4 Surgical and Technical Aspects of Deep Brain Stimulation

Rick Schuurman and Stephan Chabardes

Abstract

The basis of the stereotactic operation technique consists of the superposition of a three-dimensional coordinate system onto the brain, either by attaching a rigid stereotactic frame with a fixed spatial reference system to the skull, or by rigidly fixing the skull in a set relation to the internal spatial references of a robotic system. The position of the target structure for deep brain stimulation (DBS) as determined on a MRI scan is translated into spatial coordinates. Then the electrodes are implanted into the brain through burr holes in the skull, either using a stereotactic arc that is attached to the stereotactic frame and guides instruments toward the target, or using a robot arm to guide electrode placement.

Other technical developments have been recently applied. Improved MRI techniques enable the direct visualization of target structures for DBS, allowing for more accurate electrode implantation. New MRI techniques also contribute to the understanding of brain circuitry, which can lead to the development of new targets and new indications for DBS. Many DBS implantations are carried out under local anesthesia in order to evaluate the effectiveness of symptom reduction and the occurrence of side effects by stimulation at the target site. In the near future this may become redundant in the majority of indications, when preoperative MRI scans and intraoperative neurophysiology are shown to provide enough information to adequately determine the optimal location for electrode implantation. The latest DBS systems enable steering of the applied current through multifaceted electrodes. This may further increase the effectiveness of DBS while limiting side effects by higher precision of current delivery to the brain. Finally, adaptive stimulation in closed-loop systems can lead to the development of the DBS that is continuously adjusted based on the real-time condition of the patient.

Introduction

Deep brain stimulation (DBS) is a treatment whereby the functioning of structures that lay deep in the brain can be influenced or altered by direct application of electrical current using electrodes implanted into the brain. These electrodes are connected through subcutaneous extension cables to a stimulator that is implanted on the chest or abdominal wall. The delivery of current from the stimulator to the electrodes in the brain

R. Schuurman (✉)
Department of Neurosurgery, Amsterdam University Medical Centers, Amsterdam, the Netherlands
e-mail: p.r.schuurman@amsterdamumc.nl

S. Chabardes
Service de Neurochirurgie, Centre Hospitalier Universitaire Grenoble Alpes, Grenoble, France
e-mail: SChabardes@chu-grenoble.fr

Y. Temel et al. (eds.), *Fundamentals and Clinics of Deep Brain Stimulation*,
https://doi.org/10.1007/978-3-030-36346-8_4

can be programmed and settings can be changed using an external programming device.

Stereotactic Implantation Technique of DBS Electrodes

Successful treatment with DBS requires implantation of electrodes with high precision. At present, the most often used target structures for stimulation are: (1) subnuclei of the thalamus for tremor, task-specific dystonia, pain syndromes, and epilepsy; (2) the deeply positioned basal ganglia such as the subthalamic nucleus for Parkinson's disease and the globus pallidus for generalized and focal dystonia with and without structural brain abnormalities; and (3) deep white matter tracts connecting various brain areas for psychiatric indications, such as obsessive compulsive disorder, and also for tremor.

After the target structures have been made visible with detailed MRI scanning, implantation of the electrodes into these target structures is performed using stereotactic surgical techniques.

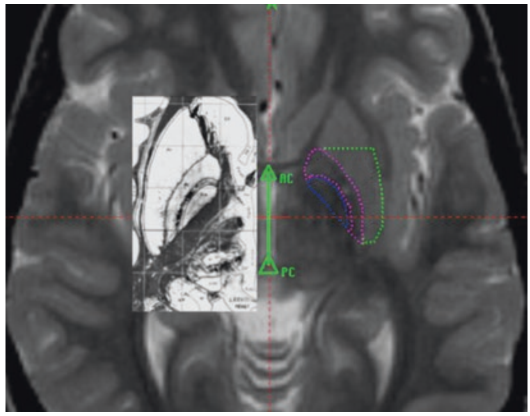

Fig. 4.1 Example of an axial slice of an MRI scan for the determination of the position of the target structure for DBS, in this case the globus pallidus. In the center of the image, the AC–PC line is portrayed. On the left side of the image, the stereotactic atlas is projected onto the brain as an example. On the right side of the image, the contours of the internal (blue) and external (pink) segments of the globus pallidus and the putamen (green) are drawn by surgical planning software, adjusting the position of the atlas structures to the individual anatomy of the patient. Note: the anterior margin of the putamen is cut off depending on the extent to which the atlas plate of this axial level reaches

