Improving surgical treatment for movement disorders

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Chapter 2

Postoperative curving and upward displacement of deep brain stimulation electrodes caused by brain shift

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ABSTRACT

Objective
Accurate electrode position is important for the efficacy of deep brain stimulation (DBS). Several reports revealed errors during stereotactic surgery due to cerebrospinal fluid (CSF) loss and subdural air invasion. Because subdural air resolves in the weeks following surgery and the brain returns to its original position, DBS electrodes may become displaced postoperatively. The aim of this study was to quantitatively assess postoperative DBS electrode displacement in relation to subdural air invasion.

Methods
We retrospectively analyzed fourteen patients with advanced Parkinson's disease and subthalamic nucleus DBS electrodes that underwent immediate postoperative frame-based stereotactic computer tomography (CT) and repeated CT after longer follow-up. We performed volumetric measurements of postoperative subdural air collections on both sides of the brain and determined stereotactic coordinates of the deepest DBS contact on the direct postoperative and follow-up CT.

Results
Subdural air collections measured on average 17 cm$^3 \pm 24$. Consequently, the frontal cortex shifted posteriorly. On follow-up imaging after 16 months $\pm 8$, air collections had resolved and the frontal cortex had returned to its original position, causing anterior curving of the electrodes. The electrodes moved on average 3.3 mm $\pm 2.5$ upward along the trajectory. This displacement significantly correlated with the amount of postoperative subdural air.

Conclusion
Considerable displacement of DBS electrodes may occur in the weeks following surgery, especially in cases with large postoperative subdural air volumes. Postoperative documentation of electrode localization should therefore be repeated after longer follow-up.
INTRODUCTION

Treatment success of deep brain stimulation (DBS) surgery depends on careful patient selection, localizing the neural structure anatomically, neurophysiologically and functionally, accurate electrode positioning and meticulous postoperative care. An underlying stereotactic assumption is that anatomical structures do not move between preoperative image acquisition and surgery, during surgery and postoperatively. However, several recent reports revealed errors during the stereotactic procedure due to cerebrospinal fluid (CSF) loss and subdural air invasion, resulting in shift of up to 5 mm of deep brain structures on pre- and postoperative magnetic resonance imaging (MRI).\textsuperscript{1-4} This brain shift caused failure of DBS leads to be implanted at the intended stereotactic coordinates.\textsuperscript{4} Operative subdural air invasion resolves in the weeks following surgery. Because the brain returns to its original position, DBS electrodes may move after surgery, in the first postoperative weeks. To assess this phenomenon, we determined DBS electrode localization on immediate postoperative stereotactic imaging and compared this with electrode position after longer follow-up.

PATIENTS AND METHODS

We retrospectively analyzed data obtained in all patients with advanced Parkinson’s disease (PD) that underwent bilateral or unilateral subthalamic nucleus (STN) DBS surgery with intraoperative neuronal microrecordings and immediate postoperative stereotactic computer tomography (CT) between 2003 and 2005.

Surgical targeting and procedure

Preoperative frame-based MRI, parallel multi-tract microrecordings and macrostimulation were used for target localization. All patients were operated without sedation in supine position with the head elevated at 10-20°. In bilateral cases, surgery started on the left side. One to five parallel steel canulas and microelectodes were inserted through a 12-mm-diameter precoronal burr hole placed 3-4 cm lateral from the midline. None of the planned microelectrode trajectories penetrated the lateral ventricles. All steel canulas stayed in place throughout the surgical procedure, including during electrode implantation. A quadripolar DBS electrode (model 3389\textsuperscript{®}; Medtronic, Minneapolis, MN) was implanted under fluoroscopic guidance and fixed at the border of the burr hole with a custom made titanium microplate and plastic covering to prevent electrode damaging (similar to the technique reported by Favre et al.\textsuperscript{5}). Two to seven days after electrode implantation, bilateral pulse generators (Soletra\textsuperscript{®}; Medtronic, Minneapolis, MN) were implanted in a subcutaneous pocket in the infraclavicular region under general anesthesia.
CT measurements
Because of manufacture’s recommendations and hospital regulations at the time, postoperative MRI was not allowed. A postoperative stereotactic CT (MX 8000 multislice CT; Philips, Eindhoven, The Netherlands) with 2-mm slices was performed immediately after electrode implantation, with the stereotactic frame still in place. After several months, patients underwent a follow-up CT at 2-mm slices that was co-registered with the stereotactic CT using Leksel SurgiPlan® software (Elekta Instruments AB, Stockholm, Sweden). We delineated subdural air collections on both sides of the brain independently in all patients on three-dimensional reconstruction of the immediate postoperative stereotactic CT and measured volumes using Leksel SurgiPlan® software. Stereotactic coordinates of the metallic artifact of the deepest contact of DBS electrodes were determined on the immediate postoperative and follow-up CT. Differences in stereotactic coordinates were calculated to measure postoperative displacement of the DBS electrodes in three dimensions. Total electrode displacement was calculated as the scalar quantity derived from $X^2+Y^2+Z^2$.

