Deep Brain Stimulation for Parkinson’s Disease: Surgical Technique and Perioperative Management

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Abstract: Deep brain stimulation (DBS) is a widely accepted therapy for medically refractory Parkinson’s disease (PD). Both globus pallidus internus (GPi) and subthalamic nucleus (STN) stimulation are safe and effective in improving the symptoms of PD and reducing dyskinesias. STN DBS is the most commonly performed surgery for PD as compared to GPi DBS. Ventral intermediate nucleus (Vim) DBS is infrequently used as an alternative for tremor predominant PD patients. Patient selection is critical in achieving good outcomes. Differential diagnosis should be emphasized as well as neurological and nonneurological comorbidities. Good response to a levodopa challenge is an important predictor of favorable long-term outcomes. The DBS surgery is typically performed in an awake patient and involves stereotactic frame application, CT/MRI imaging, anatomical targeting, physiological confirmation, and implantation of the DBS lead and pulse generator. Anatomical targeting consists of direct visualization of the target in MR images, formula-derived coordinates based on the anterior and posterior commissures, and reformatted anatomical stereotactic atlases. Physiological verification is achieved most commonly via microelectrode recording followed by implantation of the DBS lead and intraoperative test stimulation to assess benefits and side effects. The various aspects of DBS surgery will be presented. © 2006 Movement Disorder Society

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Deep brain stimulation (DBS) has become a readily accepted treatment for medically refractory Parkinson’s disease (PD). While ablative procedures such as pallidotomy and thalamotomy have been proven to be efficacious,1–8 they are currently reserved for patients with contraindications to implantable hardware, those living in areas without access to programming equipment/expertise, and in countries with limited economic resources.

The three structures most commonly targeted for alleviating the symptoms of PD are the ventralis intermedius nucleus of the thalamus (Vim), the posteroventral portion of the internal segment of the globus pallidus (GPi), and the subthalamic nucleus (STN). Vim is generally chosen for treating tremor predominant PD with similar efficacy and lower rates of long-term neurological complications compared with thalamotomies.9–11 Alternatively, GPi and STN are chosen for treating not only tremor, but also the other cardinal symptoms of PD such as rigidity and bradykinesia as well as having benefits on reducing dyskinesias. In this context, Vim DBS is the least common surgery for treating PD.

Both GPi and STN have been shown to have similar efficacy rates.12–14 However, the literature demonstrates a trend that STN may be more efficient in managing the symptoms of PD.15 Choice of the STN over the GPi is often based on institutional experiences, surgical and programming expertise and preferences, lower current requirements with resulting longer battery life, and a
more consistent trend for significant reductions in dopaminergic medication intake with the STN target. Stimulation of the GPI may be preferred for patients with borderline cognitive changes present preoperatively. STN DBS may have a greater impact than GPI DBS on executive frontal lobe functions. Neurosurgical expertise in stereotaxy, modern imaging, widespread use and ease of image guidance, and consistent patient outcomes have encouraged the popularity of STN, GPI, and Vim DBS as a treatment for medically refractory PD. The number of implants has risen dramatically since the first reports of the therapy by the Grenoble group. Currently, there are over 400 centers worldwide with over 30,000 DBS implants to date. The operative approach varies from one center to the other, particularly in the criteria employed for microelectrode-guided recording and angles of approach to the various subcortical targets. The authors recognize that there are various surgical strategies, tools, equipment, and procedures used for DBS surgery. This is because of the experience and preference of the surgical team, individual center logistics, and healthcare system constraints. We provide a general overview of the surgical technique and perioperative management realizing these inherent variations.

**PATIENT SELECTION**

Patient selection is a critical first step as poorly chosen candidates may not have optimal benefits and have increased morbidity. Several factors must be considered before determining if a patient is an appropriate candidate for DBS surgery. A multidisciplinary approach involving the neurosurgeon, neurologist, and neuropsychologist is important to determine the appropriate surgical candidate. It is also important that the diagnosis of idiopathic PD be confirmed prior to proceeding with DBS surgery. Several neurological disorders can mimic the signs and symptoms of idiopathic PD. Multiple-system atrophy and progressive supranuclear palsy are in the differential diagnosis that must be considered. A complete, thorough neurological examination with attention to cognitive function, eye saccadic movements, postural hypotension, and postural instability, and signs of cerebellar or corticospinal involvement is important in the preoperative evaluation.

