Interdisciplinary Neurosurgery 18 (2019) 100516

Contents lists available at ScienceDirect

Interdisciplinary Neurosurgery

journal homepage: www.elsevier.com/locate/inat

Technical Notes & Surgical Techniques

Globus pallidus internus deep brain stimulation improves axial symptoms of Parkinson patients after long-term subthalamic nucleus stimulation: A case series study

Chencheng Zhang (MD)[a,1], Yixin Pan (MD)[a,1], Linbin Wang (MSc)[a], Tao Wang (MD)[a], Jing Zhang (MD)[a], Haiyan Zhou (MD)[b], Wei Hu (MD, PhD)[c], Bomin Sun (MD)[a], Adolfo Ramirez-Zamora (MD)[c], Dianyou Li (MD, PhD)[a,*]

[a] Department of Functional Neurosurgery, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200025, China
[b] Department of Neurology, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200025, China
[c] University of Florida Center for Movement Disorders and Neurorestoration, Gainesville, FL 32607, USA

ARTICLE INFO

Keywords:
Parkinson's disease
Deep brain stimulation
Globus pallidus internus
Subthalamic nucleus

ABSTRACT

Introduction: Some patients with advanced Parkinson's disease (PD) develop refractory axial symptoms and motor complications following initially effective subthalamic nucleus (STN) deep brain stimulation (DBS). We aim to determine whether globus pallidus internus (GPi) stimulation can improve refractory axial symptoms and dyskinesia, as well as psychosocial functioning and quality of life, in this group of patients who no longer benefit from STN DBS.

Methods: In this pilot study, bilateral pallidal stimulation treatment was given to 7 patients with advanced PD who had developed refractory axial symptoms, including speech and swallowing difficulties, and painful dyskinesia, after long-term (> 5 y) subthalamic stimulation. The follow-up period was 6 months. Primary clinical outcome measures focused on motor symptom severity, motor complications, psychosocial function, and quality of life. Secondary outcome measures included daily dose of antiparkinsonian medication and patient's body weight.

Results: After pallidal stimulation, patients showed an overall 44% improvement in motor symptom scores at 6-month follow-up along with a 49% improvement in dyskinesia, a 33% improvement in psychosocial functioning, and a 42% improvement in quality of life. No adverse events occurred during the study.

Conclusions: These initial results indicate that bilateral GPi DBS could provide significant clinical benefits to patients whose axial symptoms cannot or can no longer be controlled by STN DBS.

1. Introduction

Subthalamic nucleus deep brain stimulation (STN-DBS) is a safe and effective neurosurgical treatment for patients with Parkinson's disease (PD) who suffer from severe, persistent, and medication-refractory motor symptoms and complications [1–3]. Following STN-DBS, patients usually show significant improvements in both motor function and advanced disease motor complications. Moreover, patients often require less antiparkinsonian medication and report a better quality of life after STN-DBS. Recent longitudinal studies have demonstrated the effectiveness of STN-DBS in the short- to medium-term, but PD symptoms can re-emerge and initial benefits can subside in certain patients as the disease progresses over longer periods of time [4]. With disease progression, patients are becoming increasingly more likely to develop axial motor symptoms and signs (e.g., postural instability, gait disability, swallowing difficulties, and voice and speech impairments), bradykinesia, and dyskinesia. These motor symptoms and complications may respond only partially to continuing STN-DBS treatment and other therapies [5–7]. As a result, affected patients typically experience profound functional impairments and a lower quality of life [8].

