Adverse events in deep brain stimulation: A retrospective long-term analysis of neurological, psychiatric and other occurrences

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Abstract

Background and objective
The extent to which deep brain stimulation (DBS) can improve quality of life may be perceived as a permanent trade-off between neurological improvements and complications of therapy, comorbidities, and disease progression.

Patients and methods
We retrospectively investigated 123 consecutive and non-preselected patients. Indications for DBS surgery were Parkinson’s disease (82), dystonia (18), tremor of different etiology (21), Huntington’s disease (1) and Gilles de la Tourette syndrome (1). AEs were defined as any untoward clinical occurrence, sign or patient complaint or unintended disease if related or unrelated to the surgical procedures, implanted devices or ongoing DBS therapy.

Results
Over a mean/median follow-up period of 4.7 years (578 patient-years) 433 AEs were recorded in 106 of 123 patients (86.2%). There was no mortality or persistent morbidity from the surgical procedure. All serious adverse events (SAEs) that occurred within 4 weeks of surgery were reversible. Neurological AEs (193 in 85 patients) and psychiatric AEs (78 in 48 patients) were documented most frequently. AEs in 4 patients (suicide under GPI stimulation, weight gain >20 kg, impairment of gait and speech, cognitive decline >2 years following surgery) were severe or worse, at least possibly related to DBS and non-reversible. In PD 23.1% of the STN-stimulated patients experienced non-reversible (or unknown reversibility)
AEs that were at least possibly related to DBS in the form of impaired speech or gait, depression, weight gain, cognitive disturbances or urinary incontinence (severity was mild or moderate in 15 of 18 patients). Age and Hoehn&Yahr stage of STN-simulated PD patients, but not preoperative motor impairment or response to levodopa, showed a weak correlation ($r = 0.24$ and $0.22$, respectively) with the number of AEs.

**Conclusions**

DBS-related AEs that were severe or worse and non-reversible were only observed in PD (4 of 82 patients; 4.9%), but not in other diseases. PD patients exhibited a significant risk for non-severe AEs most of which also represented preexisting and progressive axial and non-motor symptoms of PD. Mild gait and/or speech disturbances were rather frequent complaints under VIM stimulation. GPI stimulation for dystonia could be applied with negligible DBS-related side effects.

**Introduction**

Deep brain stimulation (DBS) has emerged as one of the most effective treatment modalities for movement disorders. There is impartial evidence that alleviation of motor symptoms is associated with a considerable improvement in quality of life in patients with Parkinson’s disease (PD) and predominant non-axial motor symptoms or long-term complications from medical treatment [1–3]. Similarly, various types of primary dystonia and tremor show vigorous responses to DBS within the pallidum (commonly referred to as GPI stimulation; GPI, globus pallidus internus) or the ventrolateral thalamus/subthalamic region (commonly referred to as VIM stimulation; VIM, nucleus ventralis intermedius thalami) [4–7].

The surge in quality of life brought on by deep brain stimulation (DBS) is largely determined by cumulated motor improvements balanced against complications of therapy, comorbidities, and disease progression (all referred to as adverse events; AEs). In fact, considering that the overall clinical efficacy of DBS has remained very similar since the advent of well-engineered systems some 20 years ago, the actual gain in quality of life and patient satisfaction is largely determined by the avoidance of AEs.

Whereas AEs related to surgery, such as hemorrhage, infection or surgical revision of hardware are rather obvious and objective, the assessment of neurological AEs (e.g. speech problems) and especially the acquisition of psychiatric AEs (e.g. depression) is more subjective and less consistent. Multiple factors contribute to this. First of all, patients may not voice these kind of complaints or doctors may not pay proper attention to patient complaints. In addition, doctors may not ask patients specifically for possible AEs or may not recognize an unexpected AE. Documentation of AEs may be missing or may only be made when an AE is considered severe enough (threshold effects). Even in clinical trials rating the severity of AEs, for example, semiquantitative rating according to Common Terminology Criteria for Adverse Events (CTCAE), remains somewhat subjective, and standardized rating of patient complaints is almost never performed in the clinical routine. It is often difficult to judge whether or to what degree an AE is directly related to DBS therapy, in particular with regard to preexisting symptoms and comorbidities that tend to worsen over the natural course of the disease. Moreover certain AEs occur with latency under DBS, and short-term assessments in the stimulation “on” and”off” conditions may not suffice to distinguish between DBS-related- and DBS-non related
adverse events and such assessments are prone to underestimate the actual rate of DBS-induced AEs. A typical example for this would be axial symptoms in PD. Furthermore, AEs may be itemized using varying and arbitrary categories, i.e. AEs may be assigned to more specific or broader terms. For example, gait disturbances in PD may be subsumed under different terms and more than one of the following items may apply to a given patient: gait problems, postural instability, balance disorder, freezing of gait, festination, start hesitation, and falls. This makes it difficult to compare studies and to estimate the overall incidence of DBS-related AEs. Last but not least, the collection and assessment of DBS-related AEs is guided by current knowledge and is evolving over time. For example, the perception of the behavior of some STN-stimulated PD patients that had been celebrated as gain of initiative, independence, and mobility over a decade ago will nowadays raise red flags with regard to disturbed impulse control.

