Automatic segmentation of the optic tracts for computer assistance of deep brain stimulation procedures.

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ABSTRACT
Deep brain stimulation (DBS) is a surgical treatment involving the implantation of a medical device called a brain pacemaker, which sends electrical impulses to specific regions of the brain for treatment of movement disorders. Because of the small size of the surgical target and possible shift of the deep brain structures due to air invasion when the dura is opened, intra-operative adjustment of the surgical approach is often necessary. Knowledge about the position of the optic tracts gained from intra-operative measurements is useful for placement guidance. Pre-operative knowledge of the location of the optic tracts may not only help the placement and programming of the DBS implant but also prove useful in estimating intra-operative brain shift. In this article we present an automatic method to localize the optic tracts in MR/CT.

Index Terms—Deep brain stimulation, planning, intra-operative brain shift, computer assisted intervention, GPI, optic tracts, segmentation

1. INTRODUCTION
Movement disorders such as Parkinson’s disease (PD), essential tremor (ET) and dystonia affect approximately 1 million, 1.5 million, and 250,000 people respectively in the United States. A viable and cutting edge treatment technique for movement disorders is deep brain stimulation (DBS) [1]. Deep brain surgery involves implanting electrodes in specific regions of the brain. This stimulation, while not completely effective, helps regulate the signals sent between different nuclei and reduces the severity of the symptoms. Because of the small size of the nuclei and the potential shift of the deep brain structures due to air invasion, this neurosurgical procedure is traditionally performed in two stages. A target location is first selected pre-operatively by a neurosurgeon and then refined intra-operatively using multiple exploratory electrodes to map the electrophysiology of the brain around the planned target. The nucleus that is targeted for stimulation depends on the disorder of the patient: the treatment of symptoms will generally be addressed by stimulating the subthalamic nucleus (Stn) for PD, the ventral intermediate nucleus (Vim) for ET and the globus pallidus internal (Gpi) for dystonia. If possible, the surgeon will stimulate Vim or Stn targets in the operating room and directly observe the patient’s response. This is used to refine the optimal position for the final implant. The surgeon typically is not able to see any clinical benefit when the Gpi is stimulated. This causes the surgery to be more difficult for dystonia. Programming the implant after the surgery can take from several months to, according to some groups, a year to see full clinical benefit [2]. Therefore, surgeons and neurologists use other landmarks to assist during the procedure. One landmark that is commonly used is the optic tract because of its proximity to the Gpi as seen on Figure 1.

Visual evoked potential (VEP) monitoring has been described by several groups as helpful in assessing the location of the optic tract during the surgery and is the traditional approach for reliably localizing relevant functional deep brain targets [3]. A VEP is defined as the electrical response of the nervous system that is directly produced by a visual stimulus.

The optic tracts are not clearly visible on the clinical image sequence used for the DBS procedure due to poor contrast. Therefore, an automated approach to segment and localize the optic tracts would be beneficial as a part of a computer assistance system, in both intra-operative guidance and post-operative programming.

To the best of our knowledge, no method for automatic segmentation of the optic tracts has been presented. Despite the fact that many techniques have been developed for the segmentation of tubular structures, see for instance [4-10], it is unlikely that using any of these techniques alone could produce robust and accurate segmentation results for the optic tracts because of the unique challenges presented by the characteristics of this problem, i.e., the lack of contrast and changing intensity characteristics along the structures’ length.

The optic tracts are a part of a larger anatomical structure, the optic pathway, which includes the optic nerves, chiasm and tracts. Bekes et al. developed a semi-automatic geometric based approach for the segmentation of the organs of sight including the eyes, optic nerves and chiasm [11]. Other approaches to localizing the same structures were formulated using atlas-based techniques [12-14]. All these methods reported difficulty with their segmentation of the optic nerves. We recently introduced a general technique for the segmentation of tubular organs, which we call the atlas-navigated optimal medial axis and deformable model algorithm (NOMAD). Using this method, we successfully segment both the facial nerve and chorda tympani [18], and the optic nerves and chiasm [19]. With this technique we overcome issues such as the lack of local intensity contrast or the changing intensity characteristics along the structures’ length that other groups have encountered, making our
2. METHOD

2.1 Image data
With IRB approval each patient had pre-operative MRI and CT, and a post-operative CT acquired on the day of the surgery. Typical CT images were acquired at kVp = 120 V, exposure = 350 mAs and 512x512 pixels. In-plane resolution and slice thickness were respectively 0.5 mm and 0.75 mm. MRI (TR 12.2 ms, TE 2.4 ms, 256x256x170 voxels, with typical voxel resolution of 1x1x1 mm³) were acquired using the SENSE parallel imaging technique (T1W/3D/TFE) from Philips on a 3T scanner.