Several case studies and case series suggest that DBS of the globus pallidus internus (GPi) could serve as a “rescue” therapy for refractory axial signs and dyskinesia after initially effective STN-DBS [9,10]. The present study aimed to further assess the effectiveness of this treatment

* Corresponding author at: Functional Neurosurgery, Ruijin Hospital Affiliated to Shanghai JiaoTong University School of Medicine, Shanghai, China.
E-mail address: ldy11483@rjh.com.cn (D. Li).
[1] These two authors contributed equally to this paper.

https://doi.org/10.1016/j.inat.2019.100516
Received 11 June 2019; Accepted 29 June 2019

strategy. In our hospital, we observed that several patients with PD had gradually developed intractable axial symptoms and painful, disabling dyskinesias across the long-term course of their disease and STN-DBS treatment. Accordingly, we decided to replace the previously implanted STN electrodes with GPi-DBS electrodes in an effort to improve not only the refractory axial symptoms and motor complications of these patients, but also their psychosocial functioning and quality of life. We also explored whether GPi-DBS yielded clinical benefits to the patients in terms of a reduced intake of antiparkinsonian medications and an increased body weight.

2. Methods

2.1. Setting and participants

180 PD cases who had received long-term (5 years or more) bilateral STN DBS treatment in Ruijin Hospital Shanghai Jiaotong University School of medicine were screened for this study. 16 cases (8.3%) were eligible for rescue GPi DBS treatment, 7 patients (3.9%) received the rescue GPi DBS treatment and fulfilled the following four study inclusion criteria: (1) primary diagnosis of PD based on UK Brain Bank diagnostic criteria [11]; (2) the presence of severe axial symptoms and motor complications (motor fluctuations and dyskinesia) that could not be resolved by the administration or adjustment of medications and STN-DBS parameters, as described in our protocol below; (3) having received STN-DBS treatment for at least 5 y; and (4) a history of good clinical response to levodopa and STN-DBS. We used two exclusion criteria: (1) the presence of dementia or mild cognitive impairment, assessed by the Montreal Cognitive Assessment; and (2) contraindication to surgery, anesthesia, or magnetic resonance imaging (MRI). The local ethics committee approved the study protocol. Informed consent was obtained from all participants prior to study enrollment.

Study participants consisted of five male and two female patients (N = 7; mean age = 60.1 y, standard deviation [SD] = 7.6), who had PD for about 16 y (Table 1). All patients had received STN-DBS for at least 6 y prior to GPi-DBS surgery (median interval between STN-DBS and GPi-DBS surgery = 6.3 y, Q1-Q3 = 3.3–7.3). These patients opted for additional surgery due to the presence of refractory, severely disabling axial symptoms and motor complications (Table 1). Each patient was clinically assessed before and after GPi-DBS surgery, as described in the section Clinical outcome assessment.

2.2. Protocol

We applied the following algorithm for assessing the adequacy of baseline STN stimulation prior to deciding that rescue GPi electrode placement was required: 1) Confirm no hardware failures of DBS-STN system; 2) Check the location of DBS-STN contacts. 3) DBS parameters and medication adjustments, according to the Picillo et al. study [12]. Briefly, we tried to alleviate speech impairment by reducing the spreading of energy in one DBS-STN lead. The reduction of energy spreading was achieved by established approaches such as lower voltage, bipolar configuration, interleaving stimulation, low- frequency (100 Hz) stimulation and/or low pulse-width. The challenge lies here in improving speech without making involuntary movements worse. Similarly, to alleviate stimulation induced dyskinesias, we applied stimulation to a more dorsal contact with bipolar, monopolar, or double monopolar configurations. If not effective, we applied an interleaving stimulation and a low-frequency stimulation (100 Hz). Usually, bipolar setting configurations with high voltages insufficiently improved tremor, rigidity and other cardinal motor symptoms; double monopolar configurations turned out to work better. The algorithm used was substantially more complicated when a patient exhibited both speech impairment and stimulation-induced dyskinesias (and sometimes also gait impairment). In these cases, we also adjusted the patients' medication, but it became much more difficult to achieve a satisfactory clinical outcome. Constant currency [13], instead of constant voltage, was used in 3 patients but we, as well as others [14–16], observed no difference.

Table 1
Patient demographics, clinical characteristics, and rationale for switching to GPi stimulation.

