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## The role of MRI tractography in stereotactic targeting for surgical treatment of Parkinson's disease

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**Objective:** To evaluate the clinical efficacy of surgical treatment of tremor-dominant Parkinson's disease (PD) with regard to stereotactic target determination based on MRI tractography data, and to compare the outcomes of stereotactic radiofrequency (RF) thalamotomy of the ventral intermediate nucleus (Vim) with tractography-assisted lesioning of the dentatorubrothalamic tract (DRTT).

**Materials and methods:** This retrospective study included 25 patients with PD who underwent surgery between 2018 and 2025. Inclusion criteria were tremor-dominant clinical presentation, a progressive disease course, and insufficient response to pharmacological therapy. Patients were divided into two groups: the Vim group (n=19), in which stereotactic RF thalamotomy was performed using indirect target calculation, and the DRTT group (n=6), in which the surgical target was determined using MRI tractography based on diffusion tensor imaging (DTI). Surgical planning was performed using Element software (Brainlab, Germany). Clinical efficacy was assessed preoperatively and 12 months postoperatively using the Unified Parkinson's Disease Rating Scale (UPDRS, part III), the Clinical Rating Scale for Tremor (CRST, parts A and C).

**Results:** In all patients, tremor of the contralateral limb was completely abolished immediately after surgery. At 12 months, the mean UPDRS III score decreased by 44%, from 83.2±8.7 to 46.7±4.18 points (p=0.04). A statistically significant improvement in UPDRS III scores was observed in the DRTT group (p=0.032), whereas the difference in the Vim group did not reach statistical significance. Tremor regression assessed by CRST-A and CRST-C was observed in both groups but was more pronounced in patients who underwent tractography-assisted lesioning. Postoperatively, a reduction in daily levodopa dosage was noted: by 23.4% in the Vim group and by 27.7% in the DRTT group. No intraoperative complications were recorded. Transient neurological adverse effects occurred more frequently in the Vim group and resolved completely during the early postoperative period.

**Conclusions:** The use of MRI tractography for stereotactic target selection in ablative surgery for PD enables individualized surgical planning and provides more precise targeting of pathophysiologically relevant neural pathways. Tractography-assisted lesioning of the DRTT is associated with more stable tremor control, a tendency toward greater improvement of accompanying motor symptoms, and a potentially lower risk of neurological adverse effects.

**Key words:** Parkinson's disease; deep brain stimulation; stereotactic radiofrequency lesioning; dentatorubrothalamic tract

### Introduction

Parkinson's disease (PD) is one of the most prevalent neurodegenerative disorders of the nervous system, characterized by a progressive course and the necessity for lifelong levodopa replacement therapy. Surgical treatment of PD was first introduced in the mid-twentieth century and has been continuously refined over the past 25 years. The primary method of surgical intervention in PD is deep brain stimulation (DBS) [1, 2]. Over the past decade, there has been a renaissance of ablative stereotactic procedures that were widely used for PD treatment in the 1950s. Alongside classical stereotactic

radiofrequency (RF) destruction of subcortical nuclei, non-invasive techniques have been introduced, including Gamma Knife radiosurgery and MRI-guided focused ultrasound ablation [3–7].

Several approaches exist to improve the effectiveness of surgical interventions in PD. First and foremost is the advancement of modern neuroimaging technologies, which enable high-resolution MRI visualization of subcortical brain structures and white matter tracts. The introduction of high-field magnetic resonance imaging (MRI) allows not only visualization of individual anatomical structures but also differentiation of their

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subsegments and precise identification of the surgical target zone. It has been established that the dorsal portion of the subthalamic nucleus (STN) receives the highest density of projections from cortical motor areas (the hyperdirect pathway) and is considered the optimal target for DBS [8]. In most hospitals across developed countries in Europe, North America, and Asia, 3T MRI is used for stereotactic planning, while several centers have extensive experience with ultra-high-field 7T MRI [9]. A recently published study by a Dutch research group demonstrated that the use of 7T MRI enables accurate electrode placement within the motor subregion of the STN, resulting in more than a 30% improvement in motor symptom control compared with preoperative planning based on 3T MRI [10]. Another strategy to improve neuromodulation outcomes is the development of directional stimulation electrodes and the implementation of adaptive DBS, a closed-loop system capable of adjusting stimulation parameters according to biomarkers reflecting the patient's clinical state [11–13].