Stereotactic Atlases

In stereotactic surgery, special anatomical atlases are used in which brain anatomy is outlined in a high level of detail. In these atlases a virtual central axis is used connecting the anterior commissure (AC) and the posterior commissure (PC). The brain is portrayed on a submillimeter scale in three directions – axial, coronal, and sagittal – whereby images are oriented parallel or perpendicular to the AC–PC line. For every structure in the brain an average position in relation to the AC–PC line is determined. The position of the target structures in relation to the AC–PC line is relatively constant in the majority of people. However, for the final determination of the exact location of implantation, an MRI scan is used to correct for the small interindividual variations in anatomy.

Using special software, the stereotactic atlas can be adjusted and projected onto the MRI scan of the individual patient. In this way, the precise individual location of the target structures in the brain can be determined and these targets can now be given anatomical coordinates (see Fig. 4.1).

Stereotactic Frame-Based Navigation

During the surgery a rigid frame is attached to the skull. This so-called stereotactic frame (Fig. 4.2a) has a fixed position in relation to the skull and the internal brain structures. Most stereotactic frames consist of straight metal bars at right angles, with millimeter markings in the three cardinal directions. In this way, a Cartesian coordinate system is projected onto the brain, with an X-axis from right to left, a Y-axis from posterior to anterior, and a Z-axis from top to bottom.

With the frame attached to the head, a 1.5-T MRI scan can be made which directly shows the target structures for DBS or the neighboring structures in sufficient detail to obtain the position of the target structure indirectly by adjusting the stereotactic atlas. In practice, most teams obtain a preoperative 3-T, or even 7-T MRI scan, on which the target structures are clearly seen. Then, by means of surgical planning software a co-registration of these preoperative images is performed with either a frame-based 1.5-T MRI or a frame-based CT scan.

It is mandatory that in the process of co-registering images from various sources, corrections are being made for image distortions that can occur in different MRI scanning sequences to a varying degree. However, most present-day MRI scanners are equipped with adequate distortion correction algorithms and the planning software available can be used to make final corrections.

Combining the MRI scan, the atlas and the stereotactic frame in this way, the target for DBS can be described in individual anatomical coordinates with reference to the AC–PC line and with stereotactic coordinates with reference to the stereotactic frame for surgical navigation.

Stereotactic Implantation

When stereotactic coordinates of the target structure are obtained, the electrode can be implanted in a straight line through the brain from a burr hole in the skull to the target. The trajectory through the brain is determined using three-dimensional (3D) projections of the MRI scan. The path is determined in the planning software with the aim to prevent damaging the brain, mainly by avoiding all visible vessels in order to minimize the risk of inducing a bleeding.

The patient is then positioned on the operating table, with firm fixation of the head with the attached stereotactic frame. Under sterile conditions, a surgical aiming device can now be attached to the frame. This device is arc-shaped (see Fig. 4.2b), and this stereotactic arc can be positioned in such a way that the center of the virtual circle formed by the arc coincides with the stereotactic x-, y-, and z-coordinates of the target structure. The angles of implantation were provided by the trajectory planning. The electrode can now be implanted precisely along the planned path into the planned target in the brain.