In fact, the limitations of complete acquisition and proper rating of neurological and psychiatric AEs cannot be overcome by even the most impartial trial methodology. Even blinded and prospective randomized controlled trials with tight and independent data monitoring exhibit highly variable rates of neurological and psychiatric AEs, hampering comparisons between studies (cf. Table 1). Low rates of AEs may stem from both a true low incidence or from underreporting. On the other hand, higher rates might be due to ‘repeated’ reporting, e.g. the documentation of falls and gait disorders for the same patient.

Monitored trials possess a plethora of data but AEs are usually presented in a rather summarized form and further specifications of AE are sometimes lacking. This lack of detail is mainly for the reason of brevity, although, an independent workup of those substantial data sets together with a more detailed and comprehensive presentation could be addressed in a separate study [19]. We performed complete acquisition and formal rating of all AEs and comorbidities in a non-preselected ‘real-world’ DBS patient cohort analyzed in a retrospective manner. AEs are broken down with regard to severity, attribution to DBS therapy and reversibility. Data will be presented in a transparent and relatable manner, and, to best of our knowledge, a similar in-depth analysis of AEs has not been undertaken to date.

Patients and methods

AEs in 123 consecutive and non-preselected patients (56 female; 67 male) who had undergone DBS surgery at our institution between January 1, 2007 and June 30, 2011 were assessed retrospectively including a comprehensive chart review and continuous outpatient documentation. This assured a theoretical follow-up of at least 3 years for all patients until data acquisition. This analysis was performed for the purpose of internal quality control as well as proper patient counseling which should be based on actual AE rates from the treating center and not from the literature. This work is part of a doctoral thesis by one of the authors (K.E.) and was approved by the Medical Faculty of the University of Hamburg. Data entered into the database were analyzed anonymously.

Mean and median age at surgery was 59 and 63 years, respectively (range 17 to 75 years). Twenty patients were aged 70 and older. Mean and median follow-up time was 4.7 years (standard deviation 1.5 years; range 0.7 to 7.3 years). The follow-up period was <12 months for 1 patient (65 year-old patient suffering from ongoing freezing and gait disorder following STN stimulation; follow-up 8 months) and <24 months for 4 patients. In total, this represents a cumulative period of 578 patient-years (4.7 years x 123 patients).

Indications for surgery were Parkinson’s disease (82 patients; including 78 patients stimulated bilaterally in the STN, one patient stimulated bilaterally in GPI, and 3 patients stimulated (2 unilaterally) in the VIM); generalized and segmental dystonia (18) with or without
associated tremor treated bilaterally in the GPI; essential tremor (14), dystonic tremor (2),
symptomatic cerebellar tremor following tumor resection (1) and intention tremor in multiple
sclerosis (4) treated with VIM stimulation; Huntington’s disease (1; GPI), and Gilles de la
Tourette syndrome (1; centre median-parafascicular nuclei of thalamus, Cm/Pf). For STN-
stimulated PD patients disease duration was between 5 and 26 years (mean 13.5; median 14)
and mean disease severity was stage 3 according to Hoehn & Yahr. In the preoperative medica-
tion “off” state the average UPDRS III (Unified Parkinson’s disease rating scale, part III) motor
score was 37.1 (median 37; range 14–68) with an average response to levodopa of 44.9%
(median 44.4; range 0 (one levodopa non-responsive tremor-dominant PD patient) to 89.8).
Average disease duration in dystonia patients treated with GPI stimulation was 14.7 years
(median 14; range 3–51) and in tremor patients treated with VIM stimulation it amounted to
18.6 years (median 14; range 2–50). The surgical procedure has been described in a comple-
menting report detailing all surgery-related AEs (Engel et al., submitted).