Another direction for improving the efficacy and safety of stereotactic procedures involves the advancement of software systems that, using modern digital anatomical atlases accounting for individual brain morphology in three-dimensional space, allow precise visualization of the neurosurgical target. Contemporary planning platforms enable integration of multimodal neuroimaging data, more accurate definition of target coordinates, and optimization of a safe electrode trajectory. Such software also allows the creation of individualized anatomical models and determination of electrode position and orientation for each patient, which can subsequently be integrated with clinical programmers for faster and more efficient adjustment of neurostimulation parameters.

At the current stage of scientific development, PD is considered a disorder of neuronal circuits and networks responsible for motor control. Significant progress has been made in understanding the etiology and pathomorphological changes of the basal ganglia in PD patients. Dysfunction of functional connectivity between nuclei plays a central role in disease pathogenesis. Recent studies have established a clear relationship between major motor symptoms of PD and pathophysiological alterations in specific neural circuits of the brain. In particular, a meta-analysis by Rajamani *et al.* (2024) demonstrated a correlation between stimulation of specific white matter bundles and improvement in tremor, rigidity, bradykinesia, and postural instability [14].

The concept of circuit-based dysfunction is consistent with the historical evolution of surgical treatment for PD, particularly in relation to the management of tremor, one of the most disabling symptoms. Since the 1950s, the globus pallidus has been a primary target of stereotactic interventions in PD. Although morphological changes in PD are observed in the substantia nigra, which fails to produce sufficient dopamine, it is the globus pallidus that is most sensitive to dopaminergic deficiency, leading to disrupted physiological activity and the emergence of hyperkinetic disorders.

In 1954, Hassler *et al.* performed stereotactic ablation of neurons receiving pathological signals from the globus

pallidus. These neurons were localized in the posterior ventral oral (Vop) and ventral intermediate (Vim) nuclei of the thalamus. Since then, numerous studies have confirmed the high efficacy of Vim lesioning for tremor control of various etiologies. The Vim target remains the gold standard for stereotactic surgery despite several limitations. The most significant drawback is the inability to directly visualize the Vim on MRI. The Vim nucleus is a group of motor neurons located at the border of the ventrolateral thalamus, ventral oral, and ventral caudal nuclei. On conventional MRI, its boundaries cannot be clearly delineated, which necessitates an indirect targeting approach using the anterior and posterior commissures as anatomical landmarks and atlas-based coordinates. The search for alternative targets, nuclei, or white matter pathways whose stimulation or ablation could provide more effective and safer tremor control continues. One such alternative target is the posterior subthalamic area (PSA), which includes the zona incerta (Zi). These targets have demonstrated high efficacy in tremor control but also present certain limitations. Histological and MRI-DWI-based studies of basal ganglia cytoarchitecture and white matter tracts have established a relationship between tremor and the dentatorubrothalamic tract (DRTT), also known as the cerebellothalamic fasciculus. This tract runs in close proximity to all the aforementioned targets, forming the basis of the “three targets—one pathway” concept [15].

In recent years, MRI tractography based on diffusion tensor imaging (DTI) has become increasingly important in stereotactic surgical planning. Recent studies have shown that the effectiveness of surgical intervention is determined by modulation of neuronal pathways involved in the pathophysiology of movement disorders. The DRTT, originating from the dentate nucleus of the cerebellum, passing through the contralateral red nucleus, and terminating in the ventrolateral thalamic nucleus on the opposite side, plays a key role in tremor regulation of various origins. Previously, the DRTT was difficult to identify due to its long multisynaptic course across hemispheres. However, the development of DTI MRI technology and advanced software has enabled its visualization and targeted modulation using stereotactic techniques. Chronic stimulation or ablation of the DRTT has been shown to provide superior tremor control compared with interventions targeting classical subcortical structures involved in PD pathophysiology, such as the Vim, PSA, or STN [14].

Currently, a paradigm shift in tremor treatment is underway, as the DRTT is increasingly recognized as a primary pathogenetic surgical target in stereotactic interventions involving the Vim. Unlike thalamic nuclei, the DRTT white matter tract can be directly visualized using MRI tractography based on diffusion-weighted imaging (DWI). The most appropriate strategy for target definition in stereotactic surgery is a combined approach, which involves refining indirectly determined targets using tractography data. This approach reduces the risk of adverse effects while ensuring stable therapeutic efficacy.

**Objective:** To evaluate the clinical efficacy of surgical treatment of tremor-dominant PD, taking into account the possibility of stereotactic target definition based

on MRI tractography, and to compare the outcomes of classical stereotactic radiofrequency thalamotomy of the ventral intermediate thalamic nucleus with tractography-assisted ablation of the dentatorubrothalamic tract.