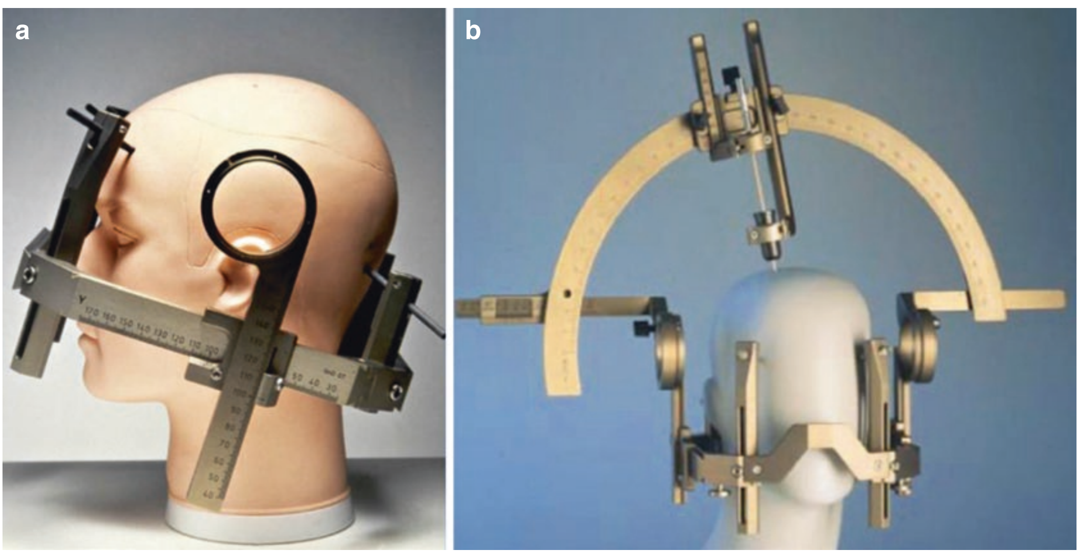

Fig. 4.2 (**a**) The stereotactic frame that is attached to the skull. The millimeter markings provide the Cartesian coordinate system that is projected onto the brain. (**b**) The stereotactic arc is attached to the frame. The center of the virtual circle formed by the arc coincides with the coordinates of the target structure. In this way, the electrode (or any other surgical instrument) can be placed along a predetermined trajectory exactly into the target structure

Intraoperative Testing

After determining the position of the target structure for DBS, this position can be verified by intraoperative neurophysiological and clinical testing when direct, observable effect is possible (which is not the case, for example, in dystonia or for psychiatric indications). In order to be able to perform such intraoperative testing, implantation of DBS electrodes is performed under local anesthesia, allowing for optimal measurements of pathophysiological brain activity in the target area and providing clinical feedback on the effect of electrical stimulation on the symptoms in the awake patients.

To maximize these effects, in Parkinson patients, antiparkinson medication is stopped overnight, so that during the surgery, symptoms severity can more easily be judged. Obviously, undergoing an ‘awake’ intracranial procedure while being off medication can be very burdensome for the patient, and special attention for the physical and emotional state is required during the surgery (see also Chap. 7).

For neurophysiological confirmation of the target location, recordings are performed using one or several micro-electrodes which are inserted into, and parallel to, the predetermined path. Signals can be obtained from individual neurons in the target area, and in this way the borders of the various target nuclei can be outlined and compared to the borders as determined by the MRI scans used for planning.

After the target area has been determined by radiological and neurophysiological means, test stimulation is carried out. This is a simulation of the DBS that will be applied to the patient after surgery, and can be used to determine if stimulation in the determined area will indeed relieve the symptoms of the disease, for example, to a reduction of tremor and rigidity in a patient with Parkinson’s disease. In addition, the electrical thresholds for the induction of side effects can be determined, such as eye movement disturbances, impaired speech, or involuntary muscle contractions, caused by inadvertent spread of current into neighboring structures.

Finally, based on radiological, neurophysiological, and clinical information, the optimal position for the DBS electrode is decided. The permanent DBS electrode is then positioned in the target area under X-ray control and anchored to the skull so that postoperative electrode displacement will not occur along the axis of the electrode.

DBS is usually applied bilaterally, so that intraoperative testing and electrode implantation are repeated in the contralateral hemisphere.

Thereafter, the frame is removed from the skull. In an ensuing operation under general anesthesia, the electrodes are connected to extension cables that run subcutaneously through the neck to the infraclavicular region, which in turn are connected to a neurostimulator. The stimulator is implanted subcutaneously on the wall of the thorax or the abdomen.

Intraoperative testing in the awake patient can be performed in DBS for movement disorders such as essential tremor, dystonia, and Parkinson’s disease, or in pain syndromes where feedback from the patient during test stimulation can be used to guide the implantation and thereby increases the chance of an effective electrode placement. In patients with severely abnormal posturing due to dystonia, especially in children, the procedure can be carried out under general anesthesia. Test stimulation can in these cases still provide feedback about the threshold for the side effect of muscular contraction. DBS for indications in which no reliable intraoperative clinical effect of test stimulation can be observed, such as in epilepsy and psychiatric disorders, can also be performed under general anesthesia.