Key to this assessment is evaluating the surgical candidate in both the on and off medication states with a corroborating levodopa challenge. Perhaps the best prognostic indicator of a patient’s suitability for DBS surgery is their response to levodopa. In general, a levodopa challenge following a 12-hour medication withdrawal should provide at least a 33% improvement in the motor section of the Unified Parkinson’s Disease Rating Scale (UPDRS). Patients who do not improve significantly with levodopa are unlikely to improve with surgery, as the therapy is largely aimed at increasing on time and decreasing on–off fluctuations. The levodopa challenge is also useful to demonstrate to the patient and family the extent that the parkinsonian symptoms are likely to improve after surgery. Patients should be educated not to expect an improvement in function greater than the best on medication period with the concomitant reduction in drug-induced dyskinesias. Tremor is an exception and can improve with STN DBS even if not significantly affected by levodopa. Patients should be advised that axial and gait symptoms are less likely to be impacted than appendicular symptoms.

One of the most important presurgical assessments is the neuropsychological evaluation. The team must be capable of identifying patients with elevated risk for surgery and those incapable of adjusting to a lifestyle compatible with implanted neurological hardware. Surgical management may be temporarily deferred or outright declined in these patients, depending on their response to adjunctive psychological counseling. Deep brain stimulation for PD does not seem to cause permanent cognitive changes. However, patients who present with cognitive decline preoperatively tend to be poor candidates and may worsen after surgery. A staged procedure is a good alternative to simultaneous bilateral surgery in elderly patients with borderline cognitive function.

Age is one of the major factors determining how a patient will cope with the surgical procedure and behave postoperatively. The risks of cardiopulmonary events are certainly higher, as in any other major surgery. More specifically to DBS, advanced age is linked to higher incidence of cognitive changes after surgery. Younger patients tend to recover faster and are usually fully oriented in the day following surgery. Older patients are more prone to experience a period of confusion that may last for several days. We do not recommend a specific cutoff for age, as the chronological age does not necessarily correlate with the biological aging among individuals. Older patients without many medical comorbidities who still present good mental and physical function during the on periods may be considered candidates. Staged or unilateral implantations may be wise alternatives for those in the eighth decade of life or older. Depression is common in the PD population. Ideally, the patient should be counseled and treated prior to surgery, with the goal of maximizing the individual’s capacity to cope with the procedure and postoperative recovery period. Psychosis may also occur primarily but is often a manifestation of dopaminergic medication side effects.
Brief periods of medication-induced psychosis may be medically managed by altering the medication regimen. However, psychosis not related to medication may be a reason to defer surgery in a particular patient. The occurrence of significant mood changes after bilateral DBS has been reported but is not common in our experience. Severe anxiety may become a major impediment for awake stereotactic surgery, especially in prolonged operations. Counseling prior to surgery might be helpful (see Voon and colleagues in this issue for a more detailed discussion of these issues).

PREOPERATIVE MANAGEMENT

A full medical assessment is a necessary part of the preoperative evaluation, as advanced PD patients tend to be elderly with significant comorbidities. The risk of discontinuing medications that affect anticoagulation and platelet aggregation should be weighed against the potential benefits in the quality of life offered by DBS surgery. However, timely discontinuation of these latter medications is mandatory for stereotactic surgery since intracerebral hematomas are the most serious of all potential complications from DBS. Any anticoagulation medications, including aspirin, ticlopidine, clopidogrel, and all nonsteroidal anti-inflammatory drugs should be discontinued at least 7 to 10 days preoperatively to ensure the return of normal blood clotting function.

Arterial hypertension can also increase the risk of intracranial bleeding during stereotactic procedures and must be controlled in the weeks prior to surgery. The night prior to DBS surgery, the antiparkinsonian medications are typically held to pronounce the Parkinson’s symptoms at the time of surgery and the families must be counseled regarding their role in facilitating the patient that day. Alternatively, some centers may choose to admit the patient the night before to aid with rigidity, bradykinesia, and/or freezing that may be profound and disabling with the medications held.

Patients should be willing and able, both physically and cognitively, to undergo an awake surgical procedure requiring several hours of immobilization in a stereotactic frame. Moreover, surgical candidates need to be able to remain attentive and cooperative under stressful conditions. Realistic expectations of outcomes are also paramount for both the patient and the family. The patient and family must be willing and able to bear the responsibilities for maintaining a chronically implanted hardware system.

A prolonged discussion on the short- and long-term effects of DBS on Parkinson’s disease should be carried out with the patient, family, and caregivers. DBS often results in dramatic changes in the patient’s motor function and consequently in independence. Patients may no longer require as much assistance in caring for themselves or for the household, which may change the family’s routine and dynamics. The preoperative neuropsychological assessment may be useful in identifying these issues and preventing them with counseling.

