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COMPUTER AIDED PLANNING AND NAVIGATION FOR PATIENT-SPECIFIC DEEP BRAIN STIMULATION

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Abstract: *Deep brain stimulation (DBS) intervention requires demanding planning steps for a precise placement of stimulating electrodes and to ensure the desired clinical result. We present a suite of procedures for computer aided DBS planning and navigation. Central to this development is the automatic extraction of a volumetric target model from magnetic resonance imaging. A two-stage approach is used containing 3D geometric transformations for alignment with a target template and shape refinement using a deformable statistical shape model. The model is then used for simulating the stimulation field and visualizing the optimal electrode position. Microelectrode recordings from test electrodes are analysed to localise their position with respect to the target model. The system has been tested with target subthalamic nucleus for Parkinson disease treatment.*

Keywords: *deep brain stimulation (DBS), DBS planning, DBS navigation, model-based segmentation, DBS-suite*

Introduction

Severe neurological diseases like movement disorders (e.g. Parkinson's disease (PD), or Dystonia (DS)) have been successfully treated by deep brain stimulation (DBS) since more than ten years. Recently, other conditions like deep depression or cluster headache are considered for DBS treatment. In all cases of DBS treatment the clinical result depends heavily on the precise positioning of the electrodes and the appropriate adjustment of the stimulation field. Up to now, the clinical procedure is mostly based on generalised data upon the target areas, instead of extracting a specific 3D target model from the imaging data of the patients brain. Advancing the DBS procedure and the feasibility of new and promising treatment fields requires computerized procedures for planning and navigation based on patient-specific data models. Manual model building as done so far is prone to errors and differs tremendously between operators.

To overcome these weaknesses we suggest an integrated system approach for pre-operative planning and intra-operative navigation. This system combines procedures for the extraction of volumetric target models from magnetic resonance imaging (MRI), building of models for patient-specific simulation of stimulation fields, and automatic 3D localisation of the actual electrode's position based on intra-operative microelectrode recordings (MER).

In the following we describe methods that have been developed based solely on data (3.0T MRI, 20kHz MER) from PD patients. The principal stimulation target was STN. We therefore refer to these items without restricting the system's applicability for other targets.

Methods

Probably the most challenging part of the planning tasks is the determination of the target position because the prevalent PD target structures STN and globus pallidus interna (GPi) are not easily identifiable in common medical imaging modalities. Therefore we developed a procedure for patient-specific segmentation of the target volume. With this volume model X we build up an electrical impedance model $Z(X)$ of the neural target region and simulate the distribution of the electrical field $E(X, P)$ of virtually placed stimulation electrodes P for finding the optimum position $P^\star$ for DBS treatment. First simulation results of regular field distribution are available and we currently investigate anisotropic electrical field modelling.

Navigating to the target position requires localisation of the electrodes position relative to the target. Up to five test electrodes are inserted in parallel as positioning errors due to technical inaccuracies and brain shift prevent from exact target positioning. MER signals are being recorded and classified with respect to the neural activity of the traversed areas while the electrodes are moved stepwise towards the target position. For classification of MER signals from STN area we have developed a procedure which labels the STN intervals on the traversing paths of the electrodes. A localisation of the labelled paths with respect to the patient's STN can be achieved by finding the best match of the STN's shape derived from the volumetric model with the borders of the STN intervals. The latter methods have basically been developed earlier [1]. Here, we show results when used in an integral system (DBS-suite).

Modelling of the STN

The STN and the substantia nigra (SNr) are barely discriminable in common MRI, therefore we model them together (STN+SNr) and divide them eventually. For patient-specific modelling of the STN+SNr object a two-stage approach is used. First, during registration, a SWAN (susceptibility-weighted MR sequence by General Electric) image of the patient is matched to a template image by a nonlinear

model-based transformation. The image of a particular patient where the STN+SNr is visualised best has been chosen as template . Second, for refinement, a deformable statistical model (active shape model) of the STN+SNr shape is created. The model is built up of automatically generated Landmarks and described as a point distribution model (PDM) $X = X_{mean} + v \cdot p$. The term $v \cdot p$ models the variability of the shape X from the mean shape X_{mean}. In order to generate a morphologically valid model X the statistical distrubition of p as seen in the training set must be adhered to. The statistical model was created from training images of seven patients. Thus, a volumetric model of STN+SNr is automatically achieved after surface smoothing (Fig. 1).

Figure 1: Volumetric model of STN+SNr (green, blue); Nucleus Ruber (red, turquoise)

MER classification and electrode localisation

MER signals can be distinguished and assigned to the specific neural areas they were recorded from. We developed a method for classification of MER signals in two steps. First, MER signals are denoised by soft-thresholding and features are extracted using multi-level decomposition and wavelet transformations. Two features are used, one measuring the MER's background activity, and one measuring the variance of the denoised and decomposed signal. Second, a Fuzzy classifier is trained for discriminating MER signals as neural or non-neural with respect to STN.
A spatial model of STN intervals on the electrode's paths is derived from the MER classification and matched with the STN model. Electrodes are considered as straight lines and their intersections with the STN model are calculated. A measure is used to compare the deviations of the model intersections for a set of possible geometric configurations and to find the optimal match. Figure 2 shows a fusion of electrode's paths after registration with a STN model.

DBS-Suite

A framework using MATLAB has been implemented, integrating existing components for automatic target segmentation, determination of optimal trajectories to the selected target point, and MER analysis. Patient MRI-data is aligned to a brain template by applying a rigid body transformation and algorithms are then carried out in a standard coordinate space. All steps are accompanied by a user friendly graphical interface (GUI) including 2D and 3D visualization capabilities.

Figure 2: Localisation of electrodes positions in STN+SNr model (from MER classification derived STN+SNr borders labelled green on electrodes paths)

Results

Patient-specific DBS planning and navigation is possible with volumetric models of neural target areas automatically extracted from patient's MRI. Simulation of the electrical field that is propagating from the electrode can visualize covering of neural areas by the stimulation field and allows for distinct positioning of the electrode. Extracting the intra-operative electrode's positions from MER data and matching it with the 3D target model allows to verify the final electrode's position.

Discussion

With the lack of a gold standard, no evident statement of the quality of the volumetric modelling can be made. However, we provide an objective method for STN modelling simplifying patient specific DBS planning. Evaluation of isotropic field simulation has been started in vitro and anisotropic modelling now requires appropriate ex vivo models. In contrast to other approaches [2] we provide an integrated solution for a patient-specific DBS planning and navigation.

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