Intraoperative Imaging for Lead Verification

Despite the effort to place a lead into an appropriate target, it is mandatory to check for any deviation or any suboptimal final lead placement in order to prevent bad clinical results. To those aims, several options are available, from very simple techniques, such as fluoroscopy, to more precise and sophisticated techniques such as intraoperative CT scanning or intraoperative MRI.

It is now possible to use intraoperative CT scans that can show the trajectory of the tube used for micro electrode recording (MER) or the final DBS leads. Those images are obtained in a DICOM (Digital Imaging and Communications in Medicine) format, and can be fused with the preoperative planning performed on a 3-T MRI for example. Those images allow us to depict any lead deviation that will be corrected during the surgery (see Fig. 4.3).

Another option has been described by Zrinzo and Hariz (Aviles-Olmos et al. 2014) that consists in intraoperative lead verification using intraoperative MRI. In this concept, the leads are implanted using a regular stereotactic frame and then, at the end of the surgery, the patient undergoes an MRI scan before the removal of the frame.

Larson and Starr (Starr et al. 2009) have developed an innovative approach using the clear point system that consists in implanting DBS lead using real-time, intraoperative MRI guidance. In that concept, the surgery is performed while the patient is installed into the MRI scan using appropriate tools (see Fig. 4.4).

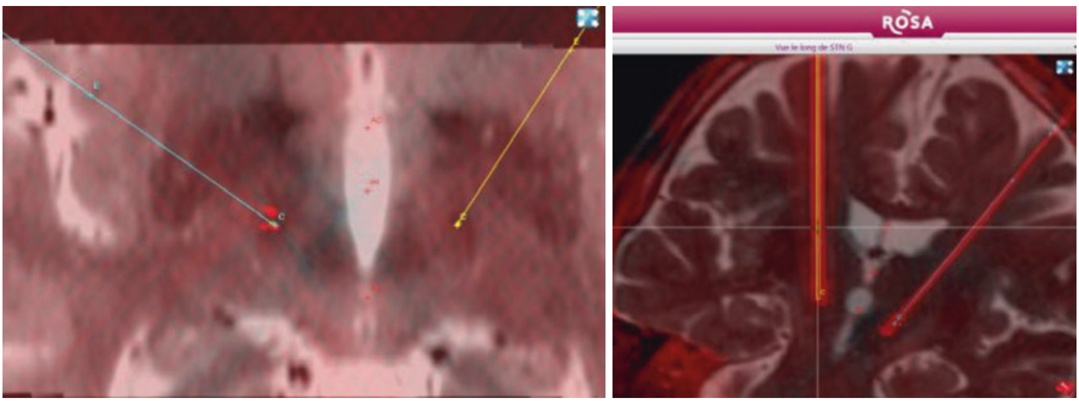

Fig. 4.3 Left: Intraoperative image fusion between a preoperative T2 MRI image showing the red nucleus and the subthalamic nucleus (STN) and 3 micro-recording electrode tips into the STN. Right: Intraoperative image fusion between a preoperative T2 MRI image showing the red nucleus and the STN and also final lead inserted along the planned trajectory

Fig. 4.4 Illustration of a case of STN-DBS lead implantation performed at Grenoble University using the Clear Point System and the concept developed by Starr and Larson at the University of California, San Francisco (UCSF), USA

Alternative Implantation Techniques

Nexframe

Electrode implantation for DBS is also possible without stereotactic frame. In that case, instead of a frame around the head, a smaller aiming device is attached to the skull. The target structure for DBS and the trajectory of implantation are determined on an MRI scan as well. Instead of a frame, fiducial markers are attached to the skull through the skin, which are visible on the MRI. Instruments are guided by steering through navigation software, applying infrared detection techniques in the same manner as used during general neurosurgical navigation.

The location of the burr hole is determined after which the aiming device, the so-called Nexframe, is attached to the skull (Starr et al. 2010). A canula is fixed in the proper orientation for implantation after which the depth of implantation is calculated and the electrode is then placed in the target area through this canula. The reported precision of electrode placement with this system is comparable to implantations using a stereotactic frame (Kelman et al. 2010).