Furthermore, while the goal of the surgery is to restore the patient’s quality of life, it is also important to discuss safety of indoor and outdoor activities. Releasing the patient from the severe motor limitations imposed by the medically refractory disease may give the individual a sense of aptitude that may be unrealistic due to the restrictions imposed by the concomitant aging vestibular, peripheral nervous, and musculoskeletal systems.

The DBS surgical candidate must be educated regarding environmental concerns with implanted hardware. Patients with DBS hardware should not be exposed to large magnetic fields. Compatibility exists with only a limited number of magnetic resonance (MR) sequences in machines that have undergone safety testing. Individuals with other health issues that may require frequent MR imaging may not be ideal candidates for DBS. Body coils are particularly dangerous for DBS systems and their need may pose a contraindication for patients with spinal disease that require future MRIs. Unfortunately, the association of spinal problems with medically refractory Parkinson’s disease is not uncommon and it may be necessary to judge along with the patient and family which disease should be prioritized.

Finally, DBS implantation should be regarded the first step in an extended management plan. The caretakers and the patient should be committed to treating the patient within the specialized center for programming, and hardware management issues (such as the need for battery change) in the near and long term.

UNILATERAL VS. BILATERAL SURGERY

There are various approaches to the surgical procedure depending on the patient’s symptoms, tolerance of surgery, and team preferences. The patients can undergo simultaneous bilateral DBS lead and pulse generator implantation the same day, unilateral implantation of the DBS lead and pulse generator the same day, bilateral implantation of the DBS lead in 1 day and subsequent staged implantation of the pulse generators, or unilateral DBS lead implantation in 1 day and secondary staged implantation of the pulse generator another day. All these approaches have been used successfully and depend on variables such as the patient symptoms, tolerance of surgery, team preference, and various other health system logistics that are individual center–dependent.
SURGICAL PROCEDURE

Application of Head Frame and Imaging

Surgical strategies and details of procedure vary with the surgical teams, the equipment they are used to, and the local healthcare system constraints. Stereotactic surgeons typically master the use of their institution’s equipment of choice, which are used for a variety of stereotactic procedures. Among them, DBS is probably one of the most technically challenging and should not be considered a beginner’s procedure. A variety of head frames can be used such as the Leksell, CRW, Riechert-Mundinger, and other commercially available systems. Placement of the head frame should be done as close as possible to surgery in order to minimize the duration of discomfort and risk of displacement. The base of the frame should be placed parallel to a line extending from the lateral canthus/orbital floor to the tragus in order to parallel approximately the anterior commissure–posterior commissure (AC–PC) line. Ear bars (with ear plugs placed for patient comfort) may be used to balance the ideal position of the frame while applying the pins. Ideally, the head should be centered in the frame, so that the midline falls within the center point of the stereotactic space defined by the head frame system. Care must be taken such that the edges of the frame should never be in contact with the nose or the occipital/neck area due to risk of skin erosion, which could be encountered during an extended stereotactic procedure. The frame should not obscure the patient’s eyes since this makes communication with the patient and assessment of eye movements more difficult during surgery.

The scalp is shaved and prepared with betadine and the pins are inserted under local anesthesia of preference, typically lidocaine and/or marcaine. A small dose of intravenous midazolam or other sedation can be given prior to insertion of the pins in order to minimize awareness and memory of frame placement. The anterior pins can be placed two finger breadths above the orbital rim, taking care to avoid the supraorbital nerve. Posteriorly, pins should be located so as to avoid penetration of the cerebral venous sinuses. The height of the base of the frame must also be taken into consideration so that prospective targets lie comfortably within the frame’s coordinate system, avoiding the extremes, which will mechanically hamper positioning the arc for targeting. In addition, since the pins can create significant artificial distortion of CT imaging, they should be placed such that they distort neither the AC, PC, nor the target.

The pins should firmly purchase the outer layer of the skull to prevent the frame from being displaced during a prolonged surgery. Alternatively, overtightening is undesirable due to potential for causing distortions in the frame and consequently in the accuracy of the system. Finding the right balance may be challenging in patients with severe tremor, who are more prone to cause dislodgment of the pins. After application of the frame, an attempt should be made to move the patient’s head and stress the pins. Any perception of pain by the patient at this point might imply inadequate insertion of the pins. Patients with severe anxiety or low tolerance to pain may not tolerate awake placement of the head frames. In those instances, the head frame may be placed under heavy sedation or general anesthesia.

Once the frame is placed, the patient is taken for preoperative imaging. CT, MRI, and ventriculography can all be used to construct the stereotactic imaging database required for DBS implantation. The surgical team can utilize any of the above imaging modalities for anatomical targeting of the STN, GPi, and Vim. Many commercially available image-guided systems offer the merging and image fusion capabilities that allow for integration of multiple imaging data sets.

