

# Accuracy of deep brain stimulation electrode placement using intraoperative computed tomography without microelectrode recording

## Clinical article

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**Object.** In this prospective study the authors' objective was to evaluate the accuracy of deep brain stimulation (DBS) electrode placement using image guidance for direct anatomical targeting with intraoperative CT.

**Methods.** Preoperative 3-T MR images were merged with intraoperative CT images for planning. Electrode targets were anatomical, based on the MR images. A skull-mounted NexFrame system was used for electrode placement, and all procedures were performed under general anesthesia. After electrode placement, intraoperative CT images were merged with trajectory planning images to calculate accuracy. Accuracy was assessed by both vector error and deviation off the planned trajectory.

**Results.** Sixty patients (33 with Parkinson disease, 26 with essential tremor, and 1 with dystonia) underwent the procedure. Patient's mean age was  $64 \pm 9.5$  years. Over an 18-month period, 119 electrodes were placed (all bilateral, except one). Electrode implant locations were the ventral intermediate nucleus (VIM), globus pallidus internus (GPI), and subthalamic nucleus (STN) in 25, 23, and 12 patients, respectively. Target accuracy measurements were as follows: mean vector error  $1.59 \pm 1.11$  mm and mean deviation off trajectory  $1.24 \pm 0.87$  mm. There was no statistically significant difference between the accuracy of left and right brain electrodes. There was a statistically significant (negative) correlation between the distance of the closest approach of the electrode trajectory to the ventricular wall of the lateral ventricle and vector error ( $r^2 = -0.339$ ,  $p < 0.05$ ,  $n = 76$ ), and the deviation from the planned trajectory ( $r^2 = -0.325$ ,  $p < 0.05$ ,  $n = 77$ ). Furthermore, when the distance from the electrode trajectory and the ventricular wall was  $< 4$  mm, the correlation of the ventricular distance to the deviation from the planned trajectory was stronger ( $r^2 = -0.419$ ,  $p = 0.05$ ,  $n = 19$ ). Electrodes placed in the GPI were significantly more accurate than those placed in the VIM ( $p < 0.05$ ). Only 1 of 119 electrodes required intraoperative replacement due to a vector error  $> 3$  mm. In this series there was one infection and no intraparenchymal hemorrhages.

**Conclusions.** Placement of DBS electrodes using an intraoperative CT scanner and the NexFrame achieves an accuracy that is at least comparable to other methods.  
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**KEY WORDS** • deep brain stimulation • intraoperative computed tomography •  
general anesthesia • functional neurosurgery

**D**EEP brain stimulation is currently used to treat medically intractable Parkinson disease,<sup>3,4,16</sup> essential tremor,<sup>1</sup> congenital and acquired dystonias,<sup>7,15</sup> and other movement disorders.<sup>9</sup> Class I evidence now supports its use in patients with advanced Parkinson disease, in comparison with best medical therapy.<sup>3,4,16</sup> Deep brain stimulation electrodes have conventionally been placed using frame-based stereotaxy with MER and physiological mapping of target structures. However, there is no extant Class I or II evidence demonstrating that MER improves the safety, accuracy, or efficacy of DBS electrode implan-

tion. In fact, it has been recently suggested that MER introduces significant additional risk.<sup>5,17</sup>

In the early stereotactic era, MER provided physiological verification of target acquisition based on ventriculography-based coordinates. Although MER systems have improved dramatically, MER still requires special equipment and expertise, requires dedicated intraoperative time to perform the recordings, and in most cases mandates that procedures are performed on awake patients under local anesthesia. Advanced MRI now allows direct visualization of target centers, a development that should reasonably raise the question of MER's value for routine movement disorder surgery.

We describe the methodology involved in and the accuracy of DBS electrode placement in patients under gen-

*Abbreviations used in this paper:* DBS = deep brain stimulation; GPI = globus pallidus internus; MER = microelectrode recording; STN = subthalamic nucleus; VIM = ventral intermediate nucleus.

eral anesthesia in whom an intraoperative CT scanner is used.

## Methods

### Patients

The first 60 consecutive patients who underwent intraoperative CT-guided DBS electrode placement were prospectively included. The study was approved by the Oregon Health & Science University Institutional Review Board. All patients were evaluated in the movement disorder program of Oregon Health & Science University to establish surgical candidacy.