Statistical analysis
The relationship between X-, Y- and Z-coordinate and total displacement of DBS leads, volume of postoperative subdural air collections, length of surgery, number of parallel used microelectrodes, age, duration of Parkinson’s disease and follow-up time was assessed with linear regression and Pearson r statistic. In bilateral cases, data from the side operated first (left) and second (right) were compared using the Student’s t-test. Mean values are presented ± standard deviation (SD).

RESULTS
Between 2003 and 2005, 29 patients with advanced PD underwent bilateral or unilateral STN DBS surgery using intraoperative neuronal microrecordings. Sixteen of these had immediate postoperative frame-based stereotactic CT. In 13 patients, electrode position was only verified by peroperative frame-based fluoroscopy or stereotactic X-ray. Two of the 16 patients with immediate postoperative frame-based stereotactic CT were excluded from data analysis because of movement artifacts and incomplete scanning. Thus, a total of 14 patients were analyzed, 13 with bilateral and one with unilateral STN DBS. Ten were women, mean age was 56.9 years ± 8.2 (range 41.5-69 years), mean duration of Parkinson’s disease was 12.3 years ± 5 (range 2-20 years), mean number of parallel used microelectrodes was 3.6 ± 1.1 (range 1-5), mean length of bilateral surgery was 262 minutes ± 31 (range 190-320 minutes), length of surgery of the unilateral case was 119 minutes, mean follow-up time between operation and follow-up CT was 16 months ± 8 (range 5-30 months).
Subdural air volume
Measurement of postoperative subdural air collections revealed air volumes between 0 and 88 cm³, with a mean of 17 cm³ ± 24. The amount of subdural air did not correlate with the number of parallel used microelectrodes, length of surgery, age or duration of disease (data not shown). In bilateral cases, the amount of subdural air on the side operated first (left, mean 18 ± 22 cm³) and second (right, mean 16 ± 27 cm³) were statistically comparable (P=0.25).
Because of postoperative subdural air collections, frontal cortex shifted posteriorly (Figure 1A and 1C). On all follow-up CTs, air collections had resolved and the frontal cortex had returned to its original position.

Postoperative DBS electrode displacement
One DBS electrode was excluded from data analysis because infection at the proximal connector of the extension cable and subsequent removal two months after implantation resulted in considerable electrode displacement and repositioning four months after initial surgery. Thus, a total of 26 DBS leads were analyzed.
None of the electrodes penetrated the lateral ventricle. Analysis of electrode tracts on semi-sagittal CT reconstructions parallel to the electrodes showed straight tracts to intended targets on immediate postoperative CTs (Figure 1A and 1C), but anteriorly curved electrode tracts on follow-up CTs (Figure 1B and 1D). In patients with larger volumes of subdural air, electrode tracts showed more anterior curving (compare Figure 1B and 1D). As a result, electrode contacts moved upward from their intended targets.
Figure 1. Analysis of electrode tracts on semi-sagittal CT reconstructions parallel to the electrodes on direct postoperative CT and follow-up CT of two patient-examples with postoperative subdural air collections, patient 1 (A and B) and 2 (C and D). Direct postoperative CTs (A and C) show subdural air collections, posteriorly shifted frontal cortex and straight electrode tracts, whereas follow-up CTs (B and D) show resolved subdural air collections and anteriorly curved electrode tracts. As a result, electrode contacts moved upward from their initial targets, marked by the black crosses. Note that the larger volume of postoperative subdural air in patient 2 compared to patient 1 was associated with more anterior electrode-curving and more upward displacement.