## Materials and methods

### Study participants

A total of 25 patients with PD were included in this retrospective study. All patients underwent surgical treatment in the Department of Functional Neurosurgery and Neuromodulation of the Romodanov Neurosurgery Institute, National Academy of Medical Sciences of Ukraine, during the period 2018–2025.

The study was conducted in accordance with the Declaration of Helsinki (1964–2013), the International Council for Harmonisation Good Clinical Practice (ICH GCP, 1996), EU Directive No. 609 (24.11.1986), and the regulatory orders of the Ministry of Health of Ukraine No. 690 (23.09.2009), No. 944 (14.12.2009), and No. 616 (03.08.2012), as well as local institutional protocols. The Ethics Committee of the Romodanov Neurosurgery Institute confirmed that no ethical or legal violations were identified during the research. All patients provided informed consent for participation, and anonymity was ensured.

### Inclusion criteria

Patients were included if they met the following criteria: predominance of tremor within the clinical symptom complex of PD, insufficient response to antiparkinsonian pharmacotherapy, progressive disease course, and use of the Element software (Brainlab, Germany) for stereotactic target planning.

### Exclusion criteria

Patients were excluded in cases of akinetic-rigid predominant PD, severe balance or coordination disturbances, significant comorbid somatic pathology that could increase surgical risk, or contraindications to MRI examination.

### Study design

Patients were divided into two groups. In the first group (Vim group), 19 patients (76%) underwent classical radiofrequency (RF) lesioning of the ventral intermediate nucleus (Vim), using standard stereotactic targeting based on the intercommissural line. In the second group (DRTT group), 6 patients (24%) underwent dentatorubrothalamic tract (DRTT) ablation assisted by tractography.

The differences in stereotactic target coordinates between the two groups were analyzed. Neurological and functional status was assessed preoperatively and at 12 months postoperatively.

### Group characteristics

The age of patients at the time of surgery ranged from 44 to 81 years (mean: 63.7 years). Males predominated (17 patients, 68%). Disease duration ranged from 4 to 22 years (mean: 12 years). Both age and disease duration were slightly higher in the Vim group; however, the differences were not statistically significant (**Table 1**).

All patients received dopamine replacement therapy at doses ranging from 450 to 1500 mg/day (mean: 812.56 mg/day). The duration of levodopa therapy prior to surgery ranged from 4 to 15 years (mean: 9 years). No significant differences were found between

the groups regarding levodopa dose or duration of therapy. Adverse effects of dopaminergic therapy in the form of motor fluctuations were observed in 4 patients (16%). Levodopa-induced dyskinesias were not detected.

At the time of surgical treatment, patients were classified as stage 2.5–3.0 on the Hoehn and Yahr scale. Although all patients exhibited bilateral manifestations of Parkinson's disease with moderate postural instability, they retained full functional independence in daily activities. In the majority of cases (88%), patients presented with tremor-dominant and tremor-rigid forms of PD (**Table 2**). Stereotactic thalamotomy and DRTT ablation were not performed in patients with akinetic-rigid predominant PD, as this type of surgical intervention is associated with an increased risk of balance and coordination disturbances, as well as potential worsening of bradykinesia.

Stereotactic planning was performed using Element software (Brainlab, Germany). The coordinates of the Vim nucleus were determined using an indirect method based on individual anatomical characteristics of the intercommissural line (AC-PC line), which connects the anterior and posterior commissures. DRTT ablation coordinates were calculated using a direct approach based on diffusion tensor imaging (DTI) obtained during MRI tractography. Visualization of the DRTT was performed by identifying its key anatomical components, namely the ipsilateral primary motor cortex (M1) and the contralateral dentate nucleus of the cerebellum (**Fig. 1 and 2**).

All surgical procedures were performed using a CRW Radionics stereotactic frame (Radionics Inc., USA) and a radiofrequency electrode with a diameter of 2.1 mm and an active tip length of 2.0 mm. Radiofrequency ablation was carried out under awake anesthesia with intraoperative test macrostimulation at high (75 Hz) and low (2 Hz) frequencies, which enabled identification of the correct and safe positioning of the RF electrode. Prior to definitive RF ablation, test lesions were performed at 45 °C and 55 °C for 30 s each. In the absence of additional neurological deficits, such as paresthesia, spastic contractions of the contralateral limbs, or speech disturbances, definitive ablation of the planned target was performed at 75 °C for 60–65 s.