### Imaging

Prior to surgery, 3-T MR images were obtained for DBS targets in all patients, using the following sequences: for the VIM, a standard 3D T1-weighted image with TE 4.61 msec, TR shortest, flip angle 30, voxel size 1.02, matrix 256 × 256; for the STN, a FLAIR sequence with TE 140 msec, TR 14,000 msec, slice thickness 2.5 mm, voxel size 1.02, matrix 256 × 256; and for the GPI an MPRAGE sequence with TE 80 msec, TR 8000 msec, slice thickness 2 mm, voxel size 0.6, matrix 256 × 256.<sup>13</sup> These digital imaging and communications in medicine (DICOM) images were downloaded into a StealthStation (Medtronic Inc.) via a network connection.

### Surgical Technique

Implant procedures were carried out in 2 stages. The first stage was an inpatient procedure for implantation of the DBS electrodes, and the second stage was the implantation of the internal pulse generator, performed on an outpatient basis approximately 1 week later.

Implantation of the DBS electrode(s) using extraoperative MR images was as described, and surgical planning

of electrode trajectories was carried out preoperatively on the StealthStation. The GPI and STN targets were visualized directly, and the VIM target was derived from the Schaltenbrand and Wahren atlas, utilizing the intercommissural plane and midcommissural point for reference<sup>8</sup> (Table 1).

All procedures were performed under general anesthesia. Following intubation, the patient's head was attached to the operating room table using a Doro Halo Retractor System with carbon-fiber extensions (Pro Med Instruments, Inc., Freiburg, Germany). After sterile preparation of the head, 5 skull-mounted fiducial markers (NexFrame, Medtronic Inc.) were placed. A stereotactic 1-mm-thick, zero-gantry-angle CT image was then obtained using a CereTom CT scanner (NeuroLogica Corp.). Subsequently these DICOM images were transferred to the StealthStation surgery navigation system and merged with the preoperative MR images.

Using a passive planar blunt probe, a nonsterile registration of the skull fiducial markers was then performed to link image and surgical spaces. The bur hole entry point of the predetermined electrode trajectory was then marked on the skin, and a small pilot hole was drilled to mark that point on the skull.

After we performed appropriate sterile preparation and draping, skin incisions were made and bur holes centered on the pilot hole were completed. The lead anchoring device (StimLoc, Medtronic, Inc.) and the NexFrame base were attached to the skull, and a second sterile registration was performed using the implanted fiducials (target registration error < 0.5 mm). The NexFrame tower was then attached and aligned to the corresponding target using FrameLink software (Medtronic Inc.). Target depth was then calculated and set on the StarDrive (FHC Inc.) positioning device. After opening the dura, a cannula was introduced all the way to the target. A DBS lead (Medtronic lead model 3387) was then advanced through the cannula

**TABLE 1: Target-derived coordinates\***

Target Nucleus	Coordinates†	Corresponding Target
STN		center of motor territory of STN
vertical	-4 mm	
lat	12 mm	
AP	-3/-4 mm	
GPI		inf border of motor territory of GPI, immediately sup to optic tract
vertical	-5 mm	
lat	18 mm from lat ventricular wall	
AP	+2 mm	
VIM		labial commissure of VIM
vertical	0 or -1 mm	
lat	50% of AC-PC distance but should be <12 mm of lat ventricular wall	
AP	25-30% of AC-PC distance anterior to PC	

\* The GPI and STN targets were visualized directly, and the VIM target was derived from the Schaltenbrand and Wahren atlas, utilizing the intercommissural plane and midcommissural point for reference. AC-PC = anterior commissure-posterior commissure; AP = anteroposterior; inf = inferior; sup = superior.

† Negative vertical values indicate the inferior; negative AP values indicate the posterior.

to the target position. The cannula was retracted and the electrode secured in the StimLoc system, and fibrin glue was used to prevent egress of CSF. The exposed electrode was then pulled back through the StarDrive, and in most cases, the process was repeated on the opposite side.

With the NexFrame towers in place, a second intraoperative CT scan was obtained to ensure satisfactory electrode placement. This postplacement scan was then merged with the preoperative planning scans, and any off-target error was recorded. Vector error was calculated as the linear distance between the center of the intended target contact on the DBS electrode and the planned target. The electrode was repositioned if the vector error was  $> 3$  mm. An arbitrary value of 3 mm was set as the threshold for lead revision because it is approximately the distance between the center of 2 adjacent contacts on lead model 3387 (3.75 mm); therefore, an error of 3 mm would imply a displacement of approximately one intercontact difference. Once the accuracy of the electrode placement was confirmed by intraoperative CT, no further imaging was carried out on these patients intra- or postoperatively.