2.2 Segmentation
In this work, we segment the optic pathway by applying the NOMAD algorithm to the left and right SOI’s and extracting the optic tracts from the results. The NOMAD algorithm first computes the medial axis of the structure as the optimal path with respect to a cost function based on image and shape features. The medial axis is then expanded into the full structure using a level-set algorithm. Unlike other methods [4-10], NOMAD uses a statistical model and image registration to provide the above segmentation framework with a priori, spatially varying intensity and shape information, thus accounting for unique local structure features. The statistical models were based on the manual segmentations of the SOI’s in 6 volumes, which are not part of the current study.

In order to compensate for the lack and changing contrast of the structures, we take advantage of both the CT and MRI to build the models used by the algorithm. To ensure that the intensity information will consist of the best possible contrast, we rely solely on the CT the region of the optic nerves, and solely on the MR in the region of the optic tracts and chiasm. The model consists of the set of points that compose the center line of the structure and their associated expected values for intensity and shape features extracted from the rigidly aligned MRs and CTs. Once the models are built, new sets of images can be segmented. Briefly stated, the NOMAD algorithm works in three steps: 1) the starting and ending points of the structure centerline are found using a basic atlas-based technique using non-rigid registration, 2) a minimum cost path algorithm finds the centerline of the structure, and 3) the structure centerline is used to initialize a level-set based geometric deformable model to segment the full structure. For a detailed explanation of the segmentation process, including equations and parameters see [19].

2.3 Evaluation of the segmentation
The goal of our method is to segment the optic tracts to be used as an internal landmark for guidance in deep brain surgeries. Therefore we concentrate our validation on the section of the optic tracts next to the Gpi. We first evaluate the segmentation visually in 8 patients and compute the related Dice index and mean surface error distance between the automatically segmented tracts and the manual segmentation. The manual segmentation was drawn by author PFD and reviewed by an experienced neurosurgeon.

3. RESULTS
Results for several cases are shown in Figure 3. The automatic segmentation is shown as the green, solid contour and manual segmentation is shown with the red contour. To generate the 2D views, a thin-plate spline transformation was computed that warps the medial axes of the structures to lie in a plane, and then the image data and contours were passed through this transformation. This was done so that a
cross section of the entire structure could be viewed in one 2D plane.

Table 1 shows the Dice index and mean surface error between the manual and automatic segmentation of the optic tracts in 8 patients. A rendering of our results, color-encoded with error distance, is shown in Figure 4.

<table>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>0.50</td>
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Table 1 Dice coefficients of the automatic segmentation results

4. DISCUSSION

Results presented in this paper corroborate the findings published in [18-19]. The automatic segmentations of the optic tracts appear to be qualitatively and quantitatively accurate. Typically, a dice coefficient of 0.8 is considered as an accurate segmentation for a regular sized structure, although the dice coefficient is typically more unforgiving on very thin structures such as the optic tracts, so 0.7 is considered a good result [12]. With the approach presented in this paper we achieve mean dice coefficients of 0.76±0.04 with an overall minimum of 0.70.

For this application, an accuracy of 2 mm is acceptable, while 1 mm (1 voxel wide in MR) is desirable. Error in our results on average is only 0.31 mm, while the worst error seen was 1.6 mm. Thus, the results from every experiment in this study were considered acceptable.

In addition to being useful for pre-operative planning, the automatic segmentations could be used for intra-operative guidance. A difference between the location of the segmented optic tracts and the location where the optic tracts are detected by monitoring the visual evoked potential could prove to be a robust measurement of intra-operative brain shift. We illustrate this concept on two cases with and without substantial intra-operative brain shift. To evaluate the brain shift, we analyze the size of air pocket in the post-operative CT of the patient acquired immediately after the procedure as described in detail in [20]. Figure 5 presents the automatically segmented optic tract overlaid with the recording electrodes used intra-operatively for the patient with no air invasion. Five electrodes were used to record VEPs. The evidences of VEP correlate well with the location of the automatic segmentation of the tracts.

In Figure 6 the concept of brain shift measurement is illustrated. The left panel shows a coronal section including a 4-contact implant overlaid with the pre-operative MRI. In this figure, the two bottom contacts appear to be located within the optic tracts. The VEPs recorded at this location during surgery, however, were not consistent with optic tracts recordings, thus suggesting brain shift. Albeit preliminary, the results we have obtained hold promise for intra-operative guidance. A combination of automatic segmentation of the optic tracts and intra-operative recordings could provide accurate measurement of intra-operative brain shift in the target area (in this case estimated to be 1.2 mm). This could, in turn, be used to update information based on pre-operative images, thus
providing intra-operative guidance. This is illustrated in the right panel of Figure 6. Here, anatomical structures segmented in the pre-operative images have been displaced by the shift estimated from the difference between the segmented optic tracts and the intraoperative measurements. The same could be done for electrophysiological maps indicating likely regions of efficacy and/or side effects [20, 21].

5. ACKNOWLEDGEMENT

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6. REFERENCES