Microelectrode recording revealing a somatotopic body map in the subthalamic nucleus in humans with Parkinson disease

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Object. The subthalamic nucleus (STN) is a key structure for motor control through the basal ganglia. The aim of this study was to show that the STN in patients with Parkinson disease (PD) has a somatotopic organization similar to that in nonhuman primates.

Methods. A functional map of the STN was obtained using electrophysiological microrecording during placement of deep brain stimulation (DBS) electrodes in patients with PD. Magnetic resonance imaging was combined with ventriculography and intraoperative x-ray film to assess the position of the electrodes and the STN units, which were activated by limb movements to map the sensorimotor region of the STN. Each activated cell was located relative to the anterior commissure–posterior commissure line. Three-dimensional coordinates of the cells were analyzed statistically to determine whether those cells activated by movements of the arm and leg were segregated spatially.

Three hundred seventy-nine microelectrode tracks were created during placement of 71 DBS electrodes in 44 consecutive patients. Somatosensory driving was found in 288 tracks. The authors identified and localized 1213 movement-related cells and recorded responses from 29 orofacial cells, 480 arm-related cells, 558 leg-related cells, and 146 cells responsive to both arm and leg movements. Leg-related cells were localized in medial (p < 0.0001) and ventral (p < 0.0004) positions and tended to be situated anteriorly (p = 0.063) relative to arm-related cells.

Conclusions. Evidence of somatotopic organization in the STN in patients with PD supports the current theory of highly segregated loops integrating cortex–basal ganglia connections. These loops are preserved in chronic degenerative diseases such as PD, but may subserve a distorted body map. This finding also supports the relevance of microelectrode mapping in the optimal placement of DBS electrodes along the subthalamic homunculus.

KEY WORDS • subthalamic nucleus • deep brain stimulation • somatotopic organization • Parkinson disease • electrophysiological study

T he STN has long been recognized as an important component of the basal ganglia circuits controlling somatic motor movements. Current theories about the function of basal ganglia pathways involved in motor control put the STN in a central position to modulate the activity of the output nuclei of the basal ganglia, according to the widely accepted “direct and indirect pathways” model introduced by Albin and colleagues and elaborated on by Alexander and associates. According to this model, the STN is a key structure involved in the control of the output nuclei of the basal ganglia by its glutamatergic excitatory connections with the Gpi, GPe, and SNr. Increased activity of the Gpi and SNr induced by STN firing is believed to increase γ-aminobutyric acid–mediated inhibition of thalamocortical neurons, thus producing the classic signs of PD.

Abbreviations used in this paper: AC = anterior commissure; BRW = Brown-Roberts-Wells; CRW = Cosman-Roberts-Wells; DBS = deep brain stimulation; GPe = globus pallidus externus; Gpi = globus pallidus internus; MR = magnetic resonance; PC = posterior commissure; PD = Parkinson disease; SNr = substantia nigra pars reticulata; STN = subthalamic nucleus.

The indirect pathway connecting the striatum with the Gpi and SNr through the GPe and STN is an important link between the motor cortex and the STN. Cortical activation of striatal neurons tends to suppress the activity of neurons in the GPe, which activates the STN and increases activity of the Gpi and SNr, thus increasing thalamocortical inhibition. Dopamine D1 inhibitory receptors provide inhibitory input to the same striatal neurons, thereby reducing thalamocortical inhibition. The STN receives somatotopically organized inputs from the primary motor cortex, as demonstrated in macaque monkeys by autoradiographic anterograde tracing. Cortical somatotopic projections to the STN in nonhuman primates have a mediolateral organization, with sites related to the hindlimb and orofacial area being situated laterally. Direct somatotopic cortical projections are mostly limited to the lateral and dorsal portions of the STN. More recently, research in macaques has provided evidence of direct cortical projections from the supplementary motor area, which are arranged somatotopically in the medial half of the STN and are indicative of multiple body maps in the STN. A mirror somatotopic organization was found, with
face-, arm-, and leg-related sites arranged mediolaterally in the medial STN and lateromedially in the lateral STN.

We have extensively explored the somatotopic organization of the STN in humans by performing microelectrode recording during implantation of DBS electrodes for the symptomatic relief of PD. Multiple tracks were created in each patient to obtain a satisfactory map of the STN. Kinesthetic activation of STN neurons after active and passive limb movements was detected, and a specific relation of different parts of the body to specific areas of the STN was found.