After ensuring satisfactory electrode placement, the NexFrame towers were removed and the StimLoc caps applied. The 2 leads were then tunneled to one side of the head away from the incisions and capped, following which the wounds were closed.

### Accuracy Assessment

Two measures were used to assess electrode placement accuracy: 1) vector error, defined as the distance between the position of the center of the target DBS electrode contact ("1" for VIM and STN, and "0" for GPI) and the intended target location as determined by the euclidean distance between these 2 points:  $[(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2]^{1/2}$ ; and 2) deviation off the trajectory, defined as the perpendicular distance from the target electrode to the planned trajectory, reflecting only the radial deviation from plan (Fig. 1). Both values were thought to be useful in determining the accuracy of placement because, while vector error reflected the true accuracy of the procedure, off-trajectory (radial) errors theoretically would be less easily correctable by signing different active contacts during DBS therapy.

The accuracy of electrode placement was compared among all 3 targets (GPI, STN, and VIM). The closest approach of the DBS lead trajectory and lateral ventricle was also measured and correlated with both the vector error and the deviation off trajectory. The postimplantation CT scan was merged with the registration merged CT/MR used for planning the electrode trajectory and target to calculate both the vector error and the deviation off-trajectory distances.

Descriptive statistics (mean  $\pm$  SD) were used to express demographics and patient characteristics. A t-test was used to compare vector and deviation errors. Correlations were tested using the Pearson correlation coefficient. For all comparisons, differences were considered statistically significant at  $p < 0.05$ .

## Results

Sixty patients (33 with Parkinson disease, 26 with

essential tremor, and 1 with dystonia) underwent DBS electrode placement applied with the aforementioned technique. Over an 18-month period, 119 electrodes were placed (all bilateral, except one). The patients' mean age was  $64 \pm 9.5$  years. The locations of the electrode implantations were as follows: VIM in 25 patients, GPI in 23 patients, and the STN in 12 patients. The mean total operating room time (time in to time out) was  $190 \pm 9.8$  minutes.

Final intraoperative CT scanning showed no evidence of intracranial air or any other potential cause for brain shift in any case.

The closest approach of the electrode trajectories to the ventricle was  $6.3 \pm 3.4$  mm (range 1–13.9 mm), and there was no statistically significant difference between sides. The mean overall vector error was  $1.59 \pm 1.11$  mm, and the trajectory deviation error was  $1.24 \pm 0.87$  mm.