Adverse events (AEs) were defined as any untoward medical occurrence, clinical sign or
patient complaint as well as unintended disease if related or unrelated to the surgical proce-
dures, implanted devices or ongoing DBS therapy. Using a conservative approach AEs
included deterioration of preexisting conditions. Abnormal laboratory findings were excluded.
AEs were collected from conventional patient records (paper charts) and electronic patient
files (Soarian; Siemens, Erlangen, Germany; Dopla system; Carus, Norderstedt, Germany, and
'BIS' system; developed by one of the authors; J.A.K.). A total of 1289 source data documents
could be retrieved and were evaluated. Data sources included discharge letters, reports from
the outpatient clinics, surgical reports, and other documents such as reports from other

Table 1. Reporting of adverse events in prospective multicentric DBS studies for movement disorders.

| Author               | Pat | SAE | Mortality | Morbidity | Speech | Gait | Depression | Cognition | Confusion |
|----------------------|-----|-----|-----------|-----------|--------|------|------------|-----------|-----------|
| Timmermann, 2015[8]  | 40  | 18  | 10        | 0 (0)     | 0 (0)  | 7 (17.5) | 14 (35.0) | 6 (15.0)  | 0 (0)     | 1 (2.5)  |
| Volkman, 2014[9]     | 62  | 16  | ND        | 0 (0)     | ND     | 7 (11.3) | 1 (1.6)   | 4 (6.5)   | 0 (0)     | 0 (0)    |
| Schuepbach, 2013[10] | 124 | 123 | 68        | 0 (0)     | 0 (0)  | 10 (8.1) | 36 (29.0) | 33 (26.6) | 1 (0.8)   | 6 (4.8)  |
| Oderkerken, 2013[11] | 128 | ND  | ND        | 0 (0)     | 1 (0.8)| 44 (34.3)| 53 (41.4) | 10 (7.8)  | 15 (11.7) | 29 (22.7) |
| Volkman, 2012[6]     | 40  | 26  | ND        | 0 (0)     | 0 (0)  | 16 (40.0)| 2 (5.0)   | 2 (5.0)   | 0 (0)     | 1 (2.5)  |
| Okun, 2012[12]       | 136 | 50  | 41        | 0 (0)     | 0 (0)  | 17 (12.5)| 49 (36.0)| 17 (12.5) | 7 (5.1)   | 22 (16.2) |
| Williams, 2010[5]    | 183 | 96  | 65        | 1 (0.5)   | ND     | only SAE specified |
| Follett, 2010[13]    | 299 | 335 | 160       | 1 (0.3)   | ND     | 94 (31.4)| 407 (136.1)| 102 (34.1)| 5 (1.7)   | 70 (23.4) |
| Okun, 2009[14]       | 52  | ND  | ND        | 0 (0)     | ND     | 29 (55.8)| 27 (51.9)| 40 (76.9) | 9 (17.3)  | 46 (88.5) |
| Weaver, 2009[2]      | 121 | 82  | 49        | 1 (0.8)   | ND     | 19 (15.7)| 85 (70.2)| ND        | ND        | 16 (13.2) |
| Vidalhlet, 2007[15]  | 22  | 3   | 3         | 0 (0)     | 0 (0)  | 2 stim related AEs |
| Kupsch, 2006[16]     | 40  | 5   | 5         | 0 (0)     | 0 (0)  | 5 (12.5) | 1 (2.5)   | ND        | ND        | 1 (2.5)  |
| Deuschl, 2006[1]     | 78  | 10  | 10        | 1 (1.3)   | 0 (0)  | 8 (10.3) | 4 (5.1)   | 5 (6.4)   | 3 (3.8)   | 8 (10.3)  |
| Vesper, 2002[17]     | 129 | ND  | ND        | 1 (0.8)   | 2 (1.6)| 3 (2.3)  | 10 (7.8)  | ND        | ND        | ND       |
| PD study, 2001[18]   | 134 | ND  | ND        | 0 (0)     | 4 (3.0)| 2 (1.5)  | ND        | ND        | ND        | 1 (0.7)  |
| Schuurman, 2000[5]   | 34  | ND  | ND        | 1 (2.9)   | ND     | 4 (11.8)| 3 (8.8)   | ND        | ND        | ND       |