Neurological and functional status was assessed preoperatively and 12 months after surgery using the Unified Parkinson's Disease Rating Scale (UPDRS). Tremor regression was evaluated using Parts A and C of the Clinical Rating Scale for Tremor (CRST) [16], as well as the total tremor score in the medication-off state (OFF state) according to Part III of the UPDRS, including assessment of head tremor, upper and lower limb tremor, action tremor, and postural tremor severity. According to this subscale, scores may range from 0 to 28 points [17].

### Statistical analysis

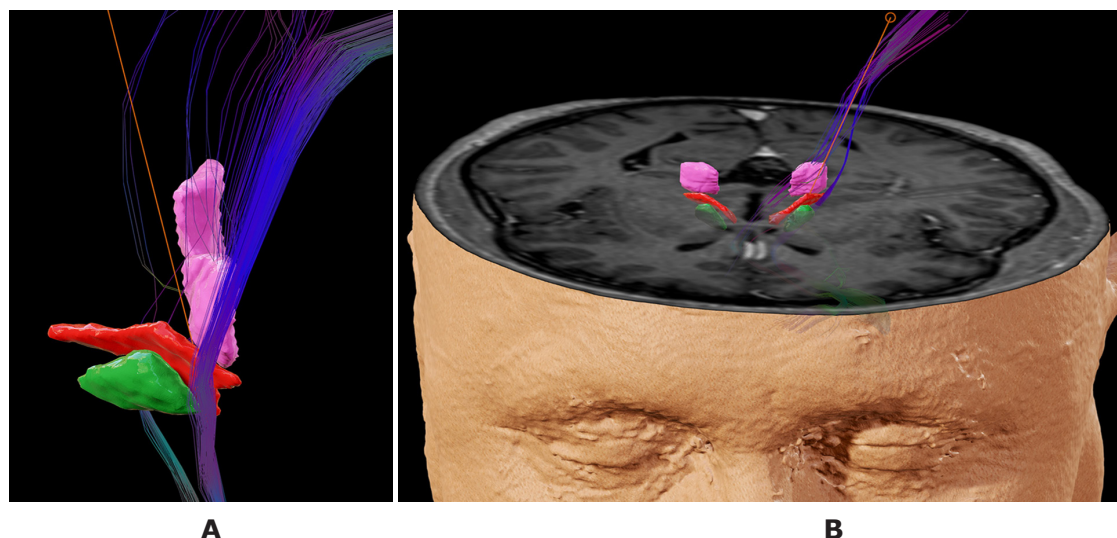
Statistical data analysis and processing were performed using IBM SPSS Statistics version 29 (license No. 512186485) and MS Excel. The Shapiro-Wilk W test was used to assess the normality of data distribution. In cases of normal distribution, Student's t-test was applied. When data distribution deviated from normality, nonparametric statistical tests were used.

**Table 1.** Clinical characteristics of patients (M ± m)

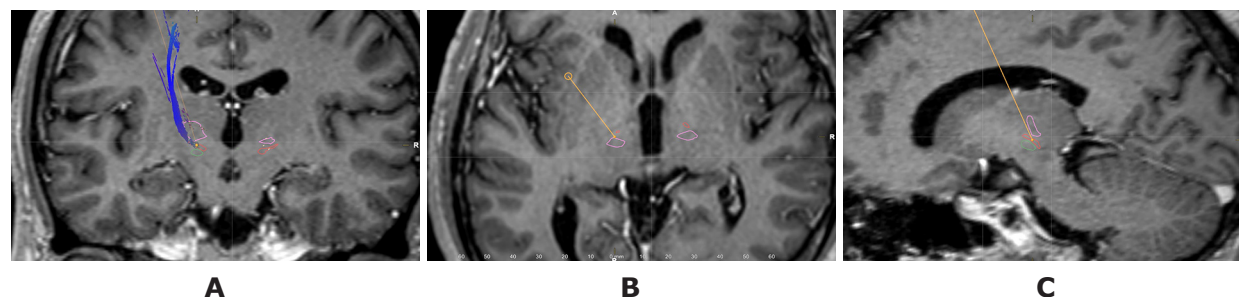
Parameter	Vim, n=19	DRTT, n=6	Total, n=25	p
Mean age, years	65±2	60±4	63,7±2,0	0,925
Sex:				
Male	12 (63%)	5 (83%)	17 (68%)	
Female	7 (37%)	1 (17%)	8 (32%)	
Mean PD duration, years	12,4±1	9,8±1,3	12,0±1,0	0,978
Mean levodopa dose, mg/day	874,8±94,3	725,8±64,2	812,56±76,50	0,962
Mean duration of levodopa therapy, years	9,4±0,7	7±0,8	9,0±1,0	0,95
Motor fluctuations	3 (15%)	1 (16%)	4 (16%)	