Robot-Guided Surgery

Robot-guided DBS lead implantation has been used for more than 20 years. However, recent technological innovations have allowed a larger dissemination of the technique (for review, see Faria et al. 2015). Indeed, electrode implantation can also be performed using a robot arm, replacing the stereotactic arc. Target and trajectory planning is performed using the MRI scan in the same manner as in frame-based procedures using the navigation software of the Robot. Intraoperatively, fiducial markers are fixed to the skull through the skin after which three-dimensional imaging is repeated using CT scan and co-registered to the MRI used for planning.

Then the robotic arm is connected to the skull by rigid fixation (using a frame as a head holder), and the steering mechanism of the robot arm is connected to the preoperative planning, after which the arm can indicate the position of the burr hole. Depending on the technique chosen, a Microdrive can be supported by the robotic arm, allowing us to guide several tubes into the brain toward the target. Next, a depth electrode can be inserted for testing, and final DBS electrode implantation can be achieved (see Fig. 4.5).

Fig. 4.5 Robot-guided surgery performed at Grenoble University. The head of the patient is rigidly fixed using a head holder (here, a Leksell Frame). The patient is installed into an intraoperative scan (Oarm, Medtronic) that allows intraoperative image verifications of lead placements

Advantages of using a robotic arm are a better precision when compared to regular frame surgery (vectorial errors: 1–1.5 mm for robot surgery versus 3 mm for frame-based surgery) (von Langsdorff et al. 2014) as well as a faster procedure, especially when multiple trajectories are needed such as for stereo-electro-encephalography (SEEG).

Recent and Future Technical Developments

Imaging

The MRI scanner was introduced in stereotactic electrode implantation procedures in the 1990s. Originally, it was mainly used for accurate determination of the position of the AC–PC line, enabling more accurate overlaying of the stereotactic atlas in comparison to the previously used ventriculography. In addition, trajectory planning became possible, avoiding vessels and the ventricular system.

With the development of new MR sequences aimed at outlining the basal ganglia, and the advent of MR scanners with higher field strengths, it became possible to outline the target structures for DBS in increasing detail (Fig. 4.6). This allows for increasingly more precise preoperative target determination.

DTI, Connectivity, fMRI

The use of diffusion tensor imaging (DTI) and tractography provides new possibilities to visualize the white matter connections between various brain structures. This can give rise to new potential target structures for DBS treatment or refinement of target already in use. Examples are the visualization of the dentato-rubro-thalamic tract which can be stimulated on different levels in the brain for the treatment of tremor (Coenen et al. 2014), and the delineation of the median forebrain bundle which can play a role in the treatment of anxiety and mood disorders (Schlaepfer et al. 2013). Connectivity studies can identify substructures in the thalamus that might be useful in the treatment of pain (Kovanlikaya et al. 2014).