The displacement in stereotactic X-coordinate of the metallic artifact of the deepest contact of DBS leads on immediate postoperative and follow-up CT varied between 0 mm to 4.5 mm more lateral (mean 1.2 mm ± 1). The displacement in stereotactic Y-coordinate varied between 0 and 7.5 mm more anterior (mean 1.2 mm ± 1.6). The displacement in stereotactic Z-coordinate varied between 0 and 10 mm more dorsal (mean 2.6 mm ± 2). Total displacement along electrode trajectories (X, Y, Z combined) varied between 0 and 13.3 mm upwards (mean 3.3 mm ± 2.5). There was significant correlation between the amount of postoperative subdural air and X-coordinate displacement ($r^2=0.39$, $P=0.01$), Y-coordinate displacement ($r^2=0.50$, $P=0.01$), Z-coordinate displacement ($r^2=0.68$, $P=0.01$) and total electrode displacement ($r^2=0.70$, $P=0.01$, figure 2). In bilateral cases, total electrode displacement on the side operated first (left, mean 3.0 mm ± 1.8) and second (right, mean 3.6 mm ± 3.2) did not differ statistically ($P=0.20$), neither did their correlation with the amount of postoperative subdural air ($r^2=0.62$ and $r^2=81$ respectively, $P=0.40$).

When we exclude the three DBS leads with exceptionally large volumes of postoperative subdural air from analysis, i.e. the ones with 53, 77 and 88 cm³ air (Figure 2), total electrode displacement still significantly correlates with the amount of postoperative subdural air ($P=0.05$). However, $r^2$ goes down from 0.70 to 0.25.
There was no correlation between total electrode displacement and number of parallel used microelectrodes, length of surgery, age, duration of disease or follow-up time (data not shown).

![Figure 2. Trend plot showing positive correlation between the amount of postoperative subdural air and upward electrode displacement along the trajectory. Correlation was significant at P=0.01.]

**DISCUSSION**

**Postoperative DBS electrode displacement**

We demonstrated that DBS leads may not have reached their final positions on immediate postoperative imaging but are still prone to significant upward displacement in the weeks following surgery. This displacement was significantly correlated with the amount of air invading the subdural space and subsequent posterior shift of frontal cortex during surgery. When the frontal cortex returns to its original position, the upper part of the DBS electrode moves together with the frontal cortex to a more anterior position and the electrode acquires an anteriorly curved shape. Because the electrode is rigidly fixed at the border of the burr hole, DBS contacts are thereby pulled upward from their initial location. With precoronal and 3-4 cm lateral burr holes, this displacement results in a more lateral, more anterior and more dorsal position of the DBS contacts. Although recent studies reported surgery-associated brain shift causing inaccuracies during stereotactic implantation of DBS electrodes, this is the first reported quantitative analysis of displacement of DBS leads occurring after surgery.
Beside subdural air, other explanations should also be considered. Our technique of anchoring DBS electrodes with titanium microplates and plastic covering at the border of the burr hole could allow migration when underneath bone erosion, subsequent loosening of the fixation and retraction of the electrode occur in the weeks following surgery. This might also be an explanation for the observed displacements, especially in several patients with no or minimal postoperative subdural air invasion (Figure 2). However, displacement of electrodes caused by improper fixation solely would result in straightly retracted electrode tracts on follow-up scans and not, as observed in this study, anteriorly curved electrode tracts with more anterior curving in patients with larger volumes of subdural air (compare Figure 1B and D). Alternatively, the physiological, outward-directed brain pulsations could push the DBS leads upwards.

**Impact of postoperative DBS electrode displacement on treatment success of DBS**

The mean dorsal lead displacement was 2.6 mm ± 2. Because the dorsoventral diameter of the STN is on average 5 mm, this postoperative displacement considerably changed the position of DBS contacts relative to the STN, although the use of CT imaging in the current study did not allow localization and potential displacement of the STN on immediate postoperative and follow-up imaging. The effect of the observed lead displacements on clinical symptoms for this group of patients as a whole could not be determined retrospectively. In individual cases, however, effects were significant. We previously reported on severe reversible, stimulation-depended, cognitive decline in one of the current patients, who had a left lead displacement of 7.2 mm and a right lead displacement of 13.3 mm. The deepest contact on the left side was determined to be located in the internal capsule, the deepest contact on the right side in the dorsomedial globus pallidus externus.

