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review

Imaging Techniques in Deep Brain Stimulation: A Review of Preoperative, Intraoperative, and Postoperative Applications

Zobrazovacie metódy pri hlbokej mozgovej stimulácii: prehľad predoperačného, intraoperačného a pooperačného využitia

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Major statement
Imaging plays a key role in all phases of deep brain stimulation, enabling personalization and improved clinical outcomes.

Hlavní stanovisko práce
Zobrazovacie metódy zohrávajú kľúčovú úlohu vo všetkých fázach hlbokej mozgovej stimulácie, pričom umožňujú individualizáciu liečby a zlepšenie klinických výsledkov.

SUMMARY

Janovič Š, Hollý S, Kušnírová A, Kľoc M, Harag T, Chmelík M, Košutzká Z. Imaging Techniques in Deep Brain Stimulation: A Review of Preoperative, Intraoperative, and Postoperative Applications

Deep brain stimulation (DBS) has over the years established as an effective and safe treatment for various neurological and psychiatric disorders, such as Parkinson's disease, essential tremor, dystonia, etc. With the advancement of this therapy, imaging techniques have gained crucial importance in all phases of treatment – from patient selection and surgical planning, through intraoperative electrode placement, to postoperative monitoring and stimulation programming. In the preoperative phase, magnetic resonance imaging (MRI) plays a fundamental role in visualizing brain structures, identifying contraindications, and planning the procedure. Advanced MRI techniques, such as diffusion imaging and tractography, enable assessment of brain structural connectivity and allow treatment to be tailored to individual symptoms. These approaches support a new perspective on neurological disorders – not as diseases of isolated structures,

SÚHRN

Janovič Š, Hollý S, Kušnírová A, Kľoc M, Harag T, Chmelík M, Košutzká Z. Zobrazovacie metódy pri hlbokej mozgovej stimulácii: prehľad predoperačného, intraoperačného a pooperačného využitia

Hlboká mozgová stimulácia (DBS, z angl. deep brain stimulation) sa v priebehu rokov etablovala ako účinná a bezpečná liečebná metóda pri rôznych neurologických a psychiatrických ochoreniach, ako sú Parkinsonova choroba, esenciálny tremor, dystónia a podobne. S rozvojom tejto terapie nadobúdajú zobrazovacie techniky zásadný význam vo všetkých fázach liečby – od výberu vhodného pacienta a plánovania zákroku, cez intraoperačné zavádzanie elektród až po pooperačné sledovanie a programovanie stimulácie.
V predoperačnej fáze zohráva magnetická rezonancia (MR) kľúčovú úlohu pri vizualizácii mozgových štruktúr, identifikácii kontraindikácií a plánovaní samotného zákroku. Pokročilé MR techniky, ako je difúzne zobrazovanie a traktografia, umožňujú hodnotenie štrukturálnej konektivity mozgu a prispôsobenie liečby individuálnym príznakom. Tieto prístupy podporujú nový pohľad na neurologické

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but of neural circuits. During DBS electrode implantation, imaging ensures precise placement – either through direct anatomical targeting with MRI or via position verification using CT or X-ray. Postoperatively, CT scanning is crucial in assessing electrode placement accuracy and identifying complications such as ischemia, hemorrhage, or pneumocephalus. Advances in information technology have enabled the development of software tools for imaging data analysis in DBS. Among the most widely used are the open-source tool Lead-DBS, and certified platforms such as SureTune™ (Medtronic) and GUIDE™ XT (Boston Scientific). These systems allow for reconstruction of electrode placement, calculation of the volume of activated tissue, and visualization of stimulation fields. Some also enable connectome and brain network analysis, supporting personalized, network-oriented stimulation settings and thereby significantly improving DBS therapy precision and effectiveness.

Key words: deep brain stimulation, neuroimaging, Parkinson disease.

poruchy – nie ako na ochorenia izolovaných oblastí, ale ako poruchy nervových okruhov. Počas samotného zavádzania DBS elektród zohráva zobrazovanie kľúčovú úlohu pri ich presnom umiestňovaní – buď prostredníctvom priameho anatomického navádzania (pomocou MR), alebo verifikácie ich polohy pomocou CT či röntgenu. V pooperačnom sledovaní zohráva kľúčovú úlohu CT vyšetrenie, ktoré umožňuje nielen posúdiť presnosť zavedenia elektród, ale aj včas identifikovať komplikácie, ako sú ischémia, hemorágia či pneumocefalus. Pokrok v informačných technológiách umožnil vývoj softvérových nástrojov na analýzu zobrazovacích dát pri DBS. Medzi najpoužívanejšie patria open-source nástroj Lead-DBS a certifikované platformy ako SureTune™ (Medtronic) a GUIDE™ XT (Boston Scientific). Tieto systémy umožňujú rekonštrukciu umiestnenia elektród, výpočet objemu aktivovaného tkaniva a vizualizáciu stimulačných polí. Niektoré umožňujú aj analýzu konektómu a mozgových sietí, čím podporujú personalizované, na sieť zamerané nastavenia stimulácie a tým výrazne zvyšujú presnosť a účinnosť DBS terapie.

Klíčová slova: hlboká mozgová stimulácia, neurozobrazovanie, Parkinsonova choroba.