Clinical Material and Methods

Patient Selection

We performed a retrospective review of intraoperative electrophysiological data obtained in 44 consecutive patients with PD who had undergone staged bilateral STN DBS, as approved by the local ethics committee. The development of motor complications, including dyskinesias, on-off phenomena, and freezing, was the main indication for STN DBS. A dopamine trial was performed to assess the presence of a robust dopaminergic response based on the Unified Parkinson Disease Rating Scale. Patients with a poor dopaminergic response, cognitive deterioration as determined on neuropsychological testing, neuroimaging abnormalities, major psychiatric illness, or general contraindications to surgery were excluded from surgical intervention.

We placed 71 STN DBS electrodes in 44 patients between October 1, 1999, and April 12, 2002. Twenty-seven patients underwent bilateral implantation of electrodes through a staged procedure, and 17 patients underwent unilateral implantation of DBS electrodes during the first stage. Thirty-six electrodes were placed on the right side and 35 on the left side.

Surgical Procedure

Long-acting parkinsonian medications were stopped 1 week before surgery and were replaced with short-acting ones. The latter were then withheld 12 hours before surgery. After placement of a CRW base ring (Radionics, Burlington, MA), stereotactic MR imaging in a 1.5-tesla Signa system imager (General Electric, Milwaukee, WI) was performed. In addition to the target voxel, the coordinates in the three MR imaging planes of the posterior component of the AC and the anterior aspect of the PC were defined. The target’s location was calculated with respect to the AC–PC line, and then the location of the visually selected target was compared with the standardized location of the target as reported in the literature. The stereotactic target coordinates for the DBS electrodes and the foramen of Monroe were calculated based on the MR images with the aid of an SCS-1 laptop computer and were entered onto a StereoPlan workstation (both from Radionics). An Excel spreadsheet (Microsoft, Redmond, WA) was used to determine the location of the target relative to the AC–PC line as shown in both MR imaging– and CRW frame–based space. We also used the workstation visually to plan a trajectory from the

Fig. 2. Graphs demonstrating activation of an STN unit by passive movement. A rapid extension was made at the wrist and measured by a velocity sensor attached to the dorsal aspect of the hand (Motus Bioengineering Inc., Benicia, CA). Positive deflection corresponds to extension. The raw data traces exhibit the firing pattern of an STN unit. Note the irregular baseline firing pattern and the increase in spike frequency on wrist extension.
cortical surface to our target to avoid cortical sulci, the ep-endoymal surface of the ventricle, and key structures such as the mammillothalamic tract. Prior to surgery, two portable x-ray units were carefully aligned to the stereotactic isocenter of a BRW floor stand (Radionics). The alignment system incorporates a radiographically visible 50-mm calibration fiducial. This allowed us to calculate for each case the magnification factors for both the anteroposterior and lateral views (~1.34 and 1.1, respectively). The target location was translated into the radiographic isocenter by manipulating the BRW floor stand x-, y-, and z-verniers, and the patient was placed supine in the floor stand. The location of the burr hole, as defined on the workstation, was determined using the CRW x-, y-, and z-coordinates and an entry site–specific ring and slide angle. These values were entered on the CRW frame, which had previously been placed on the patient’s head. After drilling the burr hole, cerebrospinal fluid loss was minimized by covering the dural opening with fibrin glue.

Ventriculography Studies

A standard ventricular catheter was stereotactically implanted through the burr hole into the foramen of Monroe, and 3 ml of cerebrospinal fluid was withdrawn to avoid volumetric distortion. This was followed by the administration of 3 ml of iohexol (300 mg/dl), and anteroposterior and lateral positive-contrast ventriculograms were obtained to delineate the posterior aspect of the AC and the anterior aspect of the PC, as well as the midline of the third ventricle. The CRW frame was then set to the functional target and placed back on the patient’s head.

Microelectrode Recording

The goal of microelectrode mapping was to define a volume based on sensorimotor responses within the STN. A 0.5- to 1-MΩ platinum-iridium microelectrode (FHC Corp., Bowdoinham, ME or Microprobe, Inc., Potomac, MD) was inserted into a guide tube lined with Teflon to reduce microphonics. The entire microelectrode/guide tube assembly was carried by a motorized microprobe mounted on an Axon x–y stage (Axon Instruments, Union City, CA) located on the CRW tool holder. Recordings were performed using an Axon Guideline 3000 system (Axon Instruments). The first microelectrode track was started 20 mm above the final target depth corresponding to the CRW frame isocenter, allowing for the physiological mapping of structures above the target. Subsequent tracks were started between 7 and 10 mm above the target to minimize recording time. At the bottom of the first microelectrode track (frame isocenter) anteroposterior and lateral x-ray films were obtained, aligned with the ventriculograms, and back illuminated (Fig. 1 upper).

