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Computed tomographic method to quantify electrode lead deformation and subdural gap after lead implantation for deep brain stimulation

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ABSTRACT

Background: Deep brain stimulation is an effective treatment for movement disorders and psychiatric conditions. Intra-operative and post-operative events can result in brain tissue deformation (i.e. subdural gaps) which may cause lead deformation and its displacement from optimal target. We developed a method to quantify post-operative lead deformation and we present two DBS cases to illustrate the phenomena of lead deformation resulting from the development of subdural gaps.

New method: We present a semi-automatic computational algorithm using Computed Tomography scanning with reconstruction to determine lead curvature relative to a theoretical straight lead between the skull entry site and lead tip. Subdural gap was quantified from the CT scan.

Results: In 2 patients who had leads implanted, analysis of CT scans was completed within 5 min each. The maximum deviation of the observed lead from the theoretical linear path was 1.1 and 2.6 mm, and the subdural gap was 5.5 and 9.6 mL, respectively.

Comparison with Existing Method(s): This is the first method allowing a comprehensive characterization of the lead deformation in situ.

Conclusions: The computational algorithms provide a simple, semiautomatic method to characterize in situ lead curvature related to brain tissue deformation after lead placement.

1. Introduction

Deep brain stimulation (DBS) is an effective treatment for movement disorders (Starr et al., 1998) and some psychiatric conditions (Lakhan and Callaway, 2010). A DBS electrode lead placed in a selected brain area is used to administer a small amount of electricity locally. Although there is controversy about the mechanism of action of DBS, the electricity applied by a train of pulses may modulate local and distal neuronal activity and change pathologic brain activity (Andres and Darbin, 2018; Chiken and Nambu, 2016; Dostrovsky and Lozano, 2002). In movement disorders, targeted nuclei for DBS include the subthalamic nucleus, globus pallidus internus, and thalamus. Misplacement of the electrode lead may decrease benefits and increase adverse events (Okun et al., 2005).

During neurosurgery for electrode lead placement, regional brain tissue deformation can occur from air entry and fluid accumulation between the dura and cortices causing a subdural gap (Halpern et al., 2008; Miyagi et al., 2007; van den Munckhof et al., 2010). Postoperative resolution of deformation and electrode lead ductility may cause lead curvature and displacement from the optimal target area. As of today, brain imaging has limited accuracy in visualizing and quantifying postoperative electrode lead position regarding to the optimal target areas. Therefore, it is important to monitor changes in DBS lead shape in-situ to evaluate the contribution of brain deformation on the short- and long-term efficacy of DBS therapy.

We hypothesized that in situ changes in DBS electrode lead curvature may enable the characterization of changes in perioperative lead position (Martinez-Ramirez et al., 2014) and developed a method to quantify in situ DBS lead curvature relative to the line of lead insertion. The purpose of this article is to describe and illustrate the use of this

Abbreviations: DBS, deep brain stimulation

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method in 2 patients who had postoperative changes in DBS lead curvature and subdural gap.

2. Materials and methods

2.1. Patients

This study was performed with 2 patients. Patient A is 21-year-old male with right-hand dystonia that began at age 18 years and progressed to include the left-hand and forearm during the 18 months before presentation. He also developed right elbow flexion, shoulder abduction, and hip, knee, and ankle dystonia during the 9 months before presentation. He remained unable to use his right hand despite treatment with carbidopa, levodopa, trihexyphenidyl, baclofen, botulinum toxin, and cyclobenzaprine, and he was referred for left globus pallidus internus DBS.

Patient B is a 58-year-old female with Parkinson disease that began with left hand tremor at age 46 years and was treated with carbidopa, levodopa, amantadine, trihexyphenidyl, and rasagiline. She had persistent dyskinesia at low doses of levodopa and a bothersome hand tremor despite levodopa and was referred for right subthalamic nucleus DBS.

The study was reviewed and approved by the University of South Alabama Institutional Review Board.

2.2. Surgery

The DBS electrode lead placement surgery was performed with stereotactic guidance (Nexframe, Medtronic, Fridley, MN, USA). After preoperative planning for each patient, bone fiducial marks were registered, the planned incision was marked, and surgery was performed with sterile technique, mild sedation, and local anesthesia. A small craniotomy (or burr hole) was made with meticulous attention to hemostasis. A burr hole cover (STIMLOC, Medtronic) was secured to the skull for mini frame attachment, and the frame was navigated (StealthStation S7 System, Medtronic) and locked into position. The motor drive was attached and 4 microelectrode recording needles were inserted to an initial position 10 mm above target. After mapping was completed, the lead (Lead 3387S-40, Medtronic, USA) was placed and secured to the skull with a locking cap.