For SAE the total number of SAEs (n) and the number of affected patients (pat) is shown. For all other items (speech etc.) the number of affected patients (n) is stated whenever this could be read out of presented data. Otherwise the total number of respective AEs is shown. Only mortality and morbidity due to intracranial hemorrhage was considered. The item ‘speech’ included dysarthria, hypophonia, and other speech problems, but not impaired word fluency or dysphasia (language problems). The item ‘gait’ included disturbed balance, freezing of gait, falls, postural instability, festination, start hesitation, and dysequilibrium. The item ‘cognition’ included memory problems, dysexecution, dysphasia, disturbed word fluency, and mental changes. The item ‘confusion’ included disorientation, agitation, postoperative psychosis, and delirium. Only patients actually implanted with DBS systems were considered (no intention-to-treat-analysis). ND, not determined or not reported in the study or not ratable from the data presented in the paper.

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institutions or hospitals. Discharge letters following DBS surgery as well as surgical reports were written by one of the authors (W.H.) experienced in deep brain stimulation since 1998. The intention was to keep these documents as complete and consistent as possible prospectively, and all patients were explicitly monitored and interviewed for possible postoperative disturbances, such as impairment of gait or speech, depression, or cognitive deficits.

AEs were grouped into different categories: neurological, psychiatric, surgery- and hardware-related, and other AEs. Documentation included the selection of appropriate items for further specification of AEs. For example, neurological AEs included gait disturbance, speech problems etc., and psychiatric AEs included depression, hallucination, confusion etc. (cf. Table 1). We preferred broader terms (e.g. gait disturbance) and added detailed free text descriptions (for example, freezing of gait, postural instability, balance disorder, festination, start hesitation). Similarly psychiatric AEs were summarized in broader items. For example, the mentioning of apathy, diminished initiative or anhedonia in source data was subsumed under depression since there is some overlap or coexistence between these symptoms, although the authors are aware that this results in considerable simplification. Reduced verbal fluency was assigned to cognitive disturbance. This provided a more complete and meaningful assessment and prevented the 'dilution' of complex but related neurological and psychiatric problems by using different entities.

All AEs were rated as to whether these were attributable to DBS or not. If AEs went along with sequelae, such as confusion and deterioration of speech resulting from intracerebral hemorrhage, each of these was documented as a separate AE. For all AEs it was determined whether these represented a serious adverse event (SAEs) according to the criteria set forth by the Food and Drug Administration of the United States of America (http://www.fda.gov). Severity of AEs was graded as mild, moderate, severe, life-threatening or disabling, or death according to the Common Terminology Criteria for Adverse Events (CTCAE; version 4.0). The relatedness of an AE to surgery or ongoing deep brain stimulation was judged as unlikely, possible, probable, definite, or not related. In addition, the duration and reversibility of AEs was assessed. Information about preexisting conditions (e.g. speech problems) and comorbidities representing a risk factor (e.g. diabetes for infection) were also recorded.

In DBS-treated PD patients axial symptoms will usually progress due to the natural course of the disease or may become more pronounced (e.g. [20]). During routine follow-up visits, patients were evaluated in the stimulation “on” and “off” conditions as AEs may resolve immediately in the stimulation “off” condition, in particular if these are related to suboptimal electrode placement too close to the internal capsule. This, however, was not observed in any of the patients in the present study. It appears that, for example, impairment of gait or speech that persists in the stimulation “off” condition in PD patients may rather be related to long-term effects of DBS therapy or disease progression. In fact, short-term assessments in the stimulation “on” and “off” states may be misleading and are prone to underestimate the rate of DBS-induced AEs, and proper assessments would require a long wash-out phase to observe potential remission, which had not been performed during routine evaluations. In order to use the most conservative approach, we arbitrarily defined that any worsening of axial symptoms during the postoperative course and within the first 6 months following DBS surgery was rated as probably related to DBS, even if there had been statements in source data describing that problems with speech or gait had persisted during short-term trials in the stimulation "off" condition. Worsening of axial symptoms >6 months following surgery was rated as unlikely related if not stated otherwise in source data. With regard to an interval of 6 months it was assumed that DBS-related AEs will occur not later than therapeutic effects that are well-known to develop with great latency (e.g. improvement of dystonia). This arbitrary distinction was not made in tremor or dystonia patients. In those patients speech or gait problems were
generally rated as possibly or probably related to DBS therapy if not caused otherwise (e.g. by cervical myelopathy).