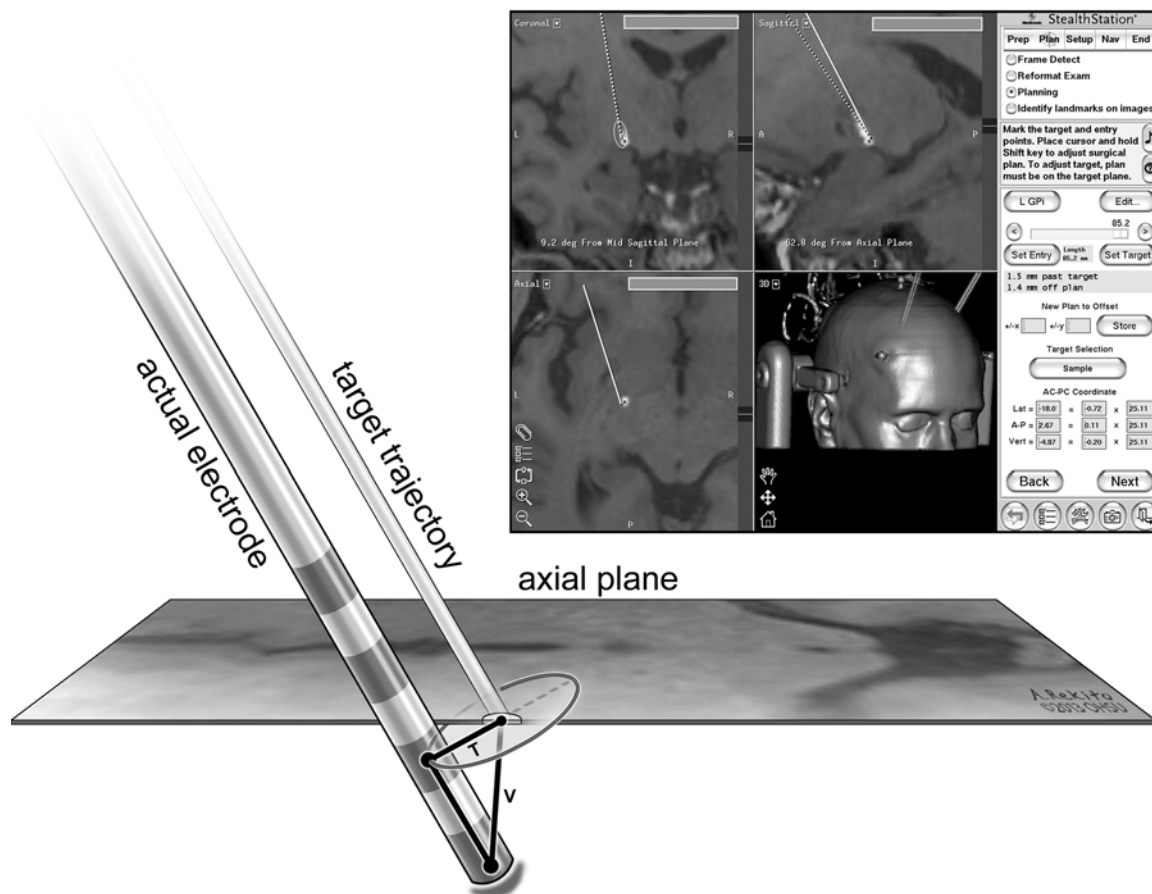
There was a significant correlation between the following: 1) the distance from the ventricle and trajectory deviation error ( $r^2 = -0.325$ ,  $p < 0.05$ ,  $n = 77$ ; Fig. 2A); and 2) the distance from the ventricle and vector error ( $r^2 = -0.339$ ,  $p < 0.05$ ,  $n = 76$ ; Fig. 2B). Furthermore, when the distance from the electrode trajectory and the ventricular wall was  $< 4$  mm, the correlation of the ventricular distance to the deviation from the planned trajectory was stronger ( $r^2 = -0.419$ ,  $p = 0.05$ ,  $n = 19$ ; Fig. 2C). Electrodes placed in the GPI were significantly more accurate than those placed in the VIM (mean vector error 1.29 vs 1.9 mm,  $p = 0.01$ ). There was no statistically significant difference in accuracy comparing the GPI to the STN, the STN to the VIM, or the GPI to the STN and VIM combined. The mean distance from the ventricle for GPI electrodes was 9 mm compared with 4.2 mm for the VIM and 5.15 mm for the STN, and these differences were significant ( $p < 0.05$ ).

In this series, one implanted electrode had a vector error of  $> 3$  mm and was revised. There was one case of a late-onset infection that required explantation of the entire system. There were no hematomas, no new neurological deficits, or deaths.

## Discussion

Using preoperative MRI, intraoperative CT, and a skull-mounted stereotactic system, we were able to achieve an unprecedented degree of accuracy for DBS electrode placement. Our results (1.59 mm vector error) compare favorably with previously reported vector errors for intraoperative MRI (2.18 mm),<sup>12</sup> intraoperative imaging (O-arm) combined with frame-based stereotaxy (1.65 mm),<sup>10</sup> and conventional frame-based stereotaxy without intraoperative imaging (3 mm).<sup>11</sup> The mean trajectory deviation error in our series was 1.24 mm, indicating that displacement was mostly radial and not along the planned trajectory (depth). Our data indicate that the electrode trajectory distance from the ventricle plays a major role in the radial deviation of the trajectory.

We attempted to correlate the vector error and trajectory deviation with factors that would impact the location of the electrodes. The only significant correlation found was the distance of the electrode trajectory from the ventricle. Starr et al. previously reported on the correlation of



**Fig. 1.** Calculation of the trajectory (T) and vector (V) errors. **Inset** demonstrates the MR image merged with the final intraoperative CT scan. The target electrode could be directly visualized, and its Cartesian coordinates (x, y, and z) determined. These coordinates were used to derive the trajectory and vector errors by direct comparison with the coordinates of the planned target. Printed with permission from Andy Rekito, M.S., Oregon Health & Science University.

the vector error and coronal approach angle, where the increased obliquity of the angle caused a higher positional error at the electrode tip.<sup>12</sup> A negative correlation was found between the distance of the electrode from the ventricle and both the vector error and trajectory deviation—in other words, both the vector error and the trajectory deviation were higher (less accuracy) when the electrode trajectory was closer to the ventricle. The strongest correlation was between the deviation error (radial displacement) and the distance from the ventricle in the range of 0–4 mm.

