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Semi-automatic stereotactic coordinate identification algorithm for routine localization of Deep Brain Stimulation electrodes

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ABSTRACT

Deep Brain Stimulation (DBS) is a routine therapy for movement disorders, and has several emerging indications. We present a novel protocol to define the stereotactic coordinates of metallic DBS implants that may be routinely employed for validating therapeutic anatomical targets.

Patients were referred for troubleshooting or new DBS implantation. A volumetric MRI of the brain obtained prior to or during this protocol was formatted to the Anterior Commissure–Posterior Commissure (AC–PC) coordinate system. Patients underwent a CT scan of the brain in an extended Hounsfield unit (EHU) mode. A semi-automatic detection algorithm based on a Normalized Mutual Information (NMI) co-registration method was implemented to measure the AC–PC coordinates of each DBS contact. This algorithm was validated using manual DBS contact identification.

Fifty MRI-CT image pairs were available in 39 patients with a total of 336 DBS electrodes. The median and mean Euclidean distance errors for automatic identification of electrode locations were 0.20 mm and 0.22 mm, respectively.

This method is an accurate method of localization of active DBS contacts within the sub-cortical region. As the investigational indications of DBS expand, this method may be used for verification of final implant coordinates, critical for understanding clinical benefit and comparing efficacy between subjects.

1. Introduction

Deep Brain Stimulation (DBS) has become a routine therapy for the management of medically intractable symptoms of movement disorders (Kiss et al., 2007; Krack et al., 2003), and is an experimental therapy for psychiatric disorders (Lozano et al., 2008; Malone et al., 2009). Studies that have provided group data on therapeutic electrode locations have brought into question the effective target for Parkinson's disease in the subthalamic region (Vergani et al., 2007). Precise measurement of active DBS contacts is therefore indicated for refining accepted targets for neurostimulation. This study presents a semi-automatic technique for the routine postoperative measurement of DBS electrode locations for the purpose of relating stimulation location with clinical benefit from therapy.

The standard frame of reference used in stereotactic neurosurgery is based on an orthogonal coordinate system with the mid-commissural point (MCP) as the origin. The y-axis is defined by the anterior and posterior commissures (AC, PC). The xy, or AC–PC plane is the axial plane coplanar with AC and PC, readily identified on Magnetic Resonance (MR) imaging. Stereotactic targets are planned as a three-dimensional vector [**x**, **y**, **z**] from MCP (formula-based targeting) or from surrounding sub-cortical structures (indirect targeting). Although Computed Tomography (CT) imaging is ideal for visualization of the implanted electrode, it may be inadequate for visualization of the AC and PC due to streak artifact from metallic implants. Co-registration of MR and CT image volumes is ideal for the localization of implanted sub-cortical metallic electrodes as these techniques are complementary. The MRI provides a frame of reference, whereas the CT provides accurate imaging of the implanted electrode.

Standard CT imaging has limited capability to differentiate between metals of different forms (e.g. thin wire vs solid metal contact). The Hounsfield unit (HU) scale, the grayscale for CT images, is an arbitrary scale of density or attenuation that is calibrated to biological tissue with water defined as 0 HU. Software algorithms for CT scanners typically limit the range of Hounsfield units to ±1000–3000 HU. Biological tissues are expected to have a range from −1000 HU (air) to +1000 HU (bone) (Jackson and Thomas, 2004). The upper and lower values of the scale are therefore inclusive of the range for biological tissues, but metallic implants have attenuation values above this range. Thus, standard CT bins the grayscale values for metal into a single maximum value and therefore is unable to differentiate, on the basis of voxel intensity, metal in an insulated DBS wire from the solid metal contacts that deliver

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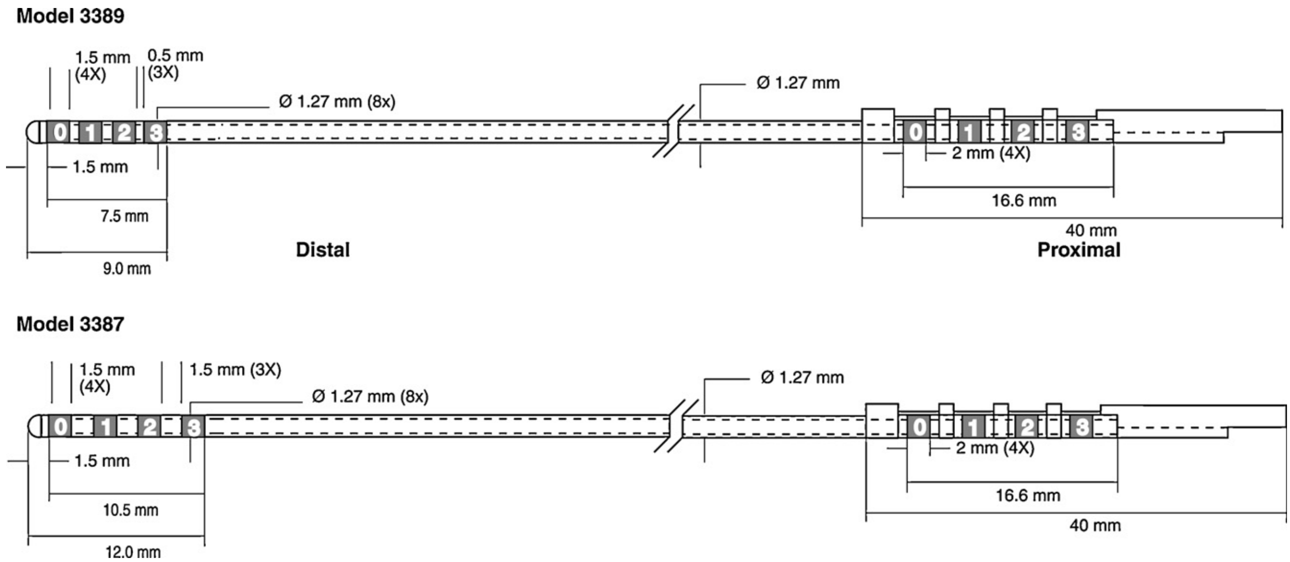