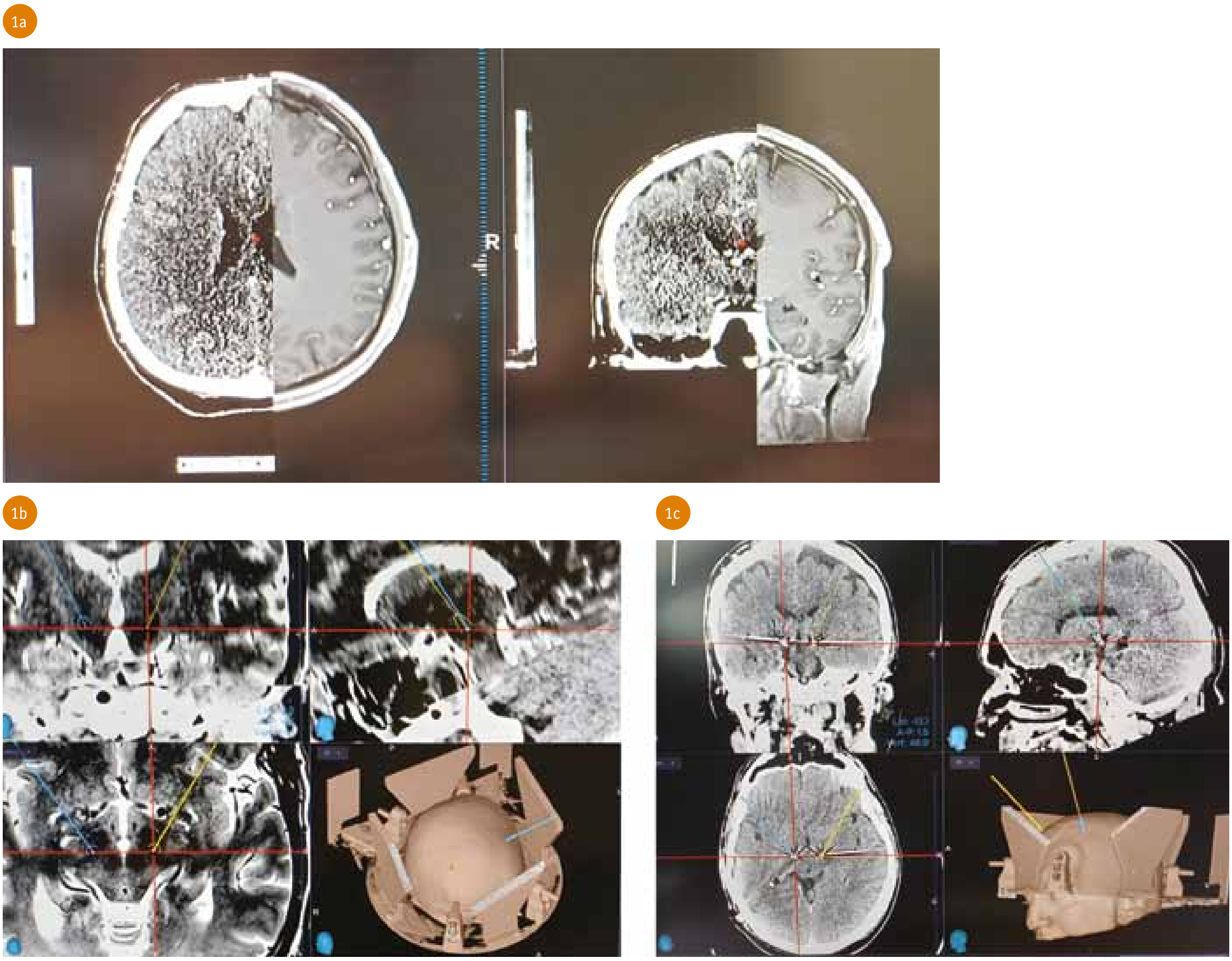
INTRODUCTION

Since the first implantation of deep brain stimulation (DBS) in 1987 for the treatment of essential tremor and later Parkinson's disease (PD), the field has undergone significant transformation. Early procedures relied primarily on stereotactic anatomy and intraoperative clinical observation. Today, DBS benefits from sophisticated neuroimaging technologies that enable highly accurate, individualized, and functionally guided targeting. The development of MRI and tractography has fundamentally changed how DBS is planned, navigated, and evaluated. Modern imaging techniques now play a central role throughout all phases of DBS therapy – from preoperative candidate selection and anatomical target definition, to intraoperative electrode guidance, and postoperative verification and stimulation programming. Advances in connectomics and the ability to visualize white matter pathways have paved the way for network-oriented neurosurgery, which considers not just anatomical structures, but also the functional brain circuits involved in disease. This shift has improved clinical outcomes, reduced stimulation-related side effects, and significantly shortened the time required for programming. The aim of this review is to present the role of neuroimaging across the full continuum of DBS management – from initial planning to long-term postoperative care – and to highlight how these advancements contribute to safer, more effective, and more personalized neuromodulation strategies.

Application of imaging techniques in the preoperative management of DBS patients

From the perspective of imaging techniques used in the preoperative phase of DBS, MRI is considered the most important modality. Its primary role lies in preoperative planning, as it enables accurate targeting of brain regions intended for stimulation (Fig. 1).