Variable		Participants (N = 7)
Sex, M (%)		5 (71)
Age, mean ± SD, years		60.1 ± 7.6
Disease duration, mean ± SD, years		16.0 ± 2.2
Rationale	Balance problem, n (%)	3 (43)
	Refractory dyskinesias, n (%)	5 (71)
	Freezing of gait, n (%)	1 (14)
	Dysphagia, n (%)	1 (14)
	Muffled speech, n (%)	2 (29)

2.3. Surgical procedure

Stereotaxic surgery using the Leksell G frame was performed under local anesthesia. Computed tomography (CT) scan and 1.5 T MRI were performed, and the scans were fused using the Leksell SurgiPlan® system (Electra, Sweden). The indirect GPi targeting point was located 2–4 mm anterior to the anterior commissure-posterior commissure line (AC-PC) midpoint, 18–22 mm lateral to the AC-PC line, and 2–4 mm below the AC-PC line. The coordinates of the most ventral GPi DBS contacts and the post GPi DBS image (pre-surgery MR merged with post-surgery MR) of all patients are presented in Supplementary material.

After the STN electrodes were removed, quadripolar DBS electrodes (3387; Medtronic, Minneapolis, MN) were implanted bilaterally in the GPi and the implantable pulse generator (IPG; bilateral 37602 [1], Activa RC [6]; Medtronic) was implanted subclavicularly. Surgery was performed using intraoperative fluoroscope for anatomical target delineation and macro stimulation to verify the physiological target. No microelectrode recordings were performed in this series. Patients underwent the postsurgical CT or MR scan, which was fused back to the preoperative MRI images to confirm adequate lead location (Supplementary Figures).

2.4. Clinical outcome assessment

Each patient was assessed by an independent movement disorder neurologist, blinded to the patient's medical history and study enrollment, utilizing psychometrically validated and widely used instruments. Four primary clinical outcome measures were obtained at baseline (before GPi-DBS surgery) and at 6 months after bilateral GPi-DBS treatment: (1) severity of motor symptoms, measured during the on-medication state by examiner-blinded video assessments and the Unified Parkinson Disease Rating Scale (UPDRS)-Part III (Motor Scale), which was assessed also at 3 months after surgery; (2) motor complications (in the previous week), as measured by the UPDRS-Part IV (Complications of Therapy); (3) psychosocial consequences of PD-related voice disorders, measured by the Voice Handicap Index (VHI) [17]; and (4) quality of life, assessed by the Parkinson's Disease Questionnaire (PDQ-39). We used the post-surgery Medication ON/GPi ON scores as our primary outcome measure because the alleviation of the medication ON axial symptoms and the painful medication ON dyskinesia or ON dystonia present after long-term STN-DBS was the main clinical goal of the GPi-DBS treatment given to the patients. These data were compared to the pre-surgery or baseline data (Medication ON/STN ON).

Two secondary clinical outcome measures were obtained at baseline and 6-month follow-up: (1) the dose of antiparkinsonian medications

used, converted into a total daily *levodopa equivalent dose* (LED); and (2) the body mass index (BMI). Note that we obtained the latter outcome measure to explore whether the GPi-DBS treatment was accompanied by body weight changes potentially related to an improvement or exacerbation of PD-related dysphagia.

2.5. Statistical analysis

We performed a series of paired-sample *t*-tests to assess changes in the clinical outcome measures between baseline and at the 6-month (and for the UPDRS-III also at the 3-month) follow-up, using two-tailed tests at a significance level of $P < 0.05$. Data for continuous variables are presented as mean and standard deviation (SD) or median and first (Q1) and third (Q3) quartile; data for categorical variables are presented as frequencies (%). We analyzed the data using SPSS v20.0 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Primary clinical outcomes

On average, the patients showed a significant reduction in the total motor score of the UPDRS-III at 3 and 6 months after GPi-DBS, indicating an overall motor symptom severity improvement of 43% and 44%, respectively (Table 2). Specifically, we observed significant reductions in speech scores (55% improvements at 3 and 6 months), bradykinesia scores (40% improvement at 3 months and 43% at 6 months), and scores of other axial signs, including posture, gait, and postural stability (41% improvement at 3 months and 35% at 6 months) (Table 2).