The currently used quadripolar DBS lead (model 3389®; Medtronic, Minneapolis, MN) has four 1.5 mm contacts and three 0.5 mm interspaces, spanning 7.5 mm in total. With a mean total postoperative displacement of 3.3 mm, DBS electrodes thus moved on average two contact-lengths upward along the trajectory during the first postoperative weeks. Because test-stimulation at the four different contacts to assess effects on motor symptoms and adverse reactions and to determine the optimal contact is done shortly after surgery in most centers, postoperative lead displacement could confound this clinical assessment. Similarly, lack of clinical improvement from initial stimulation, decrease of stimulation effects and the occurrence of adverse reactions during follow-up might be caused by postoperative lead displacement and necessitates repeated assessment of test-stimulation at the four different contacts.
Impact of postoperative DBS electrode displacement on assessing the anatomical localization of active DBS contacts

The outcome of STN DBS is believed by many authors to be critically dependent on accurate targeting of the sensorimotor part of the STN,\textsuperscript{8,9} although others believe the more dorsally located zona incerta (ZI) is the optimal target to alleviate symptoms of PD.\textsuperscript{10-12} This controversy stresses the importance of postoperative documentation of electrode localization to determine the precise relationship between the position of active contacts and clinical outcome. Although several reports have assessed this relationship,\textsuperscript{13-17} postoperative imaging was usually performed on the day of surgery or on the postoperative day when, according to our current data, DBS leads might not have reached their final positions but are still prone to upward migration. Only in the study by Paek et al.,\textsuperscript{17} that compared surgical outcome of bilateral STN DBS with electrode position, postoperative MRI was performed six months after surgery. Based on our current data, we strongly advocate repeated postoperative imaging after long follow-up to accurately determine the location of the lead contacts, especially in cases of subdural air on direct postoperative imaging.

How to prevent postoperative DBS electrode displacement?

Since analysis of the reported data showed significant correlation between the amount of subdural air and upward electrode displacement, we changed our operative technique and currently employ three techniques to minimize CSF loss and subdural air invasion. First, we plan the burr holes on top of a gyrus, so that brain tissue is expected to pack the burr hole from inside. Second, patients are in a semi-sitting position during surgery. Third, we close burr holes with fibrin glue after introduction of the microelectrodes. Prospective analysis will learn whether these techniques result in less subdural air invasion and less subsequent postoperative electrode displacement. Due to the upward lead displacements seen in several patients with no or minimal postoperative subdural air invasion, we also routinely implant DBS electrodes one contact deeper than the most ventral point with good response to test-stimulation, so that in case of upward electrode displacement stimulation can be reverted to the deepest contact.

The introduction of multiple parallel microelectrodes requires wider opening of the dura mater than a single electrode, thereby increasing the chance of CSF leakage, thus potentially increasing the amount of postoperative lead displacement. Whether the current study could therefore serve as evidence against the widely used parallel multi-tract microrecordings remains, however, questionable since we did not find a correlation between the number of parallel used microelectrodes and the amount of postoperative subdural air or total electrode displacement. At the same time, multiple parallel canulas staying in place throughout the surgical procedure might also protect from posterior brain displacement \textit{during} surgery. In addition, keeping all canulas in place during electrode implantation prevents the electrode from choosing the wrong tract.
CONCLUSION

Upward displacement of stereotactically implanted DBS electrodes may occur in the weeks or months following surgery. This displacement significantly correlates with the amount of air invading the subdural space and potentially changes the position of DBS contacts relative to the target area. To prevent postoperative electrode displacement, CSF loss and subdural air invasion should be minimized. In addition, because DBS electrodes may not have reached their final position in the first postoperative days, postoperative CT or MRI localization of electrodes to determine the precise relationship between the position of active contacts and clinical outcome should be repeated after longer follow-up.

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