Coregistration of the films was guided by a number of spatially invariant radiopaque items, mostly halo pins and arc and film-holder alignment markings. This radiographic analysis allows for precise definition of the microelectrode location in the intracranial space relative to the AC–PC line, thus producing measurements of instrument locations within the intracranial space with submillimetric accuracy. The position of each subsequent track relative to the first was measured in the same way, and the position of each track was plotted on a probe’s view of the anteroposterior and lateromedial plane along with the planned position. This probe’s view showed both the planned and the actual position of the microelectrode track bottom. We have frequently found discrepancies between the actual position compared with the planned position of a given track due to microelectrode deviation (Fig. 1 lower), despite a thorough check of the microelectrodes and the guide tube before and after each procedure.

Additional microelectrode tracks were made depending on the electrophysiological findings and the extent of passage through the STN during the first pass. Although some clear, single neuronal responses were observed, often we were recording the activity of more than one cell. Thus, these are more properly called “unit recordings” as opposed to true “single neuronal recordings.”15 Each unit was tested for responses to passive and/or active movements of both the arm and the leg. Within the upper extremity, responses were always tested for movement about the metacarpophalangeal, wrist, elbow, and shoulder joints. Within the lower extremity, responses were always tested for movement about the ankle, knee, and hip joints. A movement about each joint was made separately in both the flexion and extension directions, rather than a smooth sinusoidal motion. Figure 2 features an example of a rapid wrist extension movement and an increase in the firing rate of an STN unit.

The position and type of each unit’s response were recorded on a scaled piece of graph paper and then transcribed onto clear film. Absent responses were also noted. The clear film was overlaid onto an appropriately scaled, translucent Schaltenbrand and Bailey26 parasagittal plane map of the target region to compare the physiological data with a rough outline of the target’s anatomy. This constituted our electrophysiological spatial map, as opposed to the anatomical spatial map derived from the intraoperative x-ray films. The radiographic data showing the exact anatomical location of the microelectrode position in reference to AC–PC line were entered onto a spreadsheet used to determine the location of cells with somatosensory driving in the intracranial space.

Statistical Methods

The measurements for each patient, side, and limb were averaged, given that measurements from each exploration are strongly correlated in a complex way. This resulted in between two and four aggregate measurements per patient, because not all had undergone measurements on both sides and with both limbs. A mixed-effects model13 was used to measure the arm–leg location difference in all three coordinates, allowing for random patient and side effects. This model accommodates both the fact that some patients contributed left, right, or bilateral data and any interpatient variation in the position of the STN with respect to intercommissural coordinates. Units with mixed somatotopic responses (arm and leg) were excluded from analysis because we were unable to ascertain whether these represented a mixture of field potentials from neighboring arm- and leg-related cells compared with individual cells with mixed receptive fields.

The analysis was confirmed using a nonparametric bootstrap method.11 This method mimics the sampling variability by resampling the patients with replacement; each such resampling contains an entire copy of the patient’s da-
ta. One then obtains the bootstrap distribution of the arm–leg location differences. The resulting probability values were very similar to those obtained using the mixed-effects model.

Results

Three hundred seventy-nine microelectrode tracks were created during placement of 71 DBS electrodes, with a mean of 5.34 tracks per procedure. Two hundred eighty-eight (76%) tracks demonstrated evidence of driving, thus allowing for the physiological characterization of 1213 units including 480 units (39.6%) responsive to movements of the upper extremity, 558 units (46%) responsive to movements of the lower extremity, and 29 units (2.4%) responsive to movements of the orofacial region. We also found 146 mixed units (12%) activated by passive and active movements of both upper and lower extremities. Ninety-one tracks (24%) showed no evidence of somatosensory driving. This was partly due to the mapping protocol. After a track with sensorimotor driving had been isolated (usually the first), we subsequently moved posteriorly in that plane with the intent of finding the posterior boundary of the STN. This often resulted in a track posterior to the STN itself and therefore did not involve somatosensory driving.