2.3. Computed tomography

Three-dimensional computed tomography (CT) was performed immediately after surgery using a 64-slice scanner (Philips Brilliance CT scanner, Philips Medical Systems, Best, The Netherlands). The helical CT scan protocol included a lateral scout view and axial image acquisition extending from the vertex of the head to the hard palate, The following technical parameters were used: Pitch, 0.673 mm; collimation, 64 × 0.625 mm; rotation time, 0.75 s; matrix, 512 × 512 pixels. Axial image reconstruction was performed with a brain smooth UA filter (slice thickness, 3 mm; increments, 3 mm).

2.4. Electrode lead position

The CT scan was used to determine the electrode lead position in the brain. The skull entry point and lead tip were established on the transverse (or axial plane) of the CT scan (Figs. 1 and 2). The skull entry point was identified on the axial plane that best met the criteria for inclusion of the lead on the density line from the skull border. The lead tip was identified on the last axial plane with nominal density before fading.

Analysis of axial images was started at the skull entry point coordinate E(x, y, z). A method that was based on region growing and nearest neighbor principles was used to extract and isolate lead and tissue areas of CT brain images (Sandor et al., 1991). The region was grown iteratively from E(x, y, z) by comparing all unallocated neighboring pixels in the plane that was axial to the region. The difference between pixel vs mean region intensity was used as a measure of similarity. The pixel with the smallest difference measured was allocated to the respective region. The iterative process was stopped when the difference between mean region mean vs new pixel intensity became larger than a predefined threshold; for a Digital Imaging and Communications in Medicine (DICOM) file with standardized scales between 0 and 1, a threshold value of 0.1 enabled lead delimitation for all CT scans.

The center of mass of the lead was calculated and used to localize the lead in each plane. The center of mass coordinates was used in a similar calculation in the adjacent plane toward the lead tip; this was feasible because the lead trajectory was curvilinear, without any bifurcation or deformation that would exceed the lead radius section between 2 axial planes. The series of lead center of mass values that were determined between the skull entry site and lead tip defined the observed lead path (Fig. 3).

2.5. Lead deviation from linear path

The lead skull entry site and tip points were used to define a theoretical linear lead path. A line algorithm was used to determine the points of the 3-dimensional raster (scaled on the voxel dimension) that best approximated a straight line between the lead skull entry site and tip points (Bresenham, 1965). The maximum Euclidean distance between the observed and the theoretical linear paths was used as a measurement of the curvature of the lead in the brain (Fig. 3).

A circular histogram was used as a graphic tool to provide a succinct view of the distribution of electrode lead curvature in distance and direction. Using a polar coordinate system, the frequency of bend over the dorsoventral axis was plotted against direction, and color bands were used to represent distance ranges. The direction of the longest spoke showed the bend direction that had the greatest frequency (Fig. 5).

2.6. Postoperative subdural gap

The subdural gap formed during the surgical procedure was quantified using a semi-assisted algorithm that was similar to the algorithm used to evaluate the lead position, but the subdural gap had a less predictable shape between planes because of the presence of independent pockets and bifurcations. Therefore, a user-defined plane was selected to identify the initial pixel for each subdural gap (Fig. 4). All calculations were performed in Matlab environment (MATLAB R2013b, MathWorks, Natick, MA, USA).

3. Results

The methodology described above allowed to characterize the lead curvatures in less than 2 min and the subdural gap in less than 5 min. The maximum deviation of the observed lead from the theoretical linear path was 1.1 mm in the man and 2.6 mm in the woman patient (Fig. 3). For both patients, the longest spoke of the polar histogram pointed toward the rostral direction (Fig. 4). The subdural gap volume in the male patient was 5.5 mL and female patient was 9.6 mL (Fig. 5).

4. Discussion

The semiautomatic method was based on device-compatible CT scanning and enabled a quantitative description of the DBS electrode lead curvature vs the theoretical straight lead path. The region growing method enabled the definition of lead surface area in each CT axial plane. It was intuitive for the user to define the skull entry point as the initial point, and the algorithm based on CT scan readily provided the center of mass of the lead as the new point for the algorithm calculation