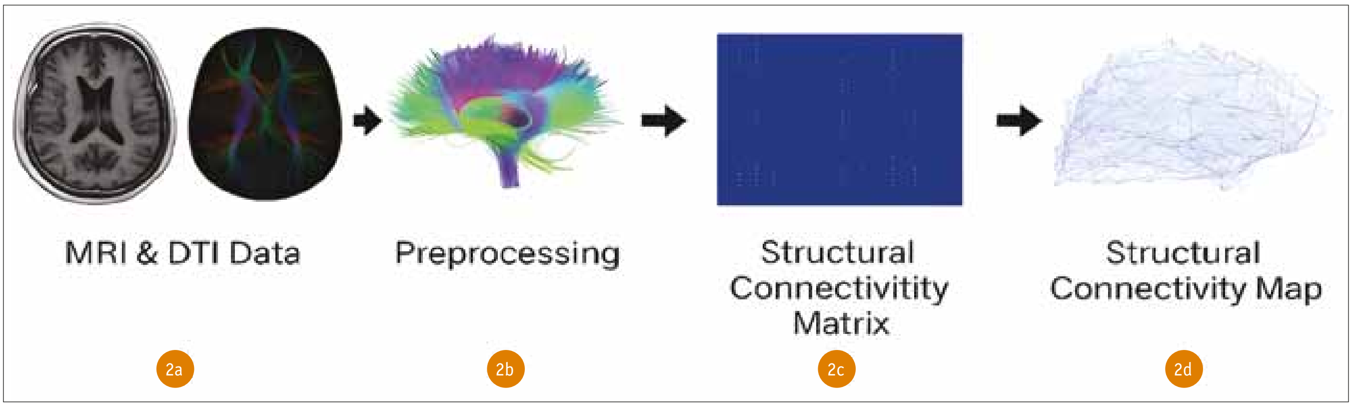
At the same time, MRI provides critical insights into a patient's overall brain condition, helping clinicians evaluate DBS candidacy and identify potential contraindications. These may include pathological lesions or tumors (depending on their location), vascular malformations that increase the risk of perioperative complications, or severe brain atrophy and other degenerative changes that could compromise treatment efficacy (1). Beyond planning and candidacy assessment, MRI also serves as a predictive tool for therapeutic outcomes. Techniques such as volumetric analysis can identify atrophy in



1 **Schematic representation of preoperative planning for stereotactic DBS implantation using the StealthStation (Medtronic) system:** (a) fusion of preoperative MRI and CT scans to align anatomical landmarks for accurate targeting; (b) planned stereotactic trajectories for DBS targeting the STN (the right-sided trajectory is shown in yellow, and the left-sided trajectory in blue); (c) postoperative CT scan showing the final position of the implanted DBS electrodes in relation to the preoperatively calculated trajectories

Schématické znázornenie predoperačného plánovania stereotaktickej implantácie DBS pomocou systému StealthStation (Medtronic): (a) fúzia predoperačných MRI a CT snímok na zosúladenie anatomických orientačných bodov s cieľom presného zacielenia; (b) naplánované stereotaktické trajektórie pre DBS zacielené na STN (pravostranná trajektória je znázornená žltou farbou a ľavostranná modrou farbou); (c) pooperačné CT zobrazujúce finálnu polohu implantovaných elektród vo vzťahu k predoperačne vypočítaným trajektóriám

regions like thalamus and cingulate cortex, which has been associated with reduced DBS effectiveness in alleviating motor symptoms in PD (2). In parallel, technological advances in MRI and neuroimaging made it possible to analyse the brain's structural connectivity, enabling a more individualized and symptom-specific approach to treatment, including DBS targeting. Structural connectivity is part of a broader concept known as the brain connectome, which encompasses both structural and functional connections within the nervous system. The term „connectome" was introduced by Olaf Sporns in 2005, inspired by the Human Genome Project, with the goal of comprehensively map the brain's neural architecture. Early connectome mapping efforts relied on MRI-based techniques such as diffusion MRI (dMRI), which laid the foundation for what would later evolve into connectomic surgery – a term coined by Henderson in 2012 (3). This approach uses diffusion tensor imaging (DTI) and tractography to visualize and target specific neural pathways involved in movement disorders. Following this line of thinking, Lozano and Lipsman proposed that many neurological conditions should be reframed as circuit-based or network disorders, introducing the term „circuitopathies" to reflect this systems-level perspective (4). The structural connectome encompasses anatomical links between brain regions, primarily mediated by white matter tracts. Disruptions in these connections are thought to contribute significantly to the pathophysiology of various neurological and psychiatric conditions. Several studies suggest that DBS can modulate these structural connections in patients with PD and related disorders. Using dMRI, clinicians can assess water diffusion patterns in white matter, enabling the reconstruction of major fiber pathways in the brain. These pathways are visualized through tractography, a technique that maps the direction and trajectory of individual fiber tracts. In more complex clinical scenarios, where higher spatial resolution is required, diffusion spectrum imaging (DSI)