Analysis of the spatial relationships between STN units with upper- or lower-extremity somatosensory driving indicated that there was a significant difference between units with upper-extremity driving compared with cells with lower-extremity driving with respect to the mediolateral and dorsoventral positions. Leg-related units were located medially and ventrally to the arm-related units. Furthermore, there was a trend for leg-related units to lay anterior to arm-related units, although this result was just short of significant (Figs. 3 and 4). The average positions of the arm units were 13.31 mm lateral, 1.65 mm posterior, and 1.58 mm ventral relative to the mid AC–PC. The average positions of the leg units were 11.95 mm lateral, 1.47 mm posterior, and 1.97 ventral relative to the mid AC–PC. The difference in each patient’s average arm unit location minus his or her average leg location was calculated and then averaged over all patients. This showed that arm units lay 1.25 ± 0.13 mm lateral, 0.25 ± 0.13 mm posterior, and 0.43 ± 0.12 mm dorsal to the leg units (standard error of the mean).

The apparent dorsoventral organization may reflect biases inherent in our microelectrode trajectory. Each track always proceeded from anterolaterodorsal to posteromedialventral, such that the microelectrode always entered the lateral nucleus in a more dorsal position than when it entered the medial component. Thus, even in the absence of a true dorsoventral arm–leg organization, the mechanics of the trajectory may impart the appearance of such in the face of the proven lateromedial organization. The same bias strengthens the observation that, although insignificant, the leg-related unit lies anterior to the arm-related unit; our trajectory tends artificially to encounter leg-responsive cells more posterior than arm-responsive ones because the arm is represented more laterally. The relative distance between arm- and leg-related units may be affected by the fact that

FIG. 3. Plots of all cell locations in cartesian space in reference to the AC–PC plane. Note the variance in the location of the cells due to the fact that the data were not corrected for the relative position of the STN across individuals. This variance would tend to smear the apparent difference in cell locations because of the across-individual variation in STN location.
the microelectrodes were moved in discrete increments, usually 2 mm (range 1–3 mm).

Discussion

In the present study microelectrode mapping was paired with ventriculography and x-ray studies to investigate the body map organization in the laterodorsal STN in patients with PD. Our relative measurements of unit locations (arm compared with leg) are highly accurate because of the use of intraoperative radiographs to reveal the true location of each microelectrode position. We detected a topography of cells differentially responsive to movements of the upper and lower extremities. The arm-responsive area was located in the more dorsolateroposterior part of the nucleus and the leg-responsive area was located more ventromedially anteriorly. No inference regarding the position of the face and neck in the laterodorsal STN body map was possible because of the small number of orofacial units identified (number of orofacial units 29). We always encountered sensorimotor driving in the dorsal aspect of the STN, but in many cases this extended ventrally to 1 to 2 mm dorsal to the floor of the STN.

Some data have demonstrated a somatotopic segregation of movement-related cells in the human STN, whereas data from a recent report showed no statistically significant segregation between the positions of upper extremity– and lower extremity–related units. Rodriguez-Oroz, et al., have analyzed single-cell recordings from the STN in 14 patients with PD who had undergone surgery for DBS. A postoperative MR image was used to locate the site of stimulation and calculate the position of the microelectrode tracks created during the procedure. Three hundred fifty neurons were recorded, and a response to active and passive movements occurred in 112 (32%). All neurons with sensorimotor responses were located in the dorsolateral region of the STN, with arm-related neurons found mostly in a lateral position (≥ 14 mm lateral to the AC–PC line) and leg-related neurons in a medial position (≤ 12 mm lateral to the AC–PC line). Representation of the oromandibular region was reported to be located in the 13-mm plane between the arm and leg area. No sensorimotor neurons were found in the ventral third of the nucleus. Approximately two thirds of the sensorimotor neurons were situated 12 or more mm lateral to the AC–PC plane. From the medial to lateral planes, the proportion of neurons responding to leg movements decreased, whereas the proportion of neurons responding to arm movements increased.

Similar results have been reported by Theodosopoulos and colleagues, who tested 303 STN cells and found that 149 cells (49%) were modulated by passive movements of the contralateral limbs. Postoperative MR imaging was used to assess the position of the DBS lead, and the location of the microelectrode tracks was, therefore, inferred. Forty-nine cells were leg related, 96 cells were arm related, and four cells were mixed. Seventy-seven percent of the movement-related cells were located in the dorsal half of the nucleus. Most of the leg-related cells (84%) were located in the central region of the medial half of the STN (< 12 mm away from the midsagittal plane). Arm-related cells predominated in the lateral planes of the STN and were evenly distributed along the rostrocaudal axis.