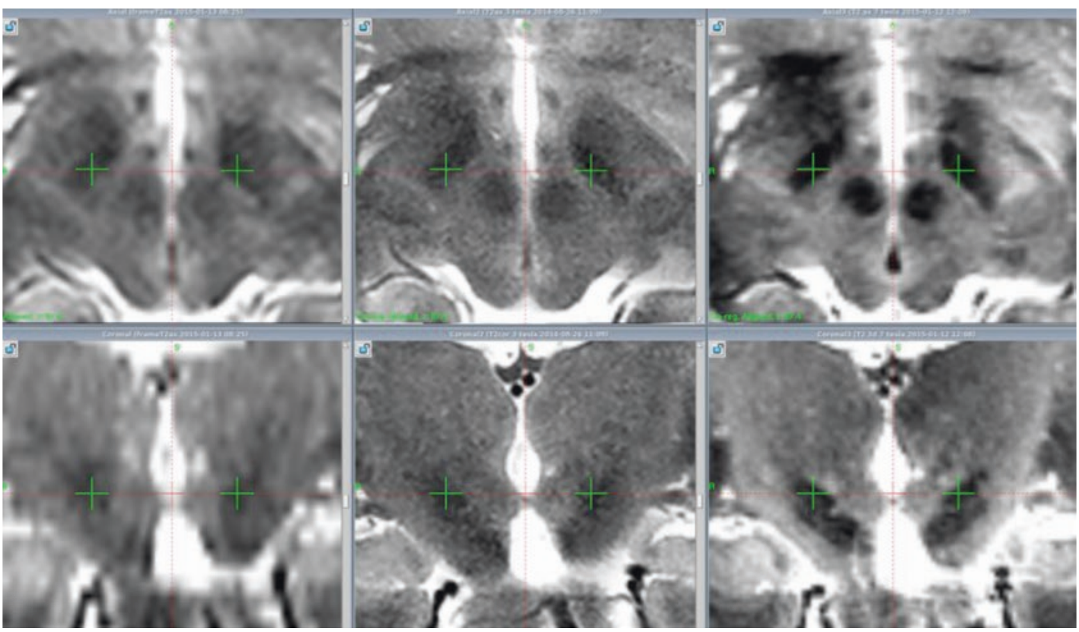

Fig. 4.6 Detailed projections of MRI scans used for planning of DBS in the subthalamic nucleus in Parkinson's disease. T2 axial (top) and coronal (bottom) sections by MR scanners with increasing magnetic field strength: left panels 1.5 T, middle panels 3 T, right panels 7 T

Functional MRI (fMRI) and connectivity studies, in addition to directly outlining targets for DBS and increasing understanding about current targets (Lambert et al. 2012), can also contribute to the understanding of functional brain circuitry, especially as these imaging techniques can also be performed with DBS systems implanted (Figee et al. 2013).

Planning Platform Using 3D Images

Recently it has become possible to create 3D models of the target and its environment either by deformable atlases or by automatic anatomical segmentation (see Fig. 4.7). These tools allow us to simulate preoperatively or to reconstruct the position of the lead during the surgery of postoperatively, and also to image the theoretical Volume of Tissue Activated (VTA) around the lead. The precision of these 3D images depends on the quality of the native images and the "fusion" process and must be interpreted with cautions.

DBS Surgery Under General Anesthesia

At present, Parkinson's disease is the most common indication for DBS. The current surgical strategy, described above, is based on the combination of radiological, neurophysiological and clinical information to determine the optimal DBS electrode location and is carried out under local anesthesia in most centers. In the past, the advantage of combining these techniques and being able to judge the effects of DBS intraoperatively largely outweighed the burden of the procedure for the patient. However, with the improvements in imaging and the fact that neurophysiological recordings can also be performed under general anesthesia with increasing signal yield (Pinkster et al. 2009), the added value of intraoperative clinical testing might diminish. Results from a series of DBS implantations under general anesthesia from a large volume center were comparable to a historic control cohort of patients who underwent awake surgery in the same center (Nakajima et al. 2011).

In addition to the diminished burden to the patient, surgery under general anesthesia might well be associated with shorter time of the surgical procedure and less postoperative confusion, thereby leading to shorter hospital admission time. Studies comparing local anesthesia to general (full) anesthesia will have to show if the new approach under general anesthesia can be adopted more generally for faster treatment time with a lower patient burden without loss of quality of the intervention.

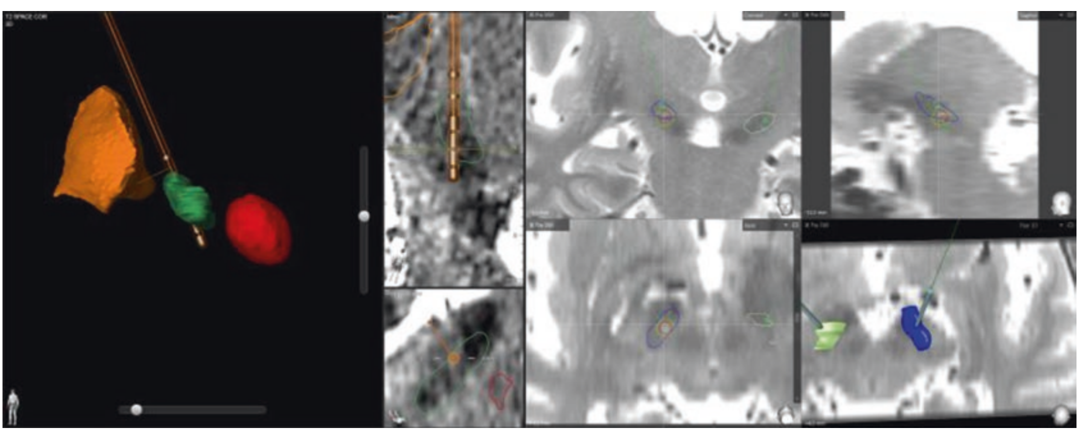

Fig. 4.7 Example of 3D representation of a DBS lead inserted into the STN (in green) using Guide XT (Brain Lab) on the left, and Sure Tune (Medtronic) on the right