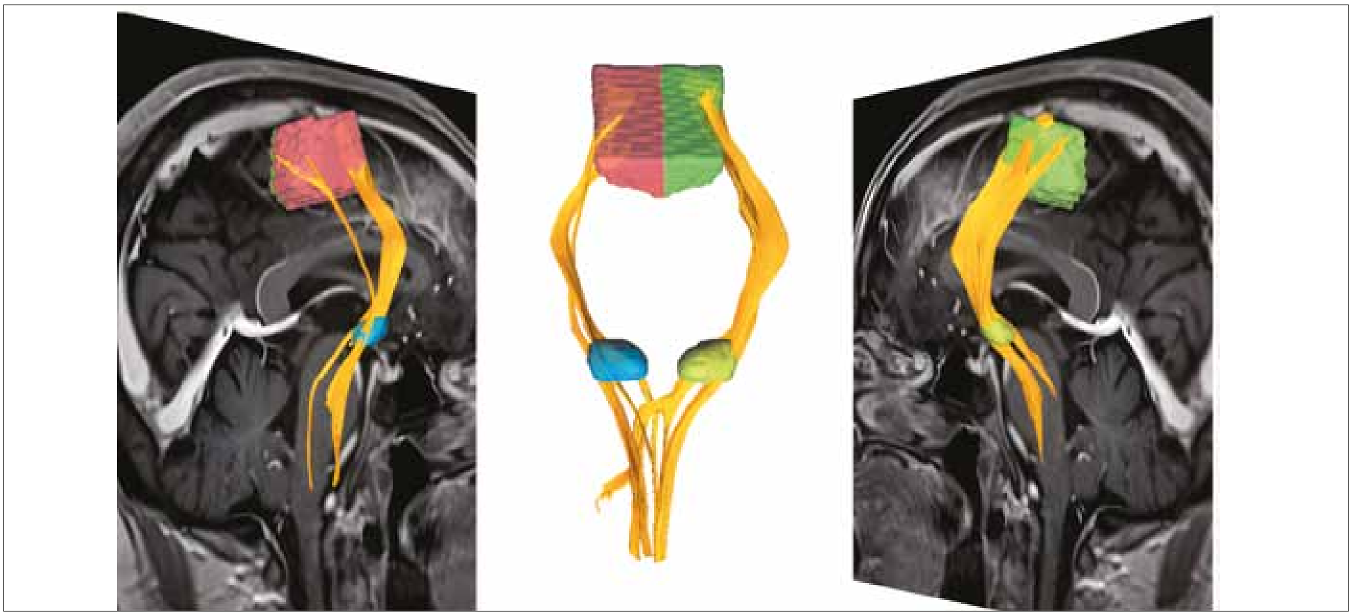


2 **Schematic representation of the processing pipeline for brain structural connectivity analysis:** (a) morphological MRI and diffusion-weighted imaging (DWI) or diffusion tensor imaging (DTI) data serve as the initial input; (b) following preprocessing — using tools such as QSIPrep, qsirecon, or similar software that performs motion correction, distortion are used; (c) the resulting data are used to generate a structural connectivity matrix, where each element represents the strength or presence of a connection between brain regions; (d) this matrix enables the reconstruction of a structural connectivity map, which can be visualized using tools such as DSI Studio, MRtrix, or other tractography platforms

Schématické znázornenie postupu spracovania dát pri analýze štrukturálnej konektivity mozgu: (a) morfologické MRI a difúzne vážené zobrazenie (DWI) alebo difúzne tenzorové zobrazenie (DTI) slúžia ako vstupné dáta; (b) po predspracovaní – pomocou nástrojov ako QSIPrep, qsirecon alebo iného softvéru, ktorý vykonáva korekciu pohybu a skreslenia – sa dáta upravia; (c) výsledné dáta sa použijú na vytvorenie matice štrukturálnej konektivity, kde každý prvok reprezentuje silu alebo prítomnosť spojenia medzi oblasťami mozgu; (d) táto matica umožňuje rekonštrukciu mapy štrukturálnej konektivity, ktorú možno vizualizovať pomocou nástrojov ako DSI Studio, MRtrix alebo iných traktografických platforiem

can be employed to more accurately resolve crossing fibers and delineate tract orientation (Fig. 2).

This imaging-based insight has important clinical implications, as it complements traditional anatomical targeting in DBS by enabling the consideration of underlying fiber architecture within the stimulation field. While central anatomical structures such as the subthalamic nucleus (STN) remain essential DBS targets and often lead to significant clinical improvement, incorporating tractography-based visualization provides an additional advantage. Specifically, understanding the spatial relationship between target structures and adjacent white matter tracts allows for more precise steering of the volume of tissue activated (VTA) toward symptom-relevant pathways. Rather than focusing solely on nuclei, stimulation that engages specific fiber tracts has been



3 **Structural Connectivity Visualization with STN and SMA.** Visualization of structural brain connectivity using DSI Studio. The DBS target structure is represented by the subthalamic nucleus (STN) – blue for the right STN and yellow for the left STN. Cortical structures are represented by the supplementary motor area (SMA) – red for the right SMA and green for the left SMA. The tractography was generated after preprocessing using the qsirecon pipeline.

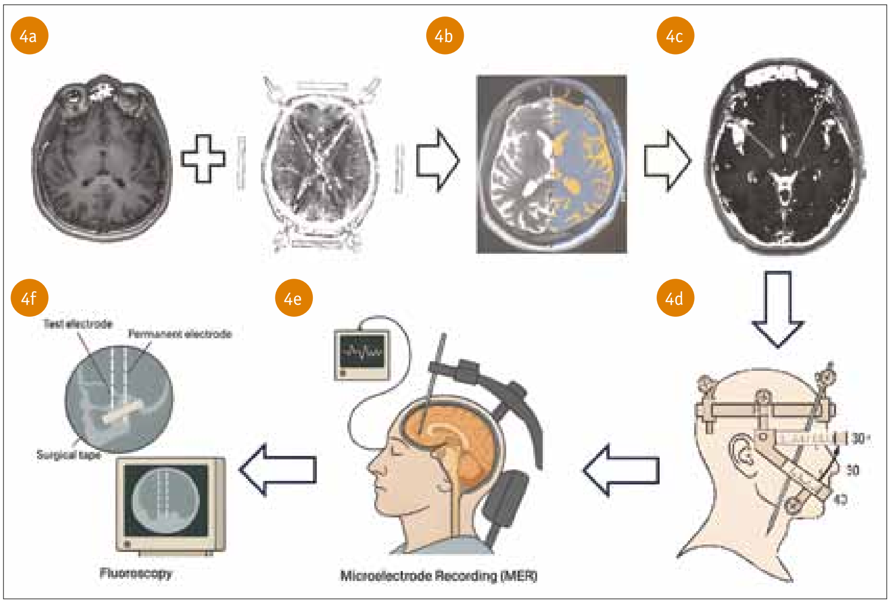
Vizualizácia štrukturálnej konektivity STN a SMA. Vizualizácia štrukturálnej konektivity mozgu pomocou nástroja DSI Studio. Cieľovou štruktúrou DBS je subtalamické jadro (STN) – modrá farba označuje pravé STN a žltá ľavé STN. Kortikálne štruktúry sú zastúpené doplnkovou motorickou oblasťou (SMA) – červená pre pravú SMA a zelená pre ľavú SMA. Traktografia bola vygenerovaná po predspracovaní dát pomocou pipeline qsirecon.