In PD axial symptoms and cognitive deficits progress over time. Strictly speaking, any deterioration documented at any time in the post-operative clinical follow-up would have counted as a new AE. However, at routine follow-up visits symptoms are normally not quantified on formal scales and rating had still remained subjective and vague. For this reason, AEs, such as speech problems or cognitive deterioration were only counted once for each patient at the first occurrence within the post-operative follow-up visits. Thus, in some cases, the severity of an AE (e.g. speech problems) may have worsened after the date of first documentation, and eventually the most severe condition was recorded. The reemergence or transient worsening of target symptoms under DBS, for example the recurrence of tremor or the development of tolerance to VIM stimulation, was not rated as an AE. AEs that were unrelated to DBS were documented only once. An example for this would be the repeated hospitalization for the treatment of a malignant tumor.

Data were collected by a senior resident (K.E.) experienced in treating movement disorder patients on the ward for several years. However, the author (K.E.) was not involved in the surgical procedures as she was part of a different subspecialty surgical team and thus relatively impartial in documentation. AEs were entered into a relational database developed by one of the authors (J.A.K.) that could be queried with MS Access 2013 (Microsoft Office Access Professional Edition 2013, Microsoft Inc., Seattle, USA). Congruence of the entered AEs with source data (i.e. medical records) was monitored (C.B., J.A.K., W.H.). Since there was no independent external monitoring process the higher CTCAE grade was assigned in case of doubt. Statistical analysis was performed with Sigmastat (Sigmastat 2.03; Systat Software Inc., Chicago, USA).

Results

Distribution of AE among patients

A total of 433 AEs were retrieved for 106 of 123 patients (86.2%); mean 3.5; median 3; range 0–10 per patient (see Fig 1 for distribution). Neurological and psychiatric AEs were more frequent than AEs related to the surgical procedure or implanted hardware (Table 2). The distribution of the number of AEs per patient is shown in Fig 1. As AEs may represent sequelae from another AE (e.g. neurological deficits from intracerebral hemorrhage) these numbers do not necessarily represent independent AEs. The average number of AEs differed between patients implanted into the STN (3.9 AEs), GPI (3.2), VIM (2.5), and C/P (2). 180 of 433 (41.5%) of the AEs were mild or moderate and unlikely or not related to DBS therapy.

Analysis of serious adverse events

A total of 96 SAEs were documented affecting 59 patients (48%). All SAEs that were at least possibly related to DBS and at least of moderate severity (n = 38) are specified in Table 3. The majority of SAEs was related to the surgical procedure or implanted devices. All surgery-related SAEs were reversible and will be detailed in a corresponding paper (Engel et al.,
submitted). In addition, all other SAEs that occurred within the first month of surgery were reversible (Table 3). These included postoperative respiratory complications, akinesia, confusion and one case of postoperative problems with initiation of movements due to a small intracerebral hemorrhage that resolved completely within the weeks following (Fig 2).

The only non reversible SAEs that were at least of moderate severity and at least possibly related to DBS were 2 gait disorders and 1 suicide. The suicide at the age of 52 occurred in a patient suffering from a parkinsonian syndrome diagnosed 11 years prior to surgery. Target

Table 2. Summary of adverse events.

|                | AE n (%) | Patients n (%) |
|----------------|----------|----------------|
| Neurological   | 193 (44.6) | 85 (69.1) |
| Psychiatric    | 78 (18.0)  | 48 (39.0) |
| Surgery-related| 23 (5.3)   | 18 (14.6) |
| Other          | 139 (32.1) | 73 (59.3) |
| Total          | 433 (100)  | 106 (86.2) |

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symptoms were severe levodopa-induced hyperkinesia as well as tardive dyskinesias that had improved significantly until death 18 months after bilateral GPI electrode implantation. The GPI, instead of the STN, was chosen as the surgical target because of the patient’s history of severe depression.