**Table 2.** Clinical forms of Parkinson’s disease

Form of PD	Vim, n=19	DRTT, n=6	Total, n=25
Tremor-dominant	10 (52%)	4 (67%)	14 (56%)
Tremor-rigid	6 (32%)	2 (33%)	8 (32%)
Tremor-akinetic-rigid	3 (16%)	0 (0%)	3 (12%)



**Fig. 1.** Planning of the target for RF DRTT ablation. Three-dimensional reconstruction model of the subcortical nuclei and tract (purple – Vim; green – STN; red – posterior subthalamic area; blue-violet – DRTT; orange – trajectory of DRTT tractotomy): A – lateral projection; B – anteroposterior projection



**Fig. 2.** Planning of the target for RF DRTT ablation. Brain MRI with intravenous contrast enhancement (orange line – electrode insertion trajectory; purple – Vim; red – posterior subthalamic area; green – STN): A – coronal projection; B – axial projection; C – sagittal projection

### Results

Analysis of differences between stereotactic target coordinates in the two groups using descriptive statistics (mean value, standard deviation, and standard error) for coordinates in three projections (anteroposterior direction, laterality, and height relative to the AC-PC line) revealed no statistically significant differences (**Table 3**).

The observed differences did not exceed the statistical error and averaged 0.5–1.0 mm. Considering that the average width of the Vim nucleus is approximately 4 mm, even such seemingly minor deviations may have substantial clinical significance, corresponding to up to 25% of the target size [18]. Given the acceptable possibility of mechanical electrode deviation from the planned trajectory by up to 1 mm, the cumulative error may reach or even exceed half of the Vim nucleus diameter. This is critically important because even minimal displacement of the ablation target may result in insufficient modulation of the intended area or unintended involvement of adjacent structures, thereby reducing therapeutic efficacy and increasing the risk of adverse effects.

Follow-up evaluation at 12 months after surgery was performed in 9 of 19 patients (47.4%) in the Vim group and in all patients in the DRTT group. Improvement in neurological status, particularly tremor regression, was observed in both groups. Complete regression of contralateral limb tremor was achieved immediately after surgery in all patients. A marked reduction in head tremor was also observed.

One year after surgery, the mean UPDRS III score improved by 44%, decreasing from  $(83.2 \pm 8.7)$  to  $(46.70 \pm 4.18)$  points ( $p = 0.04$ ). However, statistically significant improvement was observed only in the DRTT group ( $p = 0.032$ ). Regression of rigidity and tremor was more pronounced in the DRTT group, although the difference between groups did not reach statistical significance ( $p > 0.05$ ). According to the CRST-A and CRST-C scales, significant tremor reduction was observed in both groups. In all cases, improvement in motor function, self-care ability, and quality of life was documented.

Following surgery, the levodopa dose was reduced in both groups: by 23.4% in the Vim group and by 27.7% in the DRTT group (**Table 4**). Reduction of levodopa replacement therapy may help prevent the development of treatment-related adverse effects.

No intraoperative complications (hemorrhage or ischemia within the lesioning zone), infectious complications, or other adverse events were observed. Neurological complications developed in 3 (12.0%) patients (2 in the Vim group and 1 in the DRTT group). In all cases, the complications were transient and resolved within a period ranging from 1 week to 2 months after surgery. Following Vim lesioning, one patient developed transient dysarthria and moderate contralateral hemiparesis, whereas another patient experienced dysarthria. These complications were caused by injury to the internal capsule. Following DRTT lesioning, one patient developed transient dyspraxia and paresthesia of the contralateral extremities due to extension of the

**Table 3.** Mean coordinates of the Vim target

Coordinate axis	Mean value, mm		Standard deviation		Standard error	
	Vim	DRTT	Vim	DRTT	Vim	DRTT
Vertical axis	-0,22	-0,43	0,49	0,46	0,11	0,19
Lateral axis	12,71	13,12	0,78	1,21	0,49	0,17
Anteroposterior axis	-5,37	-5,85	0,77	0,56	0,17	0,22

**Table 4.** Outcomes of radiofrequency stereotactic thalamotomy at 12 months after surgery

Parameter	Vim group		DRTT group		p
	before surgery	after surgery	before surgery	after surgery	
Tremor (range 0–28)	19,1±0,9	7,56±1,40	21,17±1,60	6,67±4,18	0,047
CRST-A (range 0–88)	36,00 ± 0,88	9,4±1,2	42,50±5,08	7,33±1,97	0,038
CRST-C (range 0–32)	16,6±0,7	11,1±1,6	17,40±3,45	12,67±3,54	>0,1
Levodopa dose, mg/day	874,8±94,3	670,4±54,3	725,8±64,2	524,4±38,3	>0,1

**Table 5.** Neurological complications

Complication	Vim, n=2	DRTT, n=1
Contralateral hemiparesis	1 (5%)	0
Dysarthria	2 (10%)	0
Dyspraxia	0	1 (16%)
Paresthesia	0	1 (16%)

lesioning zone into the ventral caudal somatosensory nucleus of the thalamus (**Table 5**).