The CT scan should include the upper portion of the frame, the anterior and posterior limits of the frame, and vertex up to the skin edge in order to encompass all the fiducials. The slices are optimally obtained with the thinnest slice thickness with no gap between slices. If dislodgment of the frame occurs after the volumetric stereo CT, the entire procedure has to be restarted due to the loss of relationship between the fiducials and intracranial structures.

Volumetric, gadolinium-enhanced, T1-weighted MRI, T2-weighted images, or inversion recovery images can be obtained with the head frame on, or preoperatively to expedite the process on the day of surgery. T2 and inversion recovery images are beneficial for direct targeting of the structure of interest and surrounding areas. Inversion recovery images can be problematic with certain imaging software. Often, excessive tremor hampers the interpretation of the preoperative MRI, and another one may be obtained with the head frame on, which helps to stabilize the head during image acquisition. In order to optimize the chances for a good outpatient MRI, neurologists can prescribe levodopa to patients in such fashion as to match on medication time with the time of the examination (i.e., tremor dominant patients should be in the on medication state while dyskinetic patients should be in the off medication state). MRI will be contraindicated in patients with cardiac pacemakers making reliance on CT and ventriculography if necessary. While MRI has superior soft-tissue resolution, CT is less susceptible to the distortional artifacts produced by the inhomogeneities in the magnetic field and thus more...
accurately represents the actual position of intracerebral structures in space. Consequently, reliance on image fusion and merging will allow for visualization of multiple imaging data sets.

**Frameless Technology**

This is a method that is emerging as an alternative to frame-based stereotaxis. The so-called frameless stereotaxis has been used for brain tumors using skin fiducials for some time, transforming the process for localization of intracranial lesions. Recently, a preliminary report was released on frameless navigation for deep brain stimulation utilizing a new technology with promising results. Holloway and colleagues have compared the use of this new frameless method using skull-based fiducials with standard frame-based stereotaxis. The authors assessed the actual location of the electrode with a postoperative CT scan and compared the location with the expected intraoperative targeting. There was no statistically significant difference comparing the two surgical methods, suggesting that frameless stereotaxis may have a future role in the field of deep brain stimulation. Advantages of this method include a less restricted position during surgery and convenience for preoperative image acquisition and surgical planning. Disadvantages include the consequent risk of intraoperative dislodgment in patients with severe tremor or involuntary movements. A learning curve with this new system should also be expected for surgeons already accustomed with frame-based systems. At the current stage of development, frameless stereotaxis is not the standard choice for deep brain stimulation given that only limited experience exists with its accuracy. Figure 1 shows a frameless apparatus and its microdrive mounted in surgery.

**Target Selection**

Centers use various combinations of anatomical targeting strategies. One can target using an indirect method that involves reformatted anatomical atlases as well as formula coordinates based on known distances from the AC and the PC landmarks. The STN and GPi can also be chosen on the basis of direct targeting by visualizing the structure on T2 and inversion recovery images. With current imaging limitations, Vim can only be targeted indirectly and confirmed with intraoperative physiological data. Emphasis will be given to anatomical targeting of the STN since it is the most common target used for Parkinson’s disease but a brief description for GPi and Vim targeting is also included.

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**FIG. 1.** Frameless stereotactic system. The cranial apparatus and microdrive for frameless stereotaxis (Image Guided Neurologics). The disposable frame is attached to the skull with three self-tapping screws. The image guidance planning/neuronavigation station is used to align the entry point to the target. A microdrive is mounted on top of the hardware, which allows for microelectrode recording and DBS electrode implantation.

**Direct Targeting**

Direct targeting is based on MRI visualization of the structures. A target within STN can be chosen at the ventral part of the somatosensory STN, which is the lateral part of the nucleus. The axial and coronal T2 images are particularly important for adequate visualization of the STN as a sharp contrast can often be seen between the nucleus and the surrounding white matter. The red nucleus can also be clearly seen and the STN lies anterior and lateral to the red nucleus. The anterior border of the red nucleus can be used as a landmark for the anteroposterior localization of the STN target. This is best visualized in the axial T2 images, as shown in Figure 2.

The GPi and the adjacent optic tract and internal capsule can be visualized via inversion recovery and T2 images. Careful windowing of the images can also provide proper visualization of the internal capsule as well as the GPi and the pars externa of the globus pallidum (GPe). For GPi DBS, implantation target choice may be different from that used for pallidotomies, which are...
typically located at the posteroventral portion of the nucleus. Implantation at that position may not be optimal for DBS since the DBS stimulation field may require higher amplitudes and potential spread to the internal capsule. In this regard, for DBS, a more anterior and lateral target is preferable, which will allow the stimulation amplitude to be increased without significant involvement of the descending white matter fibers. The optic tract courses ventrally to the globus pallidus and can be used as a landmark for the approach (Fig. 3).