Table 3. CTC grade of SAE vs relatedness to DBS therapy.

|                | Definite | Probable | Possible | Unlikely | None |
|----------------|----------|----------|----------|----------|------|
| Death          | –        | –        | suicide* (18 mo) | – | 4 |
| Life threatening | akinesia (<1 mo) pneumonia/confusion* (<1 mo) respiratory distress** (<1 mo) | – | – | 1 | 10 |
| Severe         | akinesia (<1 mo) transient ‘paresis’*** (<1 mo) 20 x hardware revision 1 x explantation | 3 x injuries (<6 mo) confusion (<1 mo) gait (1 mo) 1 x hardware revision | – | 8 | 28 |
| Moderate       | 2 x intracerebral hemorrhage gait (3 mo) confusion (3 mo) | gait (16 mo) | 2 | 5 |

A total of 96 SAE were recorded. These occurred in 59 patients (48% of 123 patients). The actual event is specified for SAE that were at least of ‘moderate’ severity and at least ‘possibly related’ to DBS. Numbers in parenthesis indicate the month when the SAE occurred, for example, <1 mo indicates that the AE occurred within the first postoperative month;

*, ICU treatment without intubation;

**, preexisting chronic obstructive lung disease requiring postoperative non-invasive breathing assistance (CPAP) on ICU;

***, ‘paresis’, initiation of movements was disturbed by ICH, although, with full innervation normal muscle strength could be achieved;

*, suicide following GPI stimulation. SAEs that were unlikely or not related to DBS therapy (58) in most instances (>80%) included ‘other’ (non-neurological, non-psychiatric, not surgery-related) AEs (cf. Results). In <20% such AEs consisted of neurological or psychiatric AEs occurring >6 months after commencement of DBS leading to admission to a hospital (e.g. infection-associated motor deterioration, incontinence following spine surgery, gait problems, stroke, dysphagia, myelopathy, confusion after 76 months, dysarthria).

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Fig 2. Sum of AEs defined by same severity, reversibility, and attribution to DBS therapy. Green, reversible; orange, non-reversible; grey, unknown. The actual number of AEs is presented. The dotted area indicates AEs that were severe or worse and at least possibly related to DBS therapy and, thus, regarded the most critical. N.B. The number of affected patients may be less than the number indicated because individual patients may have suffered from more than one AE of respective groups (e.g. impairment of gait and speech rated as mild, probably related and non-reversible).

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SAEs that were unlikely related or unrelated to DBS included, for example, two deaths from malignant tumors, one death from subarachnoid hemorrhage, one death from intracerebral hemorrhage after head injury, infections with deterioration of Parkinson’s disease several years after surgery, urinary incontinence after spine surgery, decompression for cervical myelopathy and lumbar spinal stenosis, ulnar nerve decompression, treatment for various benign and malignant tumors, pneumonia, pulmonary embolism, and cardiovascular events. All of these SAEs occurred >12 months following DBS surgery except for one case of lumbar spine decompression performed after 9 months.

### Incidence of neurological, psychiatric and other AEs

Neurological AEs (related and unrelated to DBS) were observed most frequently and accounted for approximately 45% of all AEs and affected almost 70% of patients (Table 2). Gait disturbances and speech problems (related and unrelated to DBS) were by far the most prevalent AEs (cf. Table 4 for DBS-related AEs and Table 5 (Supplement) for all AEs). Psychiatric AEs (related and unrelated to DBS) represented the second most common AEs (18.0%) and affected approximately 40% of patients (Table 2). Depression and cognitive impairment were observed most frequently (cf. Table 4 for DBS-related AEs and Table 5 (Supplement) for all AEs). Other AEs (Table 2) included, for example, postoperative nausea and pain, weight gain, unwanted pregnancy with induced abortion 20 months following GPI stimulation for
dystonia, postoperative diarrhea, loosening of teeth following intubation, urinary tract infection, hematuria following catheterization, and pain associated with degenerative spine disease.

Severity and reversibility of AE vs attribution to DBS surgery and ongoing DBS therapy

In Fig 2, the severity of AEs is plotted against their attribution to DBS therapy. Only AEs that were at least possibly related to DBS therapy are considered. In the third dimension, the reversibility of AEs is shown.

Those AEs that were both rated as severe or worse and at least possibly related to DBS were regarded as the most critical (dotted area in Fig 2). The majority of such ’critical’ AEs consisted of surgery- and hardware-related complications and all of these were reversible (cf. ’Analysis of serious adverse events’). Such ’critical’ AEs were not reversible in only 4 patients: one patient committed suicide (described above), one female PD patient experienced weight gain of >20 kg, in one patient, deterioration of gait and speech impaired activities of daily life within six months of DBS surgery, and in one patient progressive cognitive disturbances documented >2 years following surgery were rated as possibly related to DBS because (initially reversible) confusion had already occurred in the postoperative period.