increasingly associated with favorable therapeutic outcomes. For example, in patients with pharmacoresistant tremor, involvement of the dentatorubrothalamic tract has been linked to over 90% symptom improvement within three months postoperatively (5). Similarly, in cases of bradykinesia and freezing of gait, optimal outcomes are associated with enhanced connectivity between the STN and cortical regions such as the supplementary motor area (SMA) and prefrontal cortex (PFC) (6) (Fig. 3).

In the context of tremor, the most significant improvements are observed when stimulation encompasses tracts structurally connected to the primary motor cortex (PMC) (5). In addition to these functional insights, MRI is indispensable for addressing individual anatomical variability, such as differences in the size, shape, or position of structures like the STN. It is also essential for visualizing electrode trajectories and confirming lead placement – topics that will be explored in more detail in subsequent chapters. In summary, structural and functional imaging enables a more rational, personalized approach to DBS planning. It allows clinicians to tailor electrode targeting to a patient's unique symptom profile and offers better predictive value for clinical outcomes. MRI not only ensures anatomical precision but also facilitates the integration of advanced imaging data into surgical planning, thereby enhancing both the safety and effectiveness of DBS interventions.

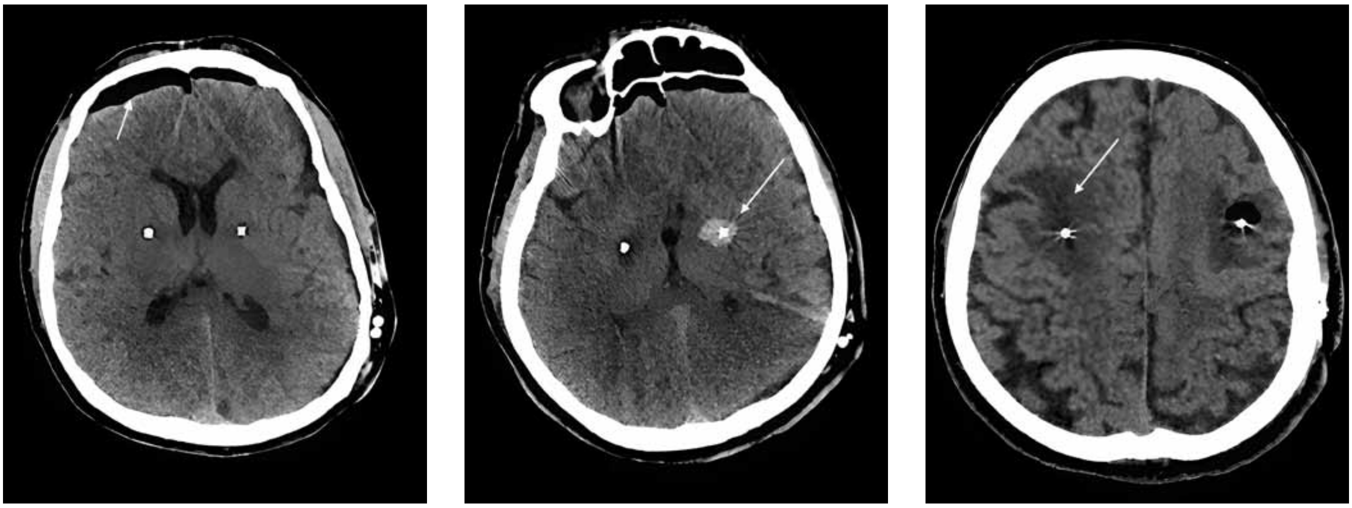
From planning to placement: the role of intraoperative and perioperative imaging in DBS

In the context of intraoperative and perioperative imaging techniques used during DBS, the primary role of imaging lies in ensuring accurate targeting of the structures to be stimulated. Two main conceptual approaches are commonly distinguished: the anatomical approach and the functional approach. These approaches describe the methods used to determine the optimal location for electrode implantation either during or after the surgical procedure. The anatomical approach is based on image-guided verification and planning, most notably through the use of intraoperative MRI (iMRI). This method allows for high-resolution visualization of the electrode trajectory and position within the target structure and is often preferred for patients who cannot tolerate awake surgery – such as individuals with severe anxiety, dystonia, dyskinesias, or spinal conditions that are aggravated by surgical positioning (7). MRI-guided and MRI-verified DBS procedures are rarely performed due to the limited availability of MRI systems directly in operating rooms. In contrast, the functional approach relies on microelectrode recording (MER), which involves the intraoperative insertion of thin recording electrodes to measure the characteristic electrical activity of neurons in the target region. For STN, the most common DBS target in PD, the sensorimotor region located dorsolaterally within the STN is typically associated with the most significant improvement in motor symptoms. By acquiring functional activity maps through MER, surgeons can identify precise anatomical correlates that are later applied to iMRI-guided implantation. A crucial step in the both approaches is verifying the final position of the permanent electrode after removing the test electrode. This verification is typically performed using standard 2D