Furthermore, patients displayed a significant reduction in the UPDRS-Part IV score, particularly concerning ON-dyskinesia, indicating a 49% improvement of motor complications at 6-month follow-up (Table 3). At the individual patient level, all patients showed an improvement of their UPDRS-Part IV scores at 6-month follow-up.

Moreover, the patients exhibited significant reductions in the VHI and PDQ-39 scores at 6-month follow-up, representing a 33% improvement of psychosocial function and a 42% improvement of overall quality of life, respectively (Table 3). According to the PDQ-39 item scores, the patients experienced a better quality of life particularly in relation to activities of daily living, emotional well-being, cognition, communication, and body discomfort (Table 3).

3.2. Secondary clinical outcomes

Overall, patients took 34% less antiparkinsonian medications at 6-month follow-up; however, the size of this reduction was not statistically significant ($P > 0.17$; Table 3). At the individual patient level, 3 patients took less medication at 6-month follow-up; medication dose did not change for the other 4 patients. Additionally, at the group level, patients had a 34% higher BMI at 6-month follow-up, but this increase only approached, and did not exceed, statistical significance ($P = 0.052$; Table 3). At the individual level, BMI was higher for 6 patients and slightly lower for 1 patient.

Table 3
Motor complications, psychosocial function, quality of life, medication and body weight of patients (N = 7) before and after GPi-DBS[a].

Outcome	Baseline	6 months	Change	P-value
UPDRS-IV (score)	6.4 ± 2.6	3.3 ± 1.5	3.1 ± 1.8	0.0034
VHI (score)	75.4 ± 6.9	50.6 ± 23.1	24.9 ± 21.3	0.0216
PDQ-39 (score)	77.1 ± 25.9	44.4 ± 28.0	32.7 ± 23.4	0.0100
Mobility	24.6 ± 10.1	15.1 ± 14.2	9.4 ± 10.8	0.0594
Activities of daily living	15.7 ± 6.9	9.9 ± 6.8	5.9 ± 5.8	0.0379
Emotional well-being	9.9 ± 4.3	5.4 ± 3.4	4.4 ± 2.4	0.0026
Stigma	4.1 ± 4.1	2.3 ± 1.9	1.9 ± 3.0	0.1489
Social support	4.0 ± 1.5	3.3 ± 1.9	0.7 ± 1.0	0.0941
Cognition	6.1 ± 2.9	3.4 ± 2.1	2.7 ± 1.9	0.0090
Communication	7.1 ± 2.6	2.9 ± 1.7	4.3 ± 2.4	0.0034
Body discomfort	5.6 ± 2.7	2.1 ± 1.6	3.4 ± 2.0	0.0038
BMI	21.7 ± 4.3	23.1 ± 4.9	1.4 ± 1.6	0.0524
Equivalent dose of levodopa (mg/d)	875.6 ± 549.2	578.6 ± 284.9	297.2 ± 474.5	0.013

GPi-DBS: globus pallidus internus-deep brain stimulation; UPDRS-IV, Unified Parkinson Disease Rating Scale-Part IV (Complications of Therapy); VHI, Voice Handicap Index; PDQ-39, Parkinson's Disease Questionnaire; BMI, Body mass index.

[a] Data are represented as mean ± SD. Before GPi-DBS (baseline) = Medication ON/STN ON. After GPi-DBS (6-month follow-up) = Medication ON/GPi ON.

3.3. DBS parameters

We optimized STN DBS parameters prior to study participation. Table 4 presents the final DBS parameters used for initial STN stimulation and at 6 months after GPi stimulation. We used high-frequency, unipolar, or double unipolar stimulation with pulse widths between 60 and 90 microseconds. Stimulation settings used closely mirrored Gpi settings reported in randomized Gpi-DBS clinical trials [18].

3.4. Adverse events and side effects

No adverse events or enduring side effects occurred during the surgery or 6-month follow-up period. We observed the occurrence of several temporary, reversible DBS-related corticobulbar or corticospinal side effects during programming, including muscle contractions, dysarthria, and eye flashes.