Abosch and colleagues identified somatosensory responses in 248 of 510 unit locations encountered in 38 patients who had undergone STN DBS; 144 of these units were determined to be within the STN itself. Of those 144, more than 95% lay in the rostral two thirds of the nucleus. Comparing arm-related with leg-related positions within the same STN was possible in only nine patients, and anal-
ysis revealed no somatotopic organization. Note, however, that whole tracks rather than individual units were compared.

**Determination of Cell Location in the Intracranial Space With Submillimetric Accuracy**

The aforementioned reports featured postoperative MR images indicating the position of the DBS lead within the STN to locate the position of movement-related cells. This localization method required researchers to infer the position of the microelectrode tracks (and, hence, the somatotopic organization) relative to the subsequent DBS electrode. In contrast, we explicitly determined the microelectrode location by using intraoperative radiographs. This method overcomes several limitations of MR imaging–based studies. First, localization of the microelectrode tracks and DBS electrode position were not subject to the spatial distortion artifact inherent in MR imaging,29 with greater errors being located on the lateral (x) and vertical (z) spatial distortion artifact inherent in MR imaging,29 with tracks and DBS electrode position were not subject to the This method overcomes several limitations of MR imaging–based studies. First, localization of the microelectrode tracks and DBS electrode position were not subject to the spatial distortion artifact inherent in MR imaging,29 with greater errors being located on the lateral (x) and vertical (z) planes. Second, anatomical positions of the microelectrode tracks were not misplaced when the DBS electrode position deviated from its intended location. We have seen shifts of more than 1.5 mm between the intended and actual location of the DBS electrode on the probe’s view. By inferring the microelectrode track position based on the DBS electrode position in such cases, one would introduce the same error because the calculation uses the position of the microelectrode tracks relative to the intended rather than the actual DBS electrode position. Last, and most important for the somatotopic observations, we explicitly dealt with deviations of the microelectrode tracks from their intended trajectories. In the MR imaging–based studies, these deviations, which can be greater than 1 mm, produce incorrect spatial relationships among the calculated cell positions. Because our plain radiographs provide submillimetric spatial resolution, the relative positions of each microelectrode track (and the calculations of the positions of recorded units along each track based on them) can maintain this level of accuracy.

We recognize that small sources of error may still occur with this technique, such as inaccuracies in marking the AC and PC locations on the ventriculogram, aligning the first microelectrode track with the ventriculogram, and accurately determining the location of the microelectrode tip (whose size is below the resolution of the radiographs). There may be small parallax errors between the ventriculogram and microelectrode radiographs, resulting from slight rotations (yaw and roll) of the patient’s head in the stereotactic head frame, although we do not know the exact contributions of each of these factors with regard to total variance. Our somatotopic conclusions are based on relative measurements within each individual patient over a small volume and are effectively immune from all of the possible sources of error in our technique except one, that is, inaccuracies in aligning the radiographs from each microelectrode track with those from the first track. We estimate this error to have a mean of approximately 0.2 mm, with a maximum of 0.5 mm.

Another of our corrections that we believe to be important is the transformation of movements of the microelectrode tip into true anatomical directions. Most stereotactic systems used for clinical microelectrode studies (including Leksell and the Radiomics CRW system used in this study) are arc-centered. The device used to drive the electrode toward the target during each pass (the microdrive) is mounted on a tool-holder block whose axis points toward the arc center. After each pass, the holder (typically an x–y stage) is translated in one or two directions, usually called “anteroposterior” and “mediolateral.” A new pass is then made by driving the electrode parallel to the previous tracks. Regardless, the three axes of this stage usually are not identical to the true anatomical axes of the patient: the anteroposterior, mediolateral, and dorsoventral directions. Often the penetration (depth) axis of the microelectrode points not just dorsoventral, but also anteroposterior and lateromedial. If one wants to express the true anatomical locations of units whose locations were measured in the tool-holder frame, it is necessary to generate the transformation between this frame and the true anatomical frame. We calculated this transformation in each patient and are, therefore, able to state our results in true anatomical space. An example of the errors that this technique corrects for is provided in the case of an arc-centered system whose base ring is applied parallel to the plane defined by the AC–PC line and the mediolateral line (the ideal ring placement). Typical settings in our cases have the arc rotated to lay 30° anterior to vertical (a CRW ring angle of 60°) and the tool holder is slid to 15° off the sagittal plane (a CRW slide angle of 15°). If one cellular unit is noted when the microelectrode is situated 5 mm above the isocenter and another is located at the isocenter on the same track, then the upper unit is 1.7 mm anterior, 1.3 mm lateral, and 4.5 mm dorsal to the lower one. If a second track is produced by translating the tool-holder (x–y) stage 2 mm in the anterior direction of the x–y stage and 2 mm in its lateral direction, a unit recorded at the same microelectrode depth as the isocenter unit in the first track will actually lie 1.7 mm anterior, 1.9 mm lateral, and 1.2 mm deeper than that cell. These differences become more pronounced as the arc is rotated more anterior and the tool holder slides more laterally. We believe that this correction is essential if one is to compare data obtained from different patients for whom the tool-holder angles are variable and to express the results in standard anatomical directions.