Table 5. (Supplement) DBS-related and -unrelated neurological and psychiatric adverse events.

|                        | Total | STN | VIM | GPI | C/P |
|------------------------|-------|-----|-----|-----|-----|
| Patients               | 123   | 78  | 24  | 20  | 1   |
| Neurological           |       |     |     |     |     |
| Gait disturbance       | 65 (52.8) | 48 (61.5) | 14 (58.8) | 3 (15.0) | -   |
| Speech disturbance     | 50 (40.7) | 36 (46.2) | 8 (33.3) | 6 (30.0) | -   |
| Akinesia               | 12 (9.8) | 11 (14.1) | -   | 1 (5.0) | -   |
| Incontinence           | 12 (9.8) | 11 (14.1) | -   | 1 (5.0) | -   |
| Dysphagia              | 9 (7.3) | 5 (6.4) | 2 (8.3) | 2 (10.0) | -   |
| Hypersalivation        | 8 (6.5) | 7 (9.0) | 1 (4.2) | -   | -   |
| Eyelid opening apraxia | 5 (4.1) | 5 (6.4) | -   | -   | -   |
| Dysesthesia            | 6 (4.9) | 1 (1.3) | 4 (16.7) | 1 (5.0) | -   |
| Paresis                | 4 (3.3) | 1 (1.3) | 1 (4.2) | 2 (10.0) | -   |
| Neurological other     | 22 (17.9) | 15 (19.2) | 4 (16.7) | 3 (15.0) | -   |

| Psychiatric            |       |     |     |     |     |
| Suicide                | 1 (0.8) | -   | -   | 1 (5.0) | -   |
| Depression             | 19 (15.4) | 12 (15.4) | 4 (16.7) | 2 (10.0) | 1   |
| Cognitive disturbance  | 20 (16.3) | 17 (21.8) | 1 (4.2) | 2 (10.0) | -   |
| Hallucination          | 10 (8.1) | 8 (10.3) | -   | 2 (10.0) | -   |
| Confusion              | 8 (6.5) | 5 (6.4) | 1 (4.2) | 2 (10.0) | -   |
| Impuls control disorder| 3 (2.4) | 3 (3.8) | -   | -   | -   |
| Anxiety                | 2 (1.6) | -   | -   | 2 (10.0) | -   |
| Submanic state         | 2 (1.6) | 2 (2.6) | -   | -   | -   |
| Psychiatric other      | 13 (10.6) | 7 (9.0) | 1 (4.2) | 5 (25.0) | -   |

Numbers indicate incidence of DBS-related and -unrelated AEs (in parenthesis percentage of patients affected); C/M, centre médian-parafascicular nuclei of thalamus. Other neurological AEs (Table 4) included AEs such as stroke (after 79 months), facial palsy (after 6 months), ulnar palsy, disturbed fine motor skills (e.g. writing), diplopia (the latter 3 occurring after >32 months), other visual problems (e.g. macular dystrophy), symptoms resembling restless legs syndrome, postural abnormalities (e.g. Pisa syndrome), and others. Other psychiatric AEs included sleep disturbances and nightmares, fatigue, somatoform disorder, convulsive sobbing, personality disorder trait, and tension.

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Most mild or moderate AEs that were at least possibly related to DBS therapy were neurological and psychiatric AEs also representing well-known and often preexisting axial problems and other comorbidities in PD patients, and these will be detailed in the following.

Speech problems were mild (66.7%) or moderate (25.0%) in most instances with 1 case of severe dysarthria in STN-stimulated PD patients. Impairment of speech that had occurred within the first 6 months (44.4% of speech problems) was mild in the vast majority of cases (81.3%). In STN-stimulated PD patients the actual risk for non-reversible (or reversibility unknown) impairment of speech that was at least possibly related to DBS was 16.7% (Table 4). With regard to speech problems that had been noticed in STN-stimulated PD patients later than 6 months following STN surgery, it was reversible in only one case. Two dystonic tremor patients complained about mild speech and gait problems within 6 months from surgery requiring adjustment of stimulator settings. Four ET patients experienced speech problems in conjunction with the requirement to increase stimulator settings > 6 months after surgery. Only 1 dystonia patient reported mild speech problems, and these were reversible within 6 months from surgery. Speech problems in all the other dystonia patients were documented > 29 months after surgery and were mild and mostly involved the mentioning of short episodes of slurred speech in the evening when being exhausted.