4. Discussion

In this study, bilateral GPi-DBS was given to several patients with

Table 2
Motor symptom severity of patients (N = 7) before and after GPi-DBS[a].

UPDRS-III	Pre-surgery	3 months	Change	P-value	6 months	Change	P-value
Speech (score)	2.9 ± 0.4	1.3 ± 0.5	1.6 ± 0.5	0.0002	1.3 ± 0.5	1.6 ± 0.5	0.0002
Bradykinesia[b] (score)	22.7 ± 6.5	13.7 ± 5.4	9.0 ± 5.2	0.0038	13.0 ± 5.0	9.7 ± 4.0	0.0007
Axial signs[c] (score)	10.1 ± 1.4	6.0 ± 1.0	4.1 ± 1.4	0.0002	6.6 ± 2.0	3.6 ± 2.2	0.0046
Tremor[d] (score)	6.1 ± 4.3	3.6 ± 2.4	2.6 ± 4.2	0.1594	3.4 ± 2.5	2.7 ± 5.3	0.8731
Total motor score	56.9 ± 12.4	32.6 ± 6.2	24.3 ± 10.1	0.0007	31.9 ± 5.3	25.0 ± 12.1	0.0016

GPi-DBS: globus pallidus internus-deep brain stimulation; UPDRS-III, Unified Parkinson Disease Rating Scale-Part III (Motor Scale); STN: subthalamic nucleus.

[a] Data are represented as mean ± SD. Before GPi-DBS (baseline) = Medication ON/STN ON. After GPi-DBS (6-month follow-up) = Medication ON/GPi ON.

[b] Bradykinesia as measured by scores on finger test, hands active, alternate motion, leg agility, and arising from chair.

[c] Axial signs as measured by scores on posture, gait, and posture stability.

[d] Tremor as measured by scores on static tremor and posture tremor.

Table 4
DBS parameters used for initial STN stimulation and GPi stimulation at 6-month follow-up.

	STN				GPi			
	Amplitude (V)	PW (μs)	Rate (Hz)	Configuration	Amplitude (V)	PW (μs)	Rate (Hz)	Configuration
1 right	3.1	60	110	1-	2.95	60	120	1-
1 left	2.9	90	110	8-9-	3.05	60	120	8-9-
2 right	3.85	90	165	0-1-	3.5	60	160	1-2-
2 left	3.6	90	105	1-	3.3	90	160	1-3-
3 right	3.7	90	125	2-3-	3.25	60	170	1-2-
3 left	3.7	90	125	6-7-	3.15	60	170	9-11-
4 right	2.95	60	125	2-3-	2.75	90	125	1-2-
4 left	2.25	60	125	6-7-	2.75	90	125	6-7-
5 right	3.65	60	115	2-3-	3.25	70	160	1-2-
5 left	3.25	90	115	5-6-	3.25	90	160	5-6-
6 right	2.95	90	160	0-1-	2.85	60	160	1-
6 left	3.25	90	160	4-5-	3.15	60	160	9-
7 right	3.45	60	185	1-2-	2.65	60	175	0-
7 left	3.35	60	185	6-7-	3	80	175	8-9-

DBS: deep brain stimulation; GPi: globus pallidus internus; STN: subthalamic nucleus.

PD who had developed refractory axial symptoms and painful dyskinesia after initially effective long-term (> 5 y) STN-DBS. Six months after GPi-DBS, the patients showed significant improvements of axial symptoms and motor complications, including dyskinesia, along with improvements of psychosocial functioning and quality of life. It is likely that these clinical benefits, although highly distinct at 6-month follow-up, emerged earlier following GPi-DBS surgery because improvements of axial symptoms and dyskinesia were already evident at 3-month follow-up. Additionally, the patients showed a decreased intake of antiparkinsonian medications and an increased body weight at 6-month follow-up. These effects, however, were not statistically significant. Finally, no adverse events occurred during the surgery and follow-up period. These results indicate that bilateral GPi DBS could provide significant clinical benefits to patients with PD whose axial symptoms and complications cannot or can no longer be controlled by STN DBS. The results of this study are in line with a meta-analytical review of long-term DBS studies [14], indicating that GPi DBS is more effective than STN DBS in alleviating later occurring axial symptoms. Accordingly, our results provide further support for the view that GPi-DBS can serve as an effective and safe “rescue” therapy for those patients who have developed refractory axial symptoms and complications after long-term STN-DBS [9,10].