Indirect Targeting

Indirect targeting is based on a standardized stereotactic atlas and on a formula-derived method based on AC and PC landmarks. While atlas-based coordinates are biased by the inherent inaccuracies of atlases, coordinates can be derived from the experience of teams and represent the average values of the coordinates of these best contacts, gathered in a rather large number of cases. Referring these coordinates to internal landmarks such as AC–PC length and height of the thalamus above the AC–PC plane provides normalized coordinates less dependent on individual variations. The formula uses the midcommissural point (MCP) or the PC as reference, which is calculated after selecting the AC and PC coordinates (Fig. 4). Typical initial anatomical coordinates for the ventral and sensorimotor STN are 11 to 13 mm lateral to the midline, 4 to 5 mm ventral to the intercommissural plane, and 3 to 4 mm posterior to the MCP. Coordinates for the sensorimotor GPi are selected as 19 to 21 mm lateral to the midline, 2 to 3 mm anterior to the MCP, and 4 to 5 mm ventral to intercommissural plane. The Vim is targeted 11 to 12 mm lateral to the wall of the III ventricle, at the level of the intercommissural plane. Most commonly, the goal is to target the topography of the upper extremity, which carries the greatest impact for quality of life. The upper extremity occupies a more intermediate position between the more medially located face representation and the laterally located lower extremity. In terms of anterior–posterior position, the Vim

FIG. 2. Direct STN targeting. Axial T2-weighed image showing the subthalamic nucleus (white arrow) anterior and lateral to the red nucleus (black arrow). Note how the anterior border of the red nucleus aligns with the posterior third of the STN. The T2 images are crucial for the direct targeting of the STN and should be windowed carefully to optimize the accuracy of the nuclei boundaries.

FIG. 3. Direct GPi targeting. Direct targeting of GPi. A: GPi (arrow) is seen on an inversion recovery axial image. B: The optic tract (tip of the trajectory line) can be identified ventral to the GPi and used as a landmark for direct targeting. Careful windowing is critical to optimize the resolution and allow accurate identification of the structures.
is typically located between 2/12 and 3/12 of the AC–PC distance rostral to the posterior commissure. These coordinates may not represent the ideal location for implantation but are used as initial anatomical targets, which are verified by physiological recordings. Figure 5 demonstrates a typical digitized version of the Schaltenbrand and Wahren atlas that is morphed, reformatted, and overlaid onto an MRI to conform to the patient’s anatomical structures such as the caudate head, thalamic height, and brainstem. This atlas-and-formula–based targets are then cross-correlated with the direct visualization target.

Indirect targeting has been the traditional method in stereotactic neurosurgery. The limitation of this method is that it does not take into account the discrete anatomical variations among individuals. Not all brains correspond to the topographical distribution depicted in a given atlas. Even the reformattable atlases available in computerized planning stations may not conform adequately to the patient’s anatomy. In this sense, direct targeting seems to have obvious benefits over indirect. It is based on the imaging data set of the individual’s own anatomy. Imaging techniques have advanced dramatically, allowing for adequate visualization of the STN in T2 images. However, several pitfalls exist, such as failure of fusion between CT scans and MRI or magnetic distortions that may alter the geometry of the nucleus. At the current stage, it is best to perform all targeting methods and correlate them prior to surgery.

**Entry Point Selection**

It is necessary to find an approach that will best facilitate interpretation of microelectrode recordings while concomitantly maximizing safety. From an electrophysiological mapping standpoint, a parasagittal approach is preferable but not feasible in all cases. Entry points are chosen based on the patient’s anatomy to provide a safe and optimal trajectory through the areas of interest. Typical angles of approach for the STN target are 15 to 30 degrees from the sagittal plane and 50 to 70 degrees in the anterior–posterior direction. The precise entry point may be refined on the planning console such that the trajectory passes through the crown of a gyrus rather than into a sulcus. This avoids inadvertently damaging sulcal or pial vessels, which lie on the cortical surface. The cortical vessels should be avoided as well as the F–F2 sulcus. After selecting preliminary entry points, the images can be reformatted to the trajectory view, which provides three orthogonal planes positioned with respect to the trajectory rather than the patient’s anatomy. The approach then may be traced at millimeter intervals to ensure that no deep sulci are transgressed and that the ventricular ependyma is not scythed. A typical approach will pass the electrode to course through the