4 **Schematic representation of imaging and navigation steps during stereotactic DBS electrode implantation:** (a) preoperative magnetic resonance imaging (MRI) and computed tomography (CT) after the application of a stereotactic frame with fiducial markers. These images are then coregistered using specialized software platforms (e.g., Brainlab, StealthStation) to allow accurate anatomical localization of target structures; (b) the fusion of MRI and CT results in a multiplanar image used for defining the implantation target (e.g., STN, GPi) and planning the trajectory; (c) the software calculates the optimal trajectory based on the coordinates of the target and the parameters of the stereotactic frame. Entry paths into the brain are visualized; (d) illustration of the stereotactic frame fixed to the patient's head, which serves as a mechanical reference for navigation throughout the surgical procedure; (e) intraoperative microelectrode recording (MER) is performed to physiologically verify the target by identifying characteristic neuronal firing patterns at various depths of brain tissue; (f) after target confirmation, the final DBS electrode is implanted. Its position is verified intraoperatively using fluoroscopy (X-ray) to ensure precise placement

Schématické znázornenie zobrazovacích a navigačných krokov počas stereotaktickej implantácie DBS: (a) predoperačné MRI a CT snímky po nasadení stereotaktického rámu s referenčnými značkami (fiduciálmi). Tieto snímky sú následne koregistrované pomocou špecializovaných softvérových platforiem (napr. Brainlab, StealthStation) s cieľom presne anatomicky lokalizovať cieľové štruktúry; (b) fúzia MRI a CT vedie k vytvoreniu multiplanárneho zobrazenia, ktoré sa používa na určenie cieľa implantácie (napr. STN, GPi) a plánovanie trajektórie; (c) softvér vypočíta optimálnu trajektóriu na základe súradníc cieľa a parametrov stereotaktického rámu. Vizualizujú sa vstupné dráhy do mozgu; (d) ilustrácia stereotaktického rámu upevneného na hlave pacienta, ktorý slúži ako mechanický referenčný bod pre navigáciu počas celého chirurgického zákroku; (e) počas operácie sa vykonáva mikroelektródový záznam (MER), ktorého cieľom je fyziologické overenie cieľovej oblasti identifikovaním charakteristických vzorcov neuronálnej aktivity v rôznych hĺbkach mozgového tkaniva; (f) po potvrdení cieľa sa implantuje finálna DBS elektróda. Jej poloha sa overuje počas operácie pomocou skiagrafie (röntgenu), aby sa zabezpečilo presné umiestnenie



5 **Visualization of intraoperative complications of DBS on postoperative CT imagining:** (a) pneumocephalus in the frontal region, predominantly on the left side; (b) intracerebral hemorrhage at the site of the left electrode insertion; (c) hypodense ischemic zone at the site of the right electrode insertion in the frontotemporal region

Vizualizácia perioperačných komplikácií DBS na pooperačnom CT zobrazení: (a) pneumocefalus vo frontálnej oblasti, prevažne na ľavej strane; (b) intracerebrálne krvácanie v mieste zavedenia ľavej elektródy; (c) hypodenzná ischemická zóna v mieste zavedenia pravej elektródy frontotemporálne

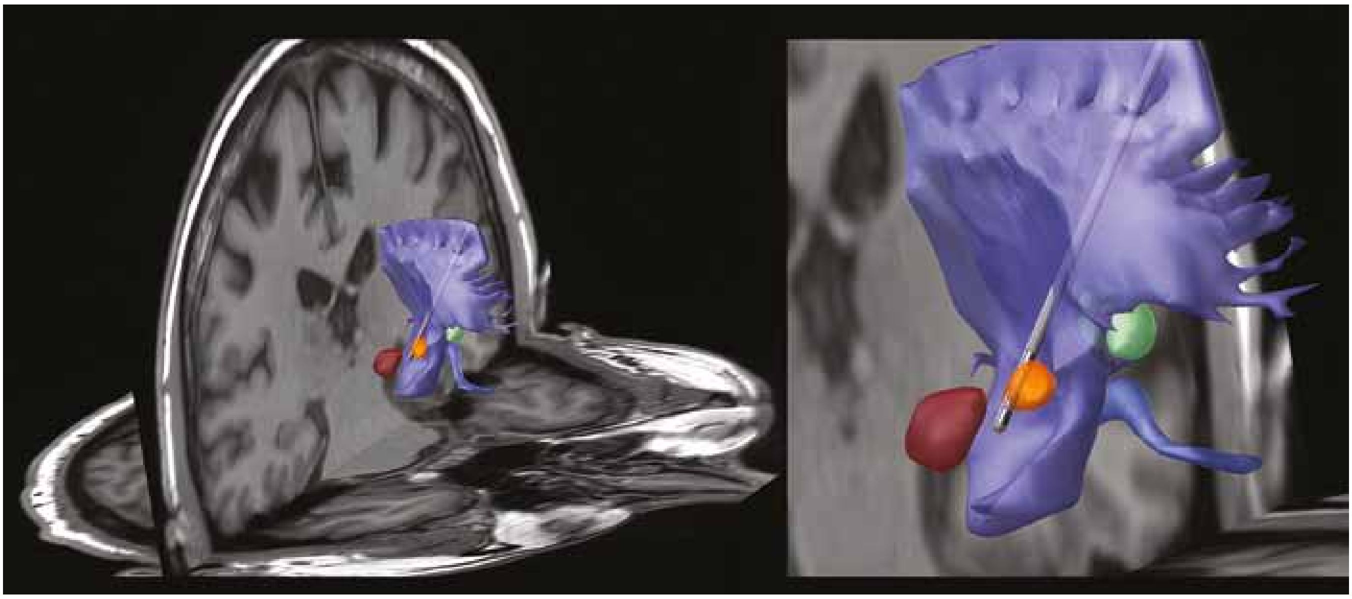
fluoroscopy (C-arm X-ray), but intraoperative computed tomography (CT) or O-arm systems can also be employed. These modalities provide three-dimensional imaging that allows for more precise confirmation of electrode position, especially useful when frame-based stereotaxy is combined with image fusion for target validation (Fig. 4).