After GPi-DBS, the patients experienced a marked reduction in the painful dyskinesias that had emerged over the long-term course of their illness and STN-DBS treatment. It has been reported, indeed, that GPi-DBS has a stronger and more enduring effect on dyskinesias than STN-DBS [19]. It seems reasonable to assume that GPi-DBS and STN-DBS activated in our patients partially distinct physiological mechanisms and processes, which could be responsible for the differential effects on dyskinesia. It is also plausible, however, that the beneficial effects of GPi-DBS on the patients' dyskinesias were not direct but indirect, that is, being a consequence of the withdrawal of STN-DBS treatment. In any case, this study indicates that GPi-DBS can alleviate severe dyskinesia in patients who are no longer responding to STN-DBS.

Furthermore, all patients displayed a substantial improvement of speech function (as indexed by the UPDRS-III) along with a reduction of the psychosocial consequences of their speech problems (indexed by the VHI). Previous studies, however, have produced mixed findings about the effects of DBS on speech function of patients with PD. In rare cases, DBS may even induce or exacerbate speech difficulties, especially following STN-DBS [14]. Nevertheless, the present study suggests that GPi-DBS improved speech difficulties that emerged after long-term STN-DBS treatment. However, as with dyskinesia, it is not possible to distinguish whether the observed improvement of speech function originated from: (a) the GPi-DBS treatment alone, (b) the withdrawal of STN-DBS treatment, or (c) a combination of these two or perhaps other factors.

In a similar vein, we observed that the GPi-DBS treatment was accompanied by an increased body weight of patients. Because speech and swallowing functions are highly correlated, it may be inferred that GPi-DBS also improved PD-related dysphagia. However, this conclusion should be qualified because the observed body weight increase was not statistically significant. Moreover, many factors other than swallowing function could underlie body weight changes, including changes in clinical symptom severity, medication, or mood.

Our results could raise questions about initial target selection in particular and the relative advantages and disadvantages of the STN and GPi as DBS targets in general. For example: Would the patients' clinical courses have been different if they initially had received GPi DBS instead of STN DBS? Although this question is impossible to answer, a critical consensus has emerged among experts that STN DBS is as effective as GPi DBS in treating motor symptoms of PD [19,20]. STN stimulation does seem to have a relative advantage in terms of a reduced intake of dopaminergic medications, whereas GPi stimulation seems more effective in reducing medication ‘on’ dyskinesias [16,19]. Target switch in some cases might be helpful (GPi to STN [21,22] and STN to GPi [9,10]) for alleviating disease progression or motor complications, as well as eliminating potential stimulation “tolerance”. However, direct comparisons between the two DBS targets have been complicated by the different amounts of time and clinical effort devoted to programming STN DBS versus GPi DBS, with the former target usually requiring more effort and a more cautious treatment approach than the latter target. Determination of the best DBS target for specific PD symptoms remains a key area of debate and research in the field.

Limitations of the current study include the small study population, and the fact that neither study subjects nor raters were blinded to condition or study objectives, with placebo serving as a confound. The methodology of only comparing ON med/ON stimulation objective outcomes limits the interpretability and generalizability of the results of this small number of selected patients. Also, using this methodology we can't tell the new GPi leads did anything useful or simply stopping STN stimulation was the cause of the improvement. However, reducing the STN stimulation has been proved unsuccessful until addiction surgery was performed. Lastly, our patients initially received STN DBS because GPi DBS was rarely used at that time in China due to the economic disadvantage of non-rechargeable battery. By contrast, multiple target options usually exist at most centers around the world. Therefore, our patients differ in this respect from patients in other countries, which may limit the generalizability of the present results.