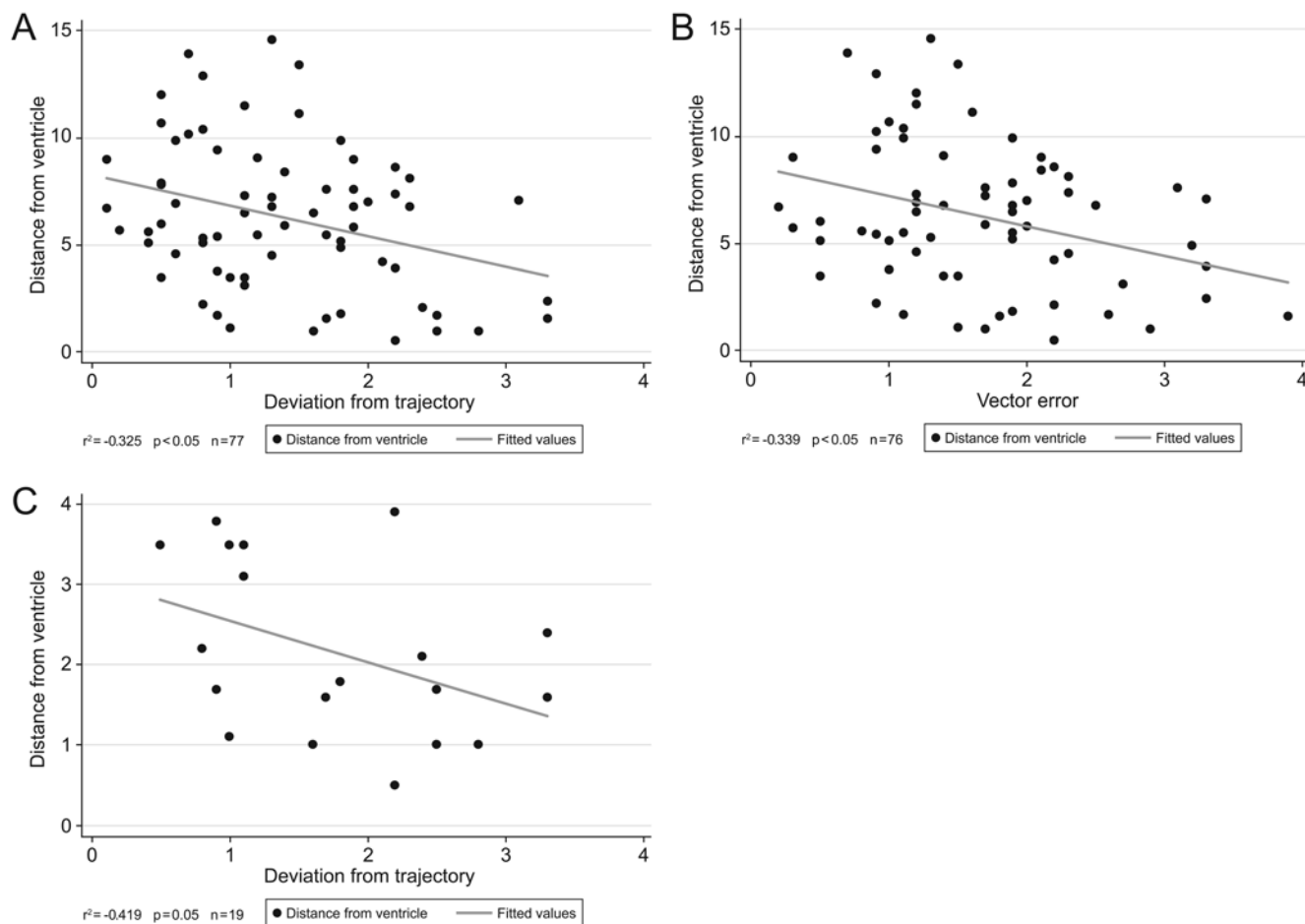
Our analysis also showed that electrode trajectories approaching the GPI are significantly ( $p < 0.01$ ) more distant from the ventricle in comparison with other targets (GPI 9 mm, STN 4.5 mm, and VIM 5.1 mm). Electrodes placed in the GPI were significantly more accurate than those placed in the VIM (mean vector error 1.29 vs 1.9 mm,  $p = 0.01$ ) but not more accurate than those placed in the STN (mean vector error 1.29 vs 1.52,  $p = 0.3$ ). Our data indicate that target trajectories that avoid a close approach to the ventricle are more likely to produce accurate placement. An alternative explanation is that traversing the internal capsule (for example, approaching the VIM target from lateral to medial) may also cause distortion of the brain, with resultant electrode malposition. Trajectories that largely avoided the compact internal capsule (for ex-