**A Somatotopic Body Map in the STN of Patients With PD**

The presence of a sensorimotor region characterized by somatotopically organized units activated by somatic movements supports the hypothesis that different functional domains coexist in the human STN. It has been thought that the ideal site of DBS resides in the sensorimotor region of the STN, based on the observation that reversible inactivation of the sensorimotor portion of the STN and GPi in 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine monkeys reduced the motor signs of parkinsonism, but inactivation of nonmotor regions did not.32 Data from several clinical reports have confirmed the efficacy of sensorimotor STN stimulation in alleviating PD.5,6 Similar results have been obtained on lesioning or stimulating the GPi, which are far more effective procedures for symptoms of PD when focused in the core of the sensorimotor region.7,12,13,16,32 In our opinion, the optimal location of the DBS electrode has yet to be firmly established, although several recent reports have demonstrated that the optimal target for DBS of the STN is actually dorsal and lateral, within the white matter surrounding the nucleus.14,25,37
Somatotopic organization in the human subthalamic nucleus

We believe that accurate electrophysiological mapping of the STN makes an important contribution for at least two reasons. First, PD is widely distributed and can affect upper and lower extremities as well as both sides of the body. Nevertheless, there can be substantial variations in the severity with which different body regions are affected. We, therefore, think that it is exciting that the neurophysiology of the STN in patients with PD reveals a somatotopic body map, because it can allow the surgeon to focus stimulation of nuclear areas that are somatotopically related to the parts of the body most affected by PD. This targeted method of DBS may result in a lower intensity of stimulation over time, thus extending the battery life of the pulse generator. Second, the correlation between the physiological map of the STN and the anatomical axes provides information that could assist electrode placement in any anatomically desired location within or adjacent to the STN. Thus, a clear identification of the functional organization of the STN could greatly improve the accuracy of DBS electrode placement and clinical outcome.

The finding that 12% of the somatosensory cells in the STN were responsive to stimulation of both arms and legs is an interesting finding. Data from healthy nonhuman primates showed that 91% of the sensorimotor cells in the STN were activated by single-joint manipulation and 9% by multiple-joint manipulation, but no cells responded to both limbs. 18 If we assume that the microelectrode was not sampling distinct adjacent cells but truly single neurons, these findings indicate that an abnormal share of sensorimotor neurons in the STN of patients with PD have enlarged receptive fields. Widened receptive fields in the pallidum and motor thalamus 18,19,31 have been reported in patients affected by dystonia. Further study is warranted to determine if enlarged receptive fields in the sensorimotor STN of parkinsonian patients are truly related to a distorted body map and if STN DBS can restore a physiological body map. Examination of the STN body map in patients who have undergone long-term STN stimulation followed by explanation due to surgical complications and subsequent repeated implantation could provide some insight into this topic.

Conclusions

Data from the present study of microelectrode mapping paired with anatomical landmarks provides evidence of the topographic segregation of lower extremity- and upper extremity–related cells in the STN, with lower extremity–related cells being located medial and ventral to the upper extremity–related cells. The finding that upper extremity– and lower extremity–related cells have consistent reciprocal spatial interrelationships can help guide the placement of subsequent microelectrode tracks and facilitate the electrophysiological delimitation of the borders of the sensorimotor STN, thus increasing the accuracy of DBS electrode placement in the center of such a region.

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