Despite selection bias and recurrence of symptoms with longer follow up are both concerns, we believe that the present study provides an alternative to the patients. There are anecdote patients who had GPi-

DBS after an initial STN-DBS but none of them had any improvement. We emphasize the need for further study of this approach to better define the longer-term efficacy and patient selection criteria, to establish the fact that whether bilateral GPi DBS could provide significant clinical benefits to patients whose axial symptoms cannot or can no longer be controlled by STN DBS.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.inat.2019.100516.

Declaration of Competing Interest

Dr. Dianyou Li and Dr. Chencheng Zhang have received honoraria and travel expenses from the Deep Brain Stimulation industry (Medtronic, PINS, SceneRay). Dr. Bomin Sun received research support from PINS and SceneRay (donated devices); Dr. Ramirez-Zamora received financial compensation for consultant activities with Medtronic and Bracket. The other authors have no conflicts of interest to report.

Acknowledgments

We thank Yingying Zhang (Research Assistant, Ruijin Hospital) for her support in this study and Dr. Odin van der Stelt (Research Consultant, Amsterdam, The Netherlands) for constructive comments on the manuscript.

Authors' roles

Conception and design: CCZ, BMS, WH, and DYL
Acquisition of data: CCZ, YXP, LBW, JZ, HYZ, and TW
Analysis and interpretation of data: CCZ, YXP, ARZ, and DYL
Statistical review and critique: WH and ARZ
Manuscript drafting: CCZ, ARZ, and DYL, with intellectual input from all other authors

Funding

This work was supported by Shanghai Minhang Health And Family Planning Commission research project [201440504 to DYL] National Natural Science Foundation of China [81471387, 81271518, 81771482 to BMS]; School of Medicine, Shanghai Jiao Tong University–Institution of Neuroscience Research Center for Brain Disorders to BMS.