Originally, anatomical approaches were viewed as less accurate than MER-guided methods. However, growing evidence suggests that electrode placement using iMRI or intraoperative CT/O-arm verification can produce clinical outcomes comparable to those achieved with MER guidance. Unlike MER, iMRI employs prospective stereotaxy, where the trajectory and target are refined in real-time based on direct imaging feedback before the final implantation. A comparative study from the University of Pittsburgh analyzed radial error, stimulation thresholds, and motor/sensory side effects in 45 PD patients undergoing DBS using either iMRI or MER guidance. While MER guidance was associated with a greater radial error from the intended target (1.3–1.8 mm vs. 0.7–0.8 mm for iMR), clinical outcomes assessed by motor scale of Unified Parkinson's Disease Rating Scale and medication reduction showed no significant difference between the groups (8). In summary, iMRI-guided electrode placement offers superior anatomical accuracy and can achieve stimulation results comparable to those obtained through functional MER-guided methods, as evidenced by similar stimulation thresholds and symptom control (9). This suggests that the choice between iMRI and MER may be guided by the preferences of the patient and clinical team, especially in suitable PD candidates. However, it is important to note that iMRI-guided DBS requires advanced equipment, technical expertise, and significant financial resources. Due to these demands, it may not be routinely available in all centers.

USE OF IMAGING TECHNIQUES IN THE POSTOPERATIVE MANAGEMENT OF PATIENTS WITH DBS

From the perspective of postoperative management in patients undergoing DBS, CT plays a key role, primarily due to its wide availability, rapid acquisition, and reduced susceptibility to artifacts caused by the presence of metallic electrodes. CT is routinely performed shortly after surgery, with its main objectives being to verify correct electrode placement within the target structures and to exclude potential complications such as intracerebral hemorrhage, ischemic lesions near the electrode trajectory, or pneumocephalus (Fig. 5).

In addition, CT has significant value when used in conjunction with neuroimaging software, which allows for fusion with preoperative MRI scans and the subsequent precise visualization of the electrode positions and individual contacts in relation to the intended anatomical targets. This localization is crucial not only for standard stimulation programming but also in cases where electrode placement is suboptimal, which may result in inadequate clinical response or the presence of stimulation-induced side effects. Image-guided programming thus enables not only the optimization of therapeutic outcomes but also a reduction in the number of postoperative visits to movement disorder centers, thereby improving the overall efficiency of patient management. According to several studies, the use of postoperative neuroimaging techniques can reduce the time required for stimulation programming by 56%, while maintaining comparable motor outcomes as measured by the motor part of Movement Disorder Society – Unified Parkinson's Disease Rating Scale (MDS-UPDRS III) scale compared to conventional clinical programming (10). Furthermore, in patients with suboptimal initial clinical settings who failed to respond adequately to standard programming, image-guided approaches



6 **Visualization of the most commonly stimulated structures in deep brain stimulation, together with adjacent anatomical regions** (orange – STN, purple – internal capsule, red – red nucleus, green – globus pallidus internus, dark blue – optic tract) (created using Lead-DBS software v3.1)

Vizualizácia najčastejšie stimulovaných štruktúr pri hlbokej mozgovej stimulácii spolu s priľahlými anatomickými oblasťami (oranžová – STN, fialová – vnútorné puzdro, červená – červené jadro, zelená – globus pallidus internus, tmavomodrá – zrakový trakt) (vytvorené pomocou softvéru Lead-DBS verzia 3.1)