Steering of Stimulation

The most widely used DBS electrodes have four active contact points which can be turned on or off independently. These contact points are 1.5 mm in height with an interspace of 0.5 or 1.5 mm. By choosing the configuration of active contacts, the location in which DBS is applied can be varied in the vertical direction, along the Z-axis, based on clinical response to stimulation. From every active contact point, current is delivered circumferentially in all directions without the option to choose the direction of stimulation in the X- and Y-direction after electrode implantation. Increasing the current to obtain more clinical effect can become limited by the occurrence of side effects due to spread of current in adjacent brain structures such as the internal capsule, the medial lemniscus, or oculomotor fibers.

New electrodes were developed in which several contacts were no longer circumferential but divided into three segments instead. It is possible to turn certain segments on and off and thus create an asymmetrical field of stimulation that can be steered into or away from any particular direction (see Fig. 4.8). Early studies have shown that the therapeutic window, that is, the difference between the threshold for positive clinical effects and the threshold for side effects, can indeed be increased by current steering, both intraoperatively with experimental steering electrodes and postoperatively with permanently implanted steering electrodes (Contarino et al. 2014; Steigerwald et al. 2016).

Adaptive Stimulation in a Closed Circuit

An advancement that can be expected in the near future is adaptive stimulation in a closed circuit (see also Chap. 5). Currently, DBS is programmed on a fixed setting which produces the same current continuously, independent of the actual need for stimulation based on fluctuations of symptom severity or disease activity within the patient. Ideally, the severity of target symptoms of DBS could be continuously monitored. Feedback into the system could lead to changes in the stimulation parameters, depending on the real-time needs.

Effectiveness of closed-circuit stimulation was shown for pallidal DBS in a model of MTPT-induced parkinsonism in monkeys, whereby cellular activity in motor cortex provided feedback to the DBS system for switching on when parkinsonism increased (Rosin et al. 2011). In man the effectiveness of this form of stimulation has also been demonstrated. In Parkinson patients with DBS electrodes in the subthalamic nucleus that were externalized through the skin for external

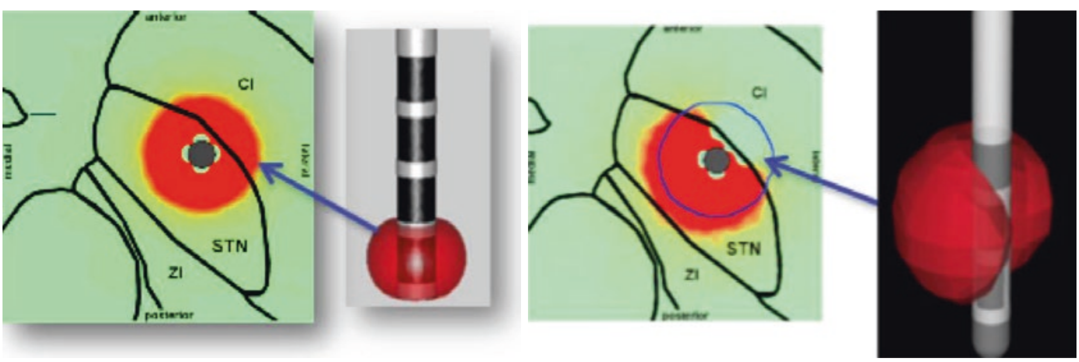

Fig. 4.8 Schematic representation of current spread, projected onto an atlas image of the subthalamic nucleus. Left panels: Current spread from conventional electrode can produce aberrant stimulation of a neighboring structure, producing positive clinical effects in the subthalamic nucleus (STN) and side effects of the internal capsule (CI). Right panels: Steering of the current by turning off segments in the active contact can shape the field of stimulation so that only the target structure is stimulated

test stimulation, local activity of clusters of brain cells was measured. Increases in beta-activity related to increased disease severity led to activation of DBS, which could produce improvements in parkinsonism comparable or even larger than with continuous DBS (Little et al. 2013). The benefit of this form of stimulation will have to be studied in more depth once permanently implantable closed-loop systems have become available.