References

[1] F.M. Weaver, K. Follett, M. Stern, et al., Bilateral deep brain stimulation vs best medical therapy for patients with advanced Parkinson disease: a randomized controlled trial, JAMA 301 (1) (2009) 63–73, https://doi.org/10.1001/jama.2008.929.
[2] M.S. Okun, Deep-brain stimulation—entering the era of human neural-network modulation, N. Engl. J. Med. 363 (1) (2014) 1–3, https://doi.org/10.1056/NEJMp1002530.
[3] N.R. Williams, K.D. Foote, M.S. Okun, Subthalamic nucleus versus globus pallidus internus deep brain stimulation: translating the rematch into clinical practice, Mov Disord Clin Pract 1 (1) (2014) 24–35, https://doi.org/10.1002/mdc3.12004.
[4] A. Fasano, A. Daniele, A. Albanese, Treatment of Motor and Non-motor Features of Parkinson's Disease With Deep Brain Stimulation, vol 11, (2012), pp. 429–442, https://doi.org/10.1016/S1474-4422(12)70049-2.
[5] D. Li, C. Cao, J. Zhang, S. Zhan, S. Chen, B. Sun, Subthalamic nucleus deep brain stimulation for Parkinson's disease: 8 years of follow-up, Transl Neurodegener 2 (1) (2013) 11, https://doi.org/10.1186/2047-9158-2-11.
[6] D.M. Patel, H.C. Walker, R. Brooks, N. Omar, B. Ditty, B.L. Guthrie, Adverse events associated with deep brain stimulation for movement disorders: analysis of 510 consecutive cases, Neurosurgery 11 (1) (2015) 190–199, https://doi.org/10.1227/NEU.0000000000000659.
[7] A. Wagle Shukla, M.S. Okun, Surgical treatment of Parkinson's disease: patients, targets, devices, and approaches, Neurotherapeutics 11 (1) (2014) 47–59, https://doi.org/10.1007/s13311-013-0235-0.
[8] M. Hariz, My 25 stimulating years with DBS in Parkinson's disease, J. Park. Dis. 7 (s1) (2017) S33–S41, https://doi.org/10.3233/JPD-179007.
[9] R.J. Cook, L. Jones, G. Fracchia, et al., Globus pallidus internus deep brain stimulation as rescue therapy for refractory dyskinesias following effective subthalamic nucleus stimulation, Stereotact. Funct. Neurosurg. 93 (1) (2015) 25–29, https://doi.org/10.1159/000365223.
[10] C.M. Matias, D. Silva, A.G. Machado, S.E. Cooper, "Rescue" of bilateral subthalamic stimulation by bilateral pallidal stimulation: case report, J. Neurosurg. 124 (February) (2015) 1–5, https://doi.org/10.3171/2015.1.JNS141604.
[11] A.J. Hughes, S.E. Daniel, L. Kilford, A.J. Lees, Accuracy of clinical diagnosis of idiopathic Parkinson's disease: a clinico-pathological study of 100 cases, J. Neurol. Neurosurg. Psychiatry 55 (3) (1992) 181–184, https://doi.org/10.1136/jnnp.55.3.181.
[12] M. Picillo, A.M. Lozano, N. Kou, R. Puppi Munhoz, A. Fasano, Programming deep brain stimulation for Parkinson's disease: the Toronto Western Hospital algorithms, Brain Stimul. 9 (3) (2016) 425–437, https://doi.org/10.1016/j.brs.2016.02.004.
[13] C.J. Hartmann, L. Wojtecki, J. Vesper, et al., Long-term evaluation of impedance levels and clinical development in subthalamic deep brain stimulation for Parkinson's disease, Parkinsonism Relat. Disord. 21 (10) (2015) 1247–1250.
[14] F.R. de Noriega, R. Eitan, O. Marmor, et al., Constant current versus constant voltage subthalamic nucleus deep brain stimulation in Parkinson's disease, Stereotact. Funct. Neurosurg. 93 (2) (2015) 114–121.
[15] F. Preda, C. Cavandoli, C. Lettieri, et al., Switching from constant voltage to constant current in deep brain stimulation: a multicenter experience of mixed implants for movement disorders, Eur. J. Neurol. 23 (1) (2016) 190–195, https://doi.org/10.1111/ene.12835.
[16] M.K. York, E. Moro, No differences in neuropsychological outcomes between constant current and voltage current subthalamic deep brain stimulation for Parkinson's disease, Ann Transl Med 5 (7) (2017).
[17] B. Jacobson, A. Johnson, C. Grywalski, The voice handicap index (VHI): development and validation, can J Speech-Language Pathol. 6 (3) (1997) 66–70 https://ajslp.pubs.asha.org/article.aspx?articleid=1774592.
[18] K.A. Follett, F.M. Weaver, M. Stern, et al., Pallidal versus subthalamic deep-brain stimulation for Parkinson's disease, N. Engl. J. Med. 362 (22) (2010) 2077–2091, https://doi.org/10.1056/NEJMoa0907083.
[19] A. Rughani, J.M. Schwalb, C. Sidiropoulos, et al., Congress of Neurological Surgeons systematic review and evidence-based guideline on subthalamic nucleus and globus pallidus internus deep brain stimulation for the treatment of patients with Parkinson's disease: executive summary, Neurosurgery 0 (0) (2018) 1–4, https://doi.org/10.1093/neuros/nyy037.
[20] A. Ramirez-Zamora, J.L. Ostrem, Globus pallidus interna or subthalamic nucleus deep brain stimulation for Parkinson disease, JAMA Neurol. 75 (3) (2018) 1–6, https://doi.org/10.1001/jamaneurol.2017.4321.
[21] J. Volkmann, N. Allert, J. Voges, V. Sturm, A. Schnitzler, H.J. Freund, Long-term results of bilateral pallidal stimulation in Parkinson's disease, Ann. Neurol. 55 (6) (2004) 871–875, https://doi.org/10.1002/ana.20091.
[22] J.L. Houeto, P.B. Bejjani, P. Damier, et al., Failure of long-term pallidal stimulation corrected by subthalamic stimulation in PD, Neurology 55 (5) (2000) 728–730, https://doi.org/10.1212/WNL.57.3.566-a.