![FIG. 4. AC–PC coordinate localization. The anterior and posterior commissures can be identified on this axial T1-weighed images.](image1)

![FIG. 5. Digital brain atlas and trajectory. Coronal and sagittal Schaltenbrand and Wahren digitized atlas is morphed, reformatted, and overlaid onto the MRI for the best fit to the individual patient’s anatomy. Note that this reformattning is not always an optimal match. The trajectory is targeted to the posterior portion of the STN nucleus.](image2)
Positioning and Anesthesia

The patient is positioned supine on the operating room table, with the knees flexed and the head of the table elevated to various degrees depending on surgeon preference. The head frame is fixed to the table with an adapter to the table or the floor. The patient’s feedback is used to find a neck position that will best tolerate extended immobility. Certain teams use intravenous sedation for the incisions and bony opening until electrophysiological mapping begins. Although sedation can be used, there is a potential risk for interference with microelectrode recording. Agents such as propofol are quickly reversible and may be preferred over other longer-lasting agents. Careful control of the arterial blood pressure is maintained to minimize the risk for intracranial bleeding. Patients with labile blood pressure may benefit from invasive monitoring for enhanced titration of the antihypertensive drugs. Preoperative antibiotics should be administered before incision and repeated thereafter. Draping should be performed to allow visual access to the patient’s face, arms, and legs while maintaining a sterile surgical site.

Older patients or those with degenerative spinal disease may not tolerate the extended awake immobilization required for microelectrode recording (MER). In these cases, epidural blocks or continuous epidural infusion of opioids may be attempted to ease the pain.

Stereotactic Approach

The coordinates for the X, Y, and Z coordinates are set and the entry points and the midline are marked on the skin and the incisions are planned. The stereotactic arc can be used to mark precisely the incision and the burr hole site, taking advantage of the trajectory planning. Depending on the thickness of the skull, the inner rim of the burr hole will limit the progression of the cannulas if the hole is drilled perpendicular to the skull surface. In order to prevent this problem, the holes should be drilled in the axis of the trajectory, at the same angle chosen for the stereotactic approach. Some teams prefer to open both incisions and burr holes before starting physiology on the first side, in order to expedite the process, but this may increase the time of exposure of the second side. It is worthwhile to start implantation on the side contralateral to the patient’s worst symptoms in case the patient does not tolerate a bilateral procedure.

The dura mater, arachnoid, and pia mater on the first side are coagulated and opened. Some teams do not open the dura and insert the tube guide by puncture of the dura, thus preventing subdural air penetration and CSF leakage. At this point, sedation can be interrupted to allow the patient to be awakened for microelectrode recording. Depending on the equipment and procedures of the various teams, different accessories are used to hold the microelectrodes and then the DBS lead. The cannula is inserted for microelectrode recording to a predetermined dorsal offset to the chosen anatomical targeting. A hydraulic or electrical microdrive is used to advance the microelectrode in submillimetric steps. Except when dura is not opened, either gelfoam and/or fibrin glue is placed around the cannula in the burr hole to provide a seal, thus minimizing CSF loss and pneumocephalus.

Electrophysiological Mapping

Intraoperative physiology including microelectrode recording and stimulation is discussed separately in this issue (see Gross and colleagues).

DBS Electrode Implantation and Testing

Various implantation approaches are used, from placing the active contacts in the center of the nucleus, at the ventral border, beyond the ventral border, or spanning multiple areas as determined by the team. After the optimal location for implantation of the electrode has been decided, the DBS lead (macroelectrode) can be implanted. The two commercially available electrodes have four contacts of 1.5 mm height and 1.27 mm diameter and differ only in the spacing between contacts: 1.5 mm in the 3387 model and 0.5 mm in the 3389 model (Medtronic, Minneapolis, MN). Contact 0 (the contact at the electrode’s tip) can be positioned at the physiologically defined ventral border of the nucleus and the remaining contacts will span for 10.5 mm (3387) or 7.5 mm (3389).
mm (3389) in the trajectory. When an inserting cannula is used, the chosen electrode is loaded in such a fashion that the first contact (and not the dead space at the tip of the electrode) is aligned with the tip of the cannula. Other systems may have different loading structures, depending on the distances between the electrode holder and the offset to target. Fluoroscopy is used by many centers to monitor DBS lead movement and migration. Some centers perform AP and lateral X-rays while others perform lateral only. In dedicated stereotactic operating rooms, the X-ray tubes and the frame are part of a solid-state setup, which avoids the instability of portable X-ray system alignments.

