing DBS surgery is a unique opportunity. Identifying where these signals were recorded from is absolutely essential to the interpretation of the electrophysiological signals. This visualization tool enables researchers to map electrophysiological properties onto a single, segmented, symmetric view of an MRI. Our approach, which involves defining a vector and a plane, could be generalized to define new coordinate systems centered around things other than DBS leads such as anatomic features [4]. Using the most natural device-centric or anatomy-centric coordinate frames enables comparison across subjects.

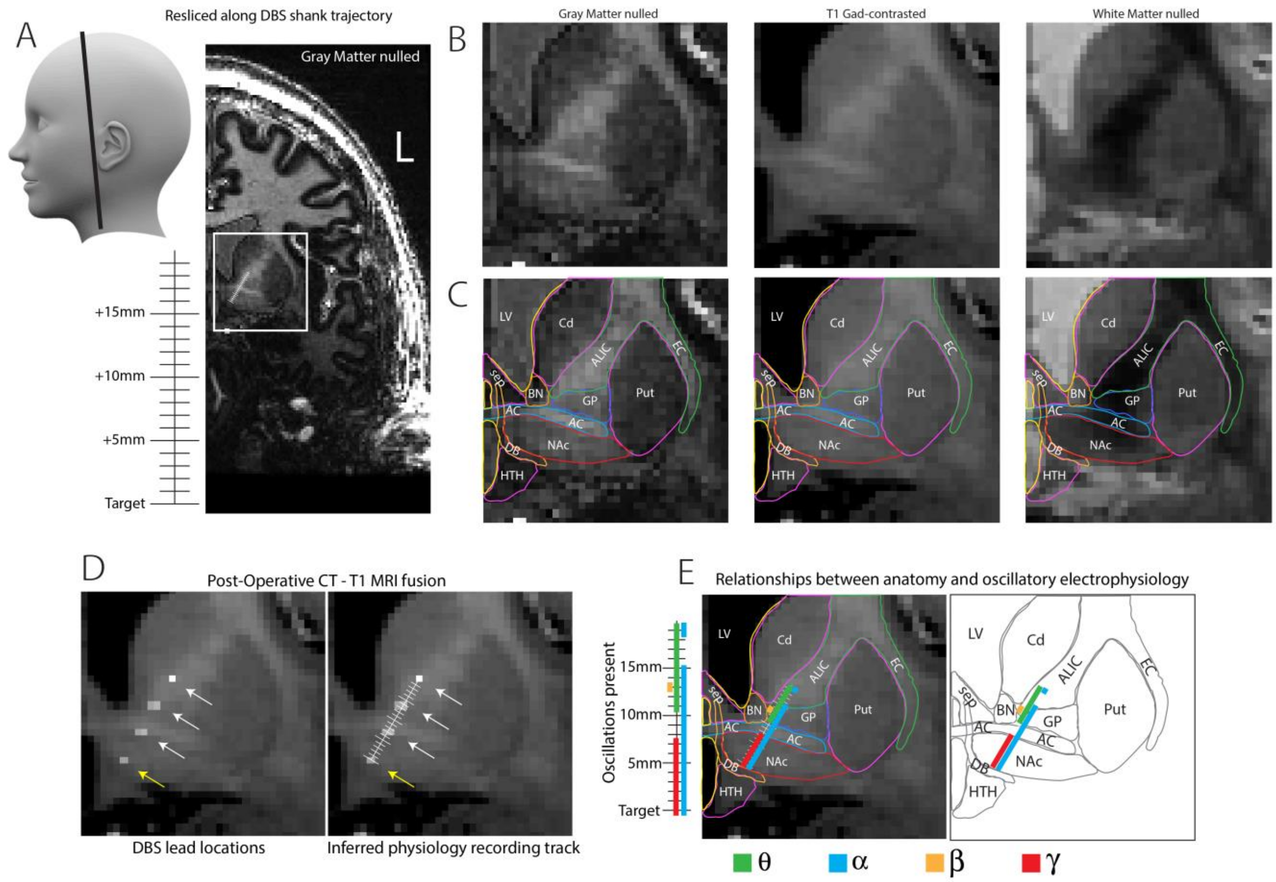

Figure 3. In-plane reslicing along the DBS lead with multiple ride-along MR images enabled anatomic localization of the microelectrode recordings. During this DBS implantation surgery to treat obsessive compulsive disorder, microelectrode recordings were made in 1 mm intervals approaching the nucleus accumbens (figure adapted from online methodology for [5], used with permission). The DBS reslicing tool was used to produce this figure and assign the microelectrode recordings to their anatomic location. (A) A pseudo-coronal slice in the plane of the DBS lead and microelectrode recordings is shown with a scale bar. (B) Gray matter nulled, T1 Gad-contrast, and white matter nulled images were simultaneously resliced using the ride along feature. (C) All three types of MR images were necessary to segment nucleus accumbens and the nearby structures. (D) The fused post-operative CT and pre-op T1 show the location of the DBS electrode sites, allowing the recording track to be inferred. (E) When combined with electrophysiology analysis, the electrophysiological properties specific to nucleus accumbens were found.

V. CONCLUSION

We hope this freely available tool will be useful to the DBS community.

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