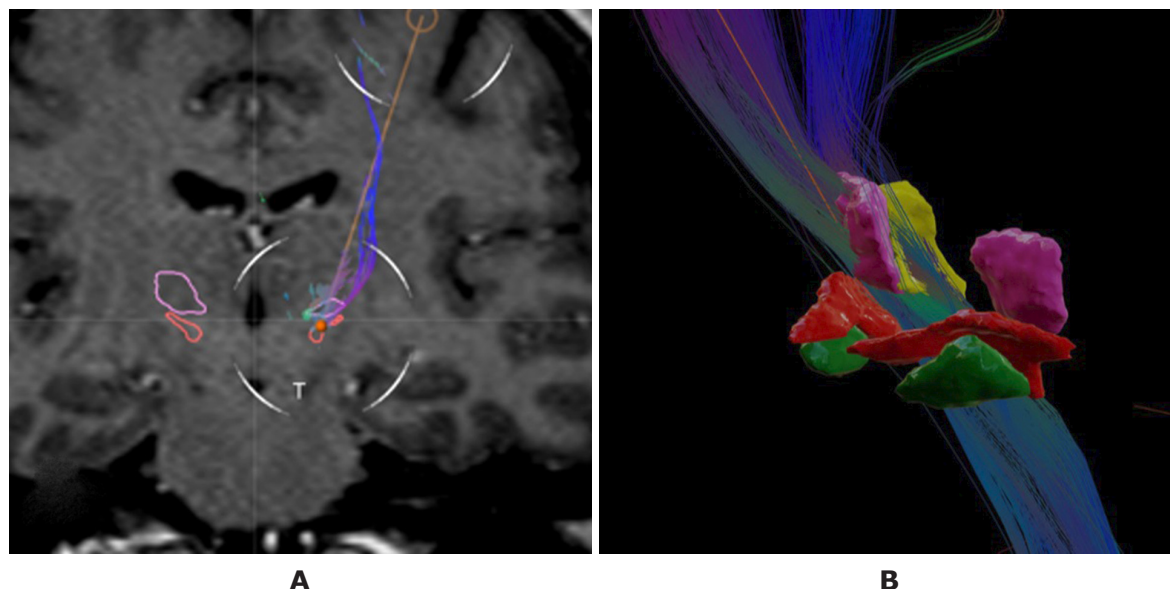
**Clinical case**

Patient D., 53 years old, was examined at the Romodanov Neurosurgery Institute of the National Academy of Medical Sciences of Ukraine. The following diagnosis was established: "Parkinson's disease, tremor-rigid form, stage 2.5 according to the Hoehn and Yahr scale, progressive course." The disease duration was 6 years. At the time of hospitalization, the patient was receiving levodopa/carbidopa at a dose of 625 mg/day, rasagiline (a monoamine oxidase inhibitor) at a dose of 1 mg/day, and pramipexole (a dopamine receptor agonist) at a dose of 1.25 mg/day. The clinical presentation was