The patient is examined for baseline tremor, rigidity, and bradykinesia. The microdrive can be used to advance the electrode to the desired target or, alternatively, manual advancement can be performed to the target. Fluoroscopy can be used to confirm that the electrode is assuming a straight trajectory. A microsubthalamotomy, thalamotomy, or pallidotomy effect may occur secondary to the mechanical insertion of the electrode, with improvements in PD symptoms.

Testing the DBS electrode for efficacy and side effects is most commonly performed by all teams. However, certain groups rely extensively on the microelectrode recording and stimulation. In STN surgery, reduction in tremor, rigidity, and bradykinesia is expected during intraoperative macrostimulation. During implantation at the GPi, less changes in PD symptoms may be found intraoperatively, but the thresholds to side effects must be determined. The electrode parameters for intraoperative testing are similar to those for final programming. Typically, a pulse width of 60 to 90 microseconds and rate of 130 Hz are used and bipolar stimulation is performed at various combinations in order to assess the most commonly used cathodes. Voltage should be increased stepwise and the effects recorded. Particular attention should be directed to determination of side effects, including corticospinal activation (upper extremity, lower extremity, and face/tongue), speech changes, conjugate (corticospinal activation) and dysconjugate (activation of the third nerve) eye deviation. For STN targeting, paresthesias may indicate a more posterior implantation of the lead and, if transitory, are not considered a contraindication for implantation. A well-targeted electrode typically allows stimulation up to 4 volts without causing side effects. Lower thresholds indicate that the lead may be close to other structures and may have to be repositioned. For the GPi, thresholds to side effects should be higher, since higher amplitudes may be necessary for therapeutic effect. Capsular activation with subsequent motor contractions should not be achieved at less than 1 or 2 volts above the voltage yielding significant beneficial effects. For GPi, the deepest contact may have visual side effects from stimulation of the optic tract.

If side effects are found at thresholds lower than expected, repositioning of the electrode will be necessary. It is advised to move by more than 2 mm, as the risk of the electrode falling into the previous tract is high. It should also be noted that multiple macroelectrode penetrations may create fluid-filled spaces that may cause stimulation to spread unpredictably and result in unreliable macrostimulation. These problems are reduced by procedures using simultaneous insertion of several microelectrodes.

Once the DBS electrode is implanted at the final location, it must be secured in place while removing the cannula, carrier, and microdrive. Continuous fluoroscopy is helpful to monitor the potential of electrode displacement. Anchoring and securing the lead can be achieved by various techniques depending on the center preference and expertise. These include securing the lead to the skull with ligature embedded in dental cement, miniplates, and screws, the Medtronic burr hole ring and cap, as well as the Navigue Stim-Loc device (Image Guided Neurologics, Melbourne, FL). Advantages and disadvantages exist to each of these methods. Dental cement and miniplates are not recommended by the lead manufacturer. Their use may be necessary in peculiar scenarios such as when a craniectomy has to be added to the burr hole due to unexpected findings and the burr hole rings will not conform to the opening in the skull. The burr hole ring that is provided by the lead manufacturer can be safely used but a tendency exists to drive the electrodes deeper when inserting the cap. This can be easily observed on live fluoroscopy. The Stim-Loc device provides good stabilization of the electrodes without a tendency to push the electrodes deeper. It is a costly tool that may not be accessible to many centers. Once secured, the lead is attached to an extension wire that is tunneled to the parietal/occipital region. The excess lead can be coiled around the burr hole device or along the path of tunneling to serve as strain relief. The burr hole and the wound should be thoroughly irrigated with rinsing solution before closing the skin. Depending on the time that will be allowed between implantation of the electrode and the pulse generator in a staged procedure, scar tissue can form around the excess wire and burr hole device. In manipulating the DBS lead, sharp instruments or instruments with “teeth” should always be avoided since insulation may be inadvertently damaged. Likewise, when using metal instruments, care should be taken to prevent accidental crushing of the wires. Rubber-
capped instruments can be used but the surgeon’s fingertips may be the best instruments to deal with these delicate devices.

**INTRAOPERATIVE ADVERSE EVENTS**

Clinical hypervigilance is imperative throughout the procedure. If there is any intraoperative evidence of hemorrhage, such as bleeding from the cannula, gentle irrigation down the cannula is performed until the effluent is clear (Fig. 6). It should be noted that the only path for the hemorrhage to come out is via the cannula and it should not be removed prematurely. It is crucial to continue gentle irrigation until the hemorrhage is cleared while monitoring the patient for neurological status. Any neurological deterioration such as the onset of lethargy or a new focal deficit is cause for stopping the procedure and proceeding immediately to the CT scanner. If the patient cannot protect his or her airway, they should be intubated prior to leaving the operating room. Equipment to perform an emergent craniotomy should be readily available at all times.