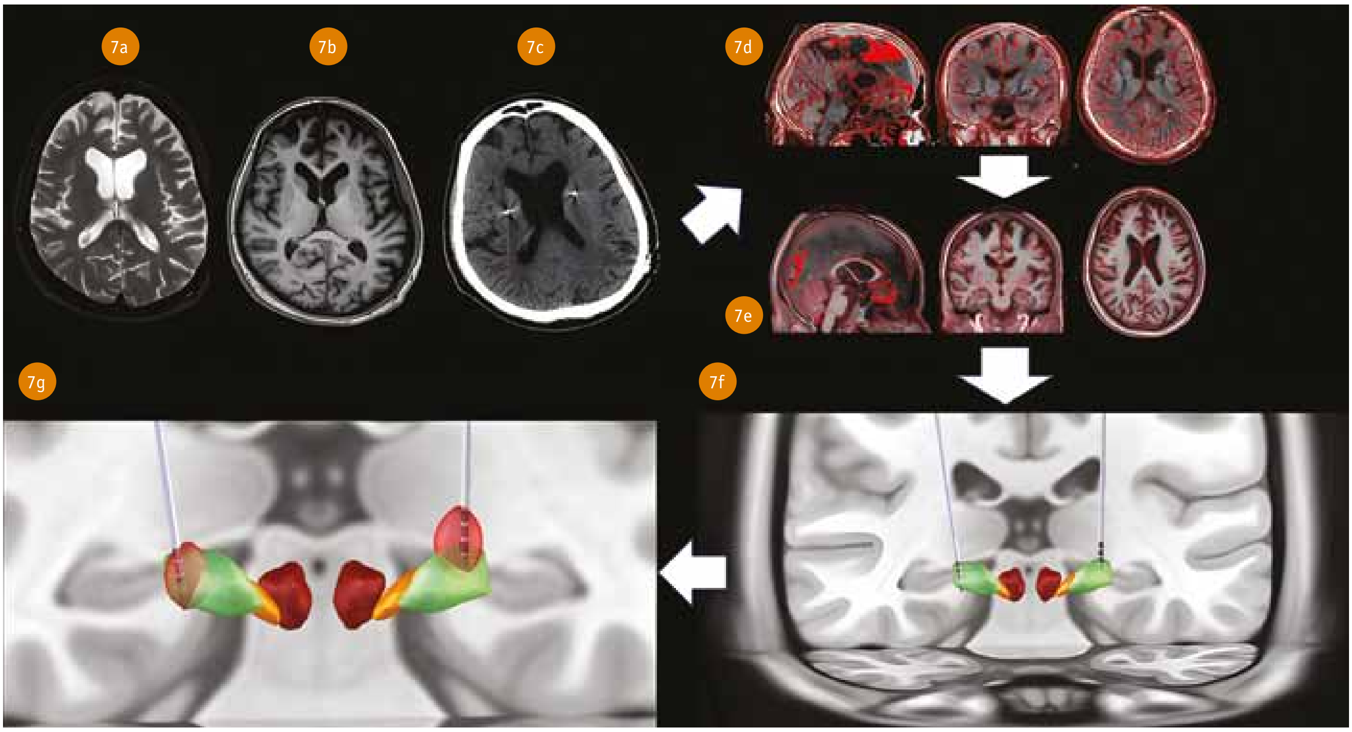
have been shown not only to streamline the programming process but also to lead to an actual improvement in motor symptoms – with an average 21.9% improvement in MDS-UPDRS III scores – and a notable improvement in quality of life, subjectively reported by up to 64.5% of patients based on patient global impression of improvement scale (11). This type of visualization is also of particular importance when using newer DBS systems equipped with directional electrodes, as it enables more precise steering of stimulation to avoid activating anatomically sensitive regions such as the internal capsule, thereby reducing the occurrence of stimulation-induced side effects (Fig. 6).

The implementation of neuroimaging-based techniques in DBS has become increasingly feasible due to the availability of freely accessible open-source software tools. Among them, Lead-DBS is one of the most widely adopted platforms. It was developed in the MATLAB programming environment by the research team of Andreas Horn and Andrea Kühn at Charité – Universitätsmedizin Berlin in 2014. Lead-DBS provides a comprehensive framework for the visualization, analysis, and modeling of electrode placement in relation to target brain structures. The software enables the fusion of preoperative MRI with postoperative CT or MRI data, followed by coregistration, normalization to a standardized anatomical space, and reconstruction of the electrode trajectory, including precise localization of individual contacts. Additionally, it allows for the estimation of the VTA, depending on stimulation parameters and electrode configuration (Fig. 7) (12).

Electrodes and stimulation fields can be visualized in both the native patient space and the standardized Montreal Neurological Institute (MNI) space. Although MNI is not a stereotactic space in the classical sense, it represents a statistically derived anatomical average of healthy individuals. This allows for intersubject comparisons and group-level analysis, which is essential for stimulation mapping, population-based modeling, and predicting clinical outcomes. When dMRI or functional MRI data are available, Lead-DBS Connectome can be used to perform structural and functional connectivity analysis. This enables targeting stimulation based on functionally relevant brain networks. Connectivity modeling can rely either on normative connectomes derived from population datasets (e.g., Human Connectome Project) or on patient-specific connectomes constructed from the individual's diffusion-weighted imaging data (13). These approaches support a personalized DBS strategy informed by both anatomical precision and network-based targeting. It should be noted that Lead-DBS is designed primarily for academic and research purposes and is not approved by the FDA or EMA for clinical diagnostic or therapeutic use. In contrast, commercial platforms such as SureTune™ (Medtronic) and GUIDE™ XT (Boston Scientific) are FDA cleared (and CE marked in the case of GUIDE™ XT) and are intended for clinical application. These tools support visualization of electrode placement, VTA calculation, and basic stimulation planning. However, compared to Lead-DBS, they present several limitations: they typically do not support advanced tractography, do not allow for custom connectome modeling or MNI-space analysis, and are closed-source, meaning they cannot be freely modified or extended for research purposes.

CONCLUSION

Neuroimaging techniques have become integral to the comprehensive management of DBS, providing critical support at each stage of the therapeutic process. In the preoperative phase, advanced MRI and diffusion-based modalities enable precise anatomical targeting and allow for the assessment of structural connectivity, facilitating individualized, symptom-specific treatment planning. Intraoperatively, imaging modalities such as intraoperative MRI and computed tomography



7 **Use of the Lead-DBS toolbox in the process of postoperative electrode visualization and VTA calculation:** (a) preoperative T2 weighting MRI; (b) preoperative T1 weighting; (c) postoperative CT; (d) preoperative image coregistration; (e) normalization; (f) 3D electrode visualization (g) VTA calculation

Použitie nástroja Lead-DBS v procese pooperačnej vizualizácie elektród a výpočtu VTA: (a) predoperačné T2-vážené MR; (b) predoperačné T1-vážené MR; (c) pooperačné CT; (d) korigovanie predoperačných snímok; (e) normalizácia; (f) 3D vizualizácia elektród; (g) výpočet VTA

enhance the accuracy of electrode placement and reduce procedural variability. Postoperatively, the use of imaging for electrode verification, complication screening, and image-guided programming significantly improves the efficiency and efficacy of stimulation. The ongoing integration of structural and functional connectomics into DBS workflows represents a paradigm shift toward network-based neuromodulation, with the potential to optimize clinical outcomes and further personalize therapy. ●

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