In STN-stimulated PD patients the actual risk for non reversible (or reversibility unknown) impairment of gait that was at least possibly related to DBS was 11.5% (Table 4). Two dystonic tremor patients and 2 ET patients recognized some difficulties with walking within 6 months from surgery and before stimulator settings had been optimized. After > 6 months 4 other ET patients mentioned at least possibly related gait problems that were associated with the need to increase stimulation amplitudes in order to maintain sufficient tremor suppression. Unsteady gait (possibly related) occurred in only 1 dystonia patient after 16 months and resolved with normalization of blood pressure after ramipril was discontinued. Severe gait disturbances that were unlikely related to DBS developed in 3 patients: one patient with progression of MS after > 24 months, one ET patient after > 4 years due to cervical myelopathy, and one PD patient after spine surgery.

Postoperative confusion and hallucinations were reversible in all cases. Two patients developed a postoperative submanic state (mild and moderate) that resolved after adaptation of medication and stimulation (one of both cases was reported in [21]).

Depression was mild (57.9%) or moderate (31.6%) in most patients, except for severe and life-threatening depression in 2 patients one of whom later committed suicide (Tables 3 and 4). Both patients (one PD patient and one patient with hyperkinetic disorder of unknown etiology) were stimulated in the GPI. In STN-stimulated PD patients the actual risk of non reversible (or reversibility unknown) depression that is at least possibly related to DBS was 6.4% (Table 4).

Cognitive decline was mild or moderate in all but one patient (dementia > 24 months following STN surgery). Transient cognitive impairment occurred in conjunction with both intracerebral hematomas. In 40% of the cases cognitive declines were observed > 24 months after surgery. In 5 cases cognitive disturbances were documented within the first 6 months following STN surgery, of which 3 were completely reversible. In STN-stimulated PD patients the actual risk for non reversible (or reversibility unknown) cognitive decline that is at least possibly related to DBS was 3.8% (Table 4).

In addition, urinary incontinence (4 patients) and weight gain (1 patient) were found among AEs that were non reversible or of unknown reversibility affecting 5.1% and 1.3% of STN-stimulated PD patients, respectively.

Taking into account that patients may be affected by more than one AE, 18 of 78 (23.1%) STN-stimulated PD patients experienced non-reversible (or unknown reversibility) AEs that
were at least possibly related to DBS in the form of impaired speech or gait, depression, weight gain, cognitive disturbances or urinary incontinence.

In ET, 5 of 14 patients were affected by speech and/or gait disturbances. In addition, both patients receiving VIM stimulation for dystonic tremor experienced dysarthria and gait disturbances that were at least possibly related to DBS. In 5 patients receiving unilateral VIM stimulation (1 ET, 2 PD, 2 MS) only one AE (gait disturbance in MS) was rated as non-reversible and possibly related to DBS.

Analysis of possible risk factors

Whereas mean and median age of patients with 0 to 5 AEs (n = 97) was 57.9 and 61 years, respectively, this was higher in patients with 6 to 10 AEs (63.3 and 66 years, respectively; n = 26). This difference came close to but missed statistical significance (p = 0.05; Mann Whitney rank sum test). Age was weakly correlated with the number of AEs (r = 0.24; r² = 0.058; p = 0.007). Both genders were similarly affected by AEs (male 228 of 433 AEs; 52.6%).

In STN-stimulated PD patients disease duration or disease severity according to the preoperative UPDRS III motor score in the medication “off” state did not reveal a positive correlation with the number of AEs that had been rated at least possibly related to DBS (Spearman’s rank coefficient, r < 0.2; p > 0.5). A weak correlation was found between disease severity according to Hoehn&Yahr stages and the number of AEs (Spearman’s rank coefficient r = 0.22; p < 0.052). In dystonia patients treated with GPI stimulation and in tremor patients treated with VIM stimulation there was no correlation between disease duration and the number of AEs (r < 0.1; p > 0.05).

Discussion

This study provides a comprehensive retrospective long-term analysis of AEs representing complications of DBS surgery and ongoing therapy as well as untoward events related to comorbidities and progression of the underlying diseases. AEs are unraveled in multiple dimensions, i.e. with respect to severity, relatedness to DBS therapy, and reversibility, and all critical AEs are detailed in a relatable manner. To the best of our knowledge, a similarly detailed assessment has not been published for DBS patients