In addition to neurological changes, changes in neuronal recordings may indicate the presence of an occult intraoperative hemorrhage. As there are no active neurons within a hemorrhage cavity, a microelectrode that encounters or produces a hemorrhage along its track will record only silence. Therefore, unexpected electrical silence not attributable to problems with the electrode itself or its position (such as in the internal capsule) should raise the suspicion of an intraoperative hemorrhage. In addition, deviation of the electrode tip on fluoroscopy after placement not only signals the presence of the development of an intracranial hemorrhage, but also provides some information as to the magnitude of the problem.

**Implantation of Pulse Generator (IPG)**

This is the last step of surgery and is performed under general anesthesia. It can be performed the same day or in a delayed/staged fashion. Due to the long duration of the procedure and the need for general anesthesia, IPGs can be implanted several days after the DBS lead implantation when the patient has recovered from the intracranial procedure.

For IPG implantation, the patient is positioned supine, with the head turned to the opposite side of the intended site of IPG implantation. Preoperative antibiotics are again administered 30 minutes prior to incision. A subcutaneous pocket is then created for the IPG and this pocket is connected to the DBS lead tunneled previously to the parietal/occipital region. The most common location for the IPG placement is infraclavicular and typically marked 2 cm below the clavicle and 4 cm away from the midline or 2 cm away from the lateral manubrial border. However, certain patients may require placement in other locations due to body habitus (very thin patients), age (pediatric patients), a history of prior surgery in the region, or vanity. In addition, certain activities such as hunting require the use of the chest to stabilize equipment. The IPG should be placed in a location that minimizes pressure and trauma to the unit. Anecdotal reports cite local trauma as an infection risk with other implanted hardware systems. Other locations include the subcostal area and the flank as well as the lumbar region and buttocks. All of these alternate sites require the use of a longer extension lead. The standard extension is 51 cm in length, but a 66 cm version is also available.

Regardless of the location, it is useful to mark the incisions before the final patient position to achieve maximal symmetry and cosmetic appeal. Marking the subclavicular incision in women deserves special attention for cosmesis. It may be useful to mark the incisions in the standing or sitting positions in order to best predict the final location of the incisions and generators. In most individuals, it is possible to create a subclavicular sub-
performed in layers after copious irrigation. The patient migration may occur due to the weight of the IPG. Closure is subcutaneous fat should be avoided since caudal migration of nonabsorbable sutures. Anchoring of the generator to generator and the IPG is anchored to the fascia with muscle. The excess extension lead is coiled behind the higher on the head, at the upper part of the temporal discomfort while wearing glasses. Some teams place it occipital nerves. If located too laterally, it may cause supine and may come in contact with the lesser or greater located too medially, it can cause pain when sleeping the connector is the retroauricular region (Fig. 7). When connected to the distal aspect of the DBS lead and IPG. The connector is internalized and pulled distally but should never be placed at the level of the neck below the mastoid, where mobility tends to cause tethering and resultant hardware failure can occur. A good position for the connector is the retroauricular region (Fig. 7). When located too medially, it can cause pain when sleeping supine and may come in contact with the lesser or greater occipital nerves. If located too laterally, it may cause discomfort while wearing glasses. Some teams place it higher on the head, at the upper part of the temporal muscle. The excess extension lead is coiled behind the generator and the IPG is anchored to the fascia with nonabsorbable sutures. Anchoring of the generator to subcutaneous fat should be avoided since caudal migration may occur due to the weight of the IPG. Closure is performed in layers after copious irrigation. The patient is re-draped for the contralateral side or when using a Kinera, both extension leads are passed under the skin on the same side. The Kinera is a larger device that can be used to control two DBS electrodes, thus allowing for a single-side IPG implantation. The disadvantages to this system include the greater volume that may impose a risk of erosion in very thin patients and the limitation to a single set of pulse frequencies.

POSTOPERATIVE MANAGEMENT

In the immediate hours after surgery, it is important to keep arterial blood pressure in the normal range. In addition, the patient’s preoperative PD regimen should be restarted immediately after surgery to avoid problems with dopaminergic withdrawal. Patients should undergo postoperative CT scans and/or MRI scans to assess the electrode location and intracranial status. In addition, plain X-rays are obtained to assess the location and geometry of the leads and hardware. Parkinson’s medications may need to be adjusted depending on the patient’s status. Cognitive and behavioral changes may occur in the postoperative period, particularly in older patients. Patients can be discharged as early as 24 hours after surgery, depending on their neurological and cognitive status.

REFERENCES