Fig. 1. Medtronic® model 3389 and 3387 Deep Brain Stimulation electrode specifications (reprinted with the permission from Medtronic, Inc. © 2008).

the electrical stimulation to the brain. An extended Hounsfield unit (EHU) mode is available on commercial CT scanners to improve the resolving capacity for metallic structures (Klotz et al., 1990; Link et al., 2000). This imaging algorithm increases the maximum HU value from 2^{12} HU to 2^{15} HU, allowing for the resolution of different metallic radio-opacities, and is ideal for visualizing DBS electrodes (Hebb and Poliakov, 2009).

DBS leads consist of four platinum/iridium exposed active contacts and platinum/iridium insulated wires. Based on our observations of routine skull x-rays, the active contacts have a greater attenuation than the insulated wires (Fig. 2A). We hypothesized that active contacts could be readily isolated from all other metallic material (i.e. the wires) using EHU-CT, and a straightforward semi-automatic detection algorithm could accurately measure the coordinates with respect to the AC–PC reference frame. We present a technique using intra-subject multimodality registration of MRI and EHU-CT imaging for the localization of DBS electrode contacts using simple thresholding to isolate active contacts of the DBS electrode. This "semi-automatic" algorithm streamlines the process of measuring DBS electrode locations postoperatively.

2. Methods

Image analysis presented in this report was performed during the course of routine clinical practice of movement disorder surgery for approved indications for DBS. Approval for the preparation of this manuscript was obtained from our Institutional Review Board.

All subjects in this study underwent implantation of unilateral or bilateral DBS electrodes. Specifications for the implanted Medtronic (Minneapolis, MN) model 3387 and 3389 DBS leads are presented in Fig. 1.

2.1. Image acquisition

A high resolution volumetric MRI of the brain was required for this protocol to define the AC–PC frame of reference. All post-DBS implantation MRIs were performed on a 1.5 T Phillips Medical Systems unit following safety guidelines accepted for DBS systems. Historical MRIs were used for patients with wire fractures due to the risk of heating in the DBS system. Pre-implantation and historical MRIs were performed on various systems. CT scans were performed on a General Electric VCT 64 detector system with Advantage Workstation version 4.4 using the EHU mode. Unmodified DICOM (Digital Imaging and Communications in Medicine) standard image files were converted to NIFTI-1 (Neuroimaging Informatics Technology Initiative) format (Data-Format-Working-Group) using SPM5 software platform (www.fil.ion.ucl.ac.uk/spm/), running under MATLAB (The Mathworks, Natick, MA). NIFTI-1 format stores both an image volume in a three-dimensional array ("voxel-space") and a 4 × 4 transformation matrix representing a scale factor and a rigid-body rotation and translation to align the volume to AC–PC ("real-world") space.

2.2. Semi-automated detection routine

A semi-automated algorithm was written in MATLAB script to (1) transform the MR image volume into AC–PC space, (2) perform co-registration of CT and MRI volumes, and (3) detect and report coordinates of active DBS electrodes in AC–PC space. This routine requires prior conversion of DICOM images to NIFTI-1 format, and manual selection of AC, PC, and midline voxels on the MRI volume on the SPM platform.

2.3. Transformation of MR image volume into AC–PC space

Voxel coordinates of AC, PC, and midline coordinates on the MRI volume were recorded using SPM and stored in a parameter file. The semi-automated routine calculated the transformation matrix for a rigid-body rotation and translation to place the MRI in the AC–PC frame of reference. This was calculated in a multi-step fashion by first translating the volume to place the origin at the AC, subsequently rotating the volume about orthogonal axes to align the AC–PC plane with the *xy* plane, and finally translating the volume to shift the MCP to the origin. The final transformation matrix was stored in the NIFTI-1 image header.

2.4. Automatic EHU-CT – MRI co-registration

SPM routines were used to calculate the rigid-body transformation of the EHU-CT volume to best-fit the MRI volume based on a Normalized Mutual Information (NMI) algorithm (Pluim et al., 2003). The AC–PC aligned MRI was used as the reference vol-