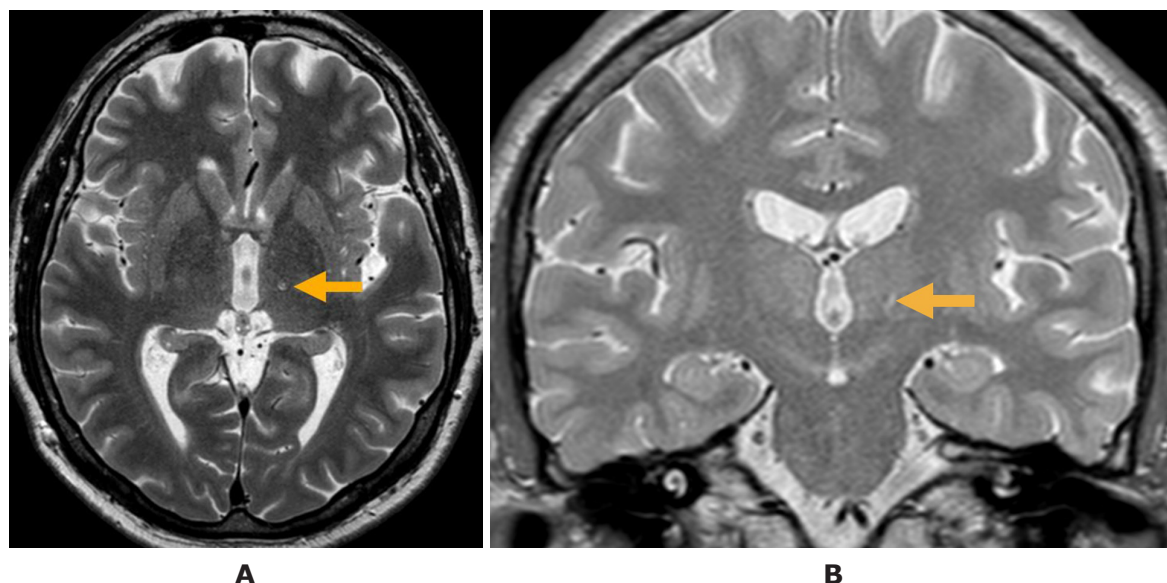
dominated by pronounced resting and postural tremor, predominantly affecting the left extremities.

The patient underwent right-sided radiofrequency (RF) DRTT lesioning using the Element software (Brainlab) for determination of target coordinates (**Fig. 3**). After surgery, tremor in the left extremities completely resolved, rigidity regressed, and motor activity improved. One year after surgery, the patient reduced the dose of levodopa therapy to 375 mg/day and pramipexole to 0.375 mg/day and discontinued rasagiline therapy.

Magnetic resonance imaging (MRI) was performed 12 months after surgery (**Fig. 4**). It was established that the UPDRS score during the "OFF" period decreased from 88 to 61 points, corresponding to a 31% reduction.



**Fig. 3.** Planning of the target for RF DRTT lesioning (orange line — trajectory of RF electrode insertion; purple — Vim; green — STN; red — posterior subthalamic area; blue-lilac — DRTT): A — coronal projection; B — 3D reconstruction of the subcortical nuclei and DRTT



**Fig. 4.** Lesioning zone 12 months after DRTT tractotomy: A — axial projection; B — coronal projection

## Discussion

Despite the dominance of neurostimulation technologies, ablative procedures continue to play a significant role in the surgical treatment of PD and certain other movement disorders. Alongside RF lesioning, novel ablative technologies have become widely adopted, particularly MRI-guided focused ultrasound ablation and Gamma Knife radiosurgical lesioning [7, 19–21].

The advantages of ablative procedures include the relative technical simplicity and short duration of neurosurgical intervention, high efficacy, a low rate of surgical complications, prevention of complications associated with implantation of deep brain stimulation systems, and the absence of a need for regular follow-up visits for adjustment of stimulation parameters.

In recent years, a renaissance of destructive stereotactic procedures has been observed, including both unilateral and staged bilateral interventions. Modern neuroimaging technologies and computer-assisted software enable highly detailed visualization of brain structures targeted during surgery and allow precise determination of their coordinates, thereby improving both the efficacy and safety of surgical procedures [7, 22].

The introduction of tractotomy represents a novel step in the treatment of PD as a systemic neurodegenerative disorder of the brain associated with dysfunction of neurotransmitter systems. Tractotomy does not target the affected anatomical brain structures themselves but rather the pathways responsible for neuronal impulse transmission, thereby enabling modulation of impaired neurotransmitter connections. Modern high-field MRI systems allow identification of tracts involved in the pathogenesis of PD and determination of the optimal sites for effective lesioning.

The present study reports the results of surgical treatment in 25 patients with PD who were divided into two groups. The Vim group underwent conventional RF thalamotomy, whereas the DRTT group underwent stereotactic RF tractotomy.

Comparison of surgical outcomes between the groups demonstrated more pronounced tremor control in the DRTT group, which contributed to increased daily activity of the patients. Regression of tremor and rigidity, reduction in levodopa dosage, and moderate improvement in bradykinesia resulted in enhanced motor activity, improved self-care capacity, and better quality of life in nearly all operated patients.

A limitation of the study is the small sample size of patients who underwent surgical intervention with tractography-assisted targeting. With an increase in sample size, the difference may exceed 0.05%.