Conclusions

Surgical techniques for DBS have improved over time since the 1990s and nowadays, new MRI sequences, using higher magnetic field, make the anatomical targets better visible in a vast majority. The possibility to check the accurate position of the lead during surgery should decrease the number of suboptimally placed leads, which remains the main goal during DBS procedure. New leads that use directional steering might, though not in all cases, compensate some slight errors of lead placements. However, recent improvement in technology and imaging must not distract from basic knowledge in anatomy, physiology, and clinical neurology or psychiatry required for optimal DBS treatment.

References

Aviles-Olmos I, Kefalopoulou Z, Tripoliti E, et al. Long-term outcome of subthalamic nucleus deep brain stimulation for Parkinson's disease using an MRI-guided and MRI-verified approach. J Neurol Neurosurg Psychiatry. 2014;85:1419–25.

Coenen VA, Allert N, Paus S, et al. Modulation of the cerebello-thalamo-cortical network in thalamic deep brain stimulation for tremor. Neurosurgery. 2014;75:657–70.

Contarino MF, Bour LJ, Verhagen R, et al. Directional steering: a novel approach to deep brain stimulation. Neurology. 2014;83:1163–9.

Faria C, Erlhagen W, Rito M, De Momi E, Ferrigno G, Bicho E. Review of robotic technology for stereotactic neurosurgery. IEEE Rev Biomed Eng. 2015;8:125–37.

Figee M, Luigjes J, Smolders R, et al. Deep brain stimulation restores frontostriatal network activity in obsessive-compulsive disorder. Nat Neurosci. 2013;16:386–7.

Kelman C, Ramakrishnan V, Davies A, Holloway K. Analysis of stereotactic accuracy of the Cosman-Robert-wells frame and nexframe frameless systems in deep brain stimulation surgery. Stereotact Funct Neurosurg. 2010;88:288–95.

Kovanlikaya I, Heier L, Kaplitt M. Treatment of chronic pain: diffusion tensor imaging identification of the ventroposterolateral nucleus confirmed with successful deep brain stimulation. Stereotact Funct Neurosurg. 2014;92:365–71.

Lambert C, Zrinzo L, Nagy Z, et al. Confirmation of functional zones within the human subthalamic nucleus: patterns of connectivity and sub-parcellation using diffusion weighted imaging. NeuroImage. 2012;60:83–94.

Little S, Pogosyan A, Neal S, et al. Adaptive deep brain stimulation in advanced Parkinson disease. Ann Neurol. 2013;74:449–57.

Nakajima T, Zrinzo L, Foltynie T, et al. MRI-guided subthalamic nucleus deep brain stimulation without microelectrode recording: can we dispense with surgery under local anaesthesia? Stereotact Funct Neurosurg. 2011;89:318–25.

Pinkster MO, Volkmann J, Falk D, et al. Deep brain stimulation of the internal globus pallidus in dystonia: target localisation under general anaesthesia. Acta Neurochir. 2009;151:751–8.

Rosin B, Slovik M, Mitelman R, et al. Closed-loop deep brain stimulation is superior in ameliorating parkinsonism. Neuron. 2011;72:370–84.

Schlaepfer TE, Bewernick BH, Kayser S, Madler B, Coenen VA. Rapid effects of deep brain stimulation for treatment-resistant major depression. Biol Psychiatry. 2013;73:1204–12.

Starr PA, Martin AJ, Larson PS. Implantation of deep brain stimulator electrodes using interventional MRI. Neurosurg Clin N Am. 2009;20:193–203.

Starr PA, Martin AJ, Ostrem JL, Talke P, Levesque N, Larson PS. Subthalamic nucleus deep brain stimulator placement using high-field interventional magnetic resonance imaging and a skull-mounted aiming device: technique and application accuracy. J Neurosurg. 2010;112:479–90.

Steigerwald F, Muller L, Johannes S, Matthies C, Volkmann J. Directional deep brain stimulation of the subthalamic nucleus: a pilot study using a novel neurostimulation device. Mov Disord. 2016;31:1240–3.

von Langsdorff D, Paquis P, Fontaine D. In vivo measurement of the frame-based application accuracy of the neuromate neurosurgical robot. J Neurosurg. 2014;31:1–4.