ample, the GPI) were significantly more accurate. The reason behind this may well be the differential compliance of nuclei and white matter tracks to the penetrating cannula.

Operative time, which included induction of and initial recovery from anesthesia, CT scanning, and image transfer, was  $190 \pm 9.8$  minutes. Our experience is such that as familiarity and expertise with this method has been acquired, in-room time continues to decrease. In an analysis of overall operative time in a similar cohort of patients who had a more traditional, MER-based approach to DBS electrode placement under local anesthesia, performed by the same primary surgeon (K.J.B.), the mean actual operative time was 145 minutes.

Imaging technology has advanced to the point at which DBS electrode placement based entirely on imaging can be considered a feasible option. Several studies have demonstrated the reliability of image-defined STN and its dorso-lateral subregion as the location for movement-related cells during MER.<sup>14</sup> We capitalized on previous reports that combined the use of a skull-mounted frame (NexFrame), intraoperative imaging, and general anesthesia.<sup>6</sup>

We have developed a method that uses an intraoperative CT scanner and a skull-mounted stereotactic system to place DBS electrodes. Our aim was to exploit the advantages of high-field extraoperative MRI, the availability



**FIG. 2.** **A:** Distance from the ventricle and trajectory deviation error ( $r^2 = -0.325$ ,  $p < 0.05$ ,  $n = 77$ ). **B:** Distance from the ventricle and vector error ( $r^2 = -0.339$ ,  $p < 0.05$ ,  $n = 76$ ). **C:** Distance from the ventricle wall  $< 4$  mm and trajectory deviation error ( $r^2 = -0.419$ ,  $p = 0.05$ ,  $n = 19$ ).

of intraoperative CT scanning, and the capacity to merge images from both sources to provide the basis for target and trajectory planning for DBS surgery. Furthermore, this system could be used to confirm target acquisition and the presence of any operative complications (for example, a hematoma) prior to leaving the operating room. Since this method relies only on anatomical target determination, the use of MER was obviated and therefore the use of general anesthesia was feasible.

This method represents a clear departure from the use of MER and physiological target confirmation during movement disorder surgery. It is our contention that MER has not been, nor will ever be, proven to add value to the implantation of DBS electrodes, or any other movement disorder procedure.<sup>2</sup> Furthermore, there is, in fact, new evidence that MER adds risk to these procedures by way of increased chances of intracerebral hemorrhage and the production new neurological deficits.<sup>5,17</sup> There is little question that MER requires additional expertise, additional operative time, and the additional expense of the recording systems and electrodes. Effectively, MER also requires that procedures be performed under local anesthetic, a daunting prospect for most patients.

We have demonstrated the feasibility and accuracy of

image-guided DBS electrode placement. If this procedure can be shown to produce clinical benefits that are equivalent to those of the more traditional methods using MER, and by historical comparison, proves to be a safer procedure, then the continuance of routine MER-based DBS electrode implantation should be questioned. Microelectrode recording may well then be relegated to the position of a research technique, potentially requiring additional informed consent by the patient. A prospective outcome assessment trial of image-guided DBS electrode implantation in patients with medically intractable Parkinson disease is already underway at our institution.

### Conclusions

We have described a new method of DBS electrode placement using intraoperative CT, without MER, and under general anesthesia. Initial results indicate the procedure is safe, with accuracy comparable to methods using MER under local anesthesia.

### Disclosure

The authors report no conflict of interest concerning the mate-

rials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Raslan, Burchiel. Acquisition of data: Raslan, Burchiel. Analysis and interpretation of data: Raslan. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Raslan. Statistical analysis: Raslan. Administrative/technical/material support: McCartney. Study supervision: Burchiel.

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