The principal feature of interventions targeting the Vim nucleus is the possibility of achieving tremor control even in cases of suboptimal electrode placement by increasing either the stimulation amplitude or the lesion volume, which was observed in all operated patients. However, enlargement of the lesion volume increases the risk of sensory disturbances, gait and coordination disorders, speech impairment, and contralateral hemiparesis due to injury to the internal capsule ("capsular effect") and the ventral caudal nucleus of the thalamus. In our study, these adverse effects were transient and regressed within 12 months after surgery.

Only two patients from the group operated on using the indirect targeting method exhibited new neurological deficits one year after surgery. In one case, the patient reported paresthesia in the treated arm, whereas another patient experienced numbness of the fingers and hand on the treated side. Such outcomes were absent in the tractography-assisted group. These findings are consistent with previously published data [18, 22].

MRI tractography continues to evolve toward more precise visualization of the DRTT in surgical treatment of PD. Currently, there is no consensus regarding the optimal definition of the region of interest (ROI) for tract reconstruction. The DRTT should not be considered a single continuous nerve fiber, as it contains numerous branches. In our study, the ipsilateral cerebellar nucleus, contralateral thalamic nuclei, and contralateral precentral gyrus were used as ROIs.

However, alternative approaches to DRTT reconstruction exist and differ in ROI selection. Given that a portion of DRTT fibers does not decussate, some protocols consider ROI determination within a single hemisphere to be sufficient. An important anatomical landmark is the tract's passage through the superior cerebellar peduncle, which is sometimes included in the ROI to improve reconstruction specificity. Furthermore, the topographic proximity of the DRTT to the *lemniscus medialis*, which has a relatively stable anatomical location, may serve as an additional landmark for verification of tractography accuracy [22, 23].

Another important issue concerns the technical aspects of tractography. The principal objective of neuroimaging analysis is determination of the vector of electrical impulse conduction through the white matter within each voxel [24, 25].

Probabilistic tractography methods make it possible to estimate the most likely pathways of nerve fiber propagation while accounting for uncertainty in diffusion direction within each voxel, thereby improving the accuracy of reconstruction of complex and crossing tracts. However, such methods require specialized equipment and substantial computational time and therefore remain limited primarily to research centers. Currently available commercial deterministic methods are based on the "average" direction of conduction within each segment. This tractography approach allows sufficiently accurate identification of the target tract. Published studies have demonstrated that deterministic methods produce an average error of up to 1.4 mm. Although substantial, this level of error remains acceptable for planning stereotactic interventions. Some authors recommend using not only target localization but also the three-dimensional orientation of the tract for planning the surgical trajectory [26, 27].

In recent years, numerous clinical studies have been published regarding the use of deterministic DRTT tractotomy of various modalities for surgical treatment of tremor using RF lesioning and high-intensity focused ultrasound ablation. The high efficacy of tractotomy in tremor management has provided the rationale for applying these methods to control other motor manifestations of PD. Ongoing investigations are evaluating the role of the pallidothalamic tract as a principal pathogenetic pathway underlying rigidity and the phenomenon of freezing of gait. In particular, studies

are being conducted to determine the projection of the pallidothalamic tract within the subthalamic region. Indirect calculations of this target are characterized by considerable variability; therefore, tractographic analysis represents a promising direction for future interventions [28].

Another important area of research concerns the "hyperdirect" neuronal connection between the STN and the premotor cortex. It is known that the STN contains segments responsible for connections with other basal ganglia structures of the cerebral cortex. These pathways are associated not only with motor but also with cognitive and emotional states in patients with PD [8]. The hyperdirect pathway can currently be influenced only by neuromodulation technologies, particularly deep brain stimulation, because destructive interventions are associated with a high risk of neurological complications.

Special consideration should also be given to the potential role of several axial fiber pathways associated with bradykinesia and postural instability in patients with PD. Current investigations focus on corticothalamic tracts and fibers connecting the pedunculopontine nucleus (PPN) with the brainstem. The effects of interventions targeting these tracts remain insufficiently studied.

### Conclusions

An advanced understanding of PD pathogenesis as a disorder of neuronal connectivity is transforming therapeutic approaches to the disease. Contemporary neurosurgical methods do not directly target pathologically altered structures but instead modulate neuronal circuits involved in the development of motor dysfunction. MRI tractography of these pathways, particularly the dentato-rubro-thalamic tract, enables selective and effective compensation of pathological activity through both lesioning and neuromodulation while minimizing effects on adjacent neural structures. Application of this method ensures high procedural efficacy while accounting for individual anatomical variability in target selection for surgery.

### Disclosure

#### Conflict of interest

The authors declare no conflict of interest.

#### Funding

The study received no external financial support.

#### Use of Artificial intelligence

No artificial intelligence systems were used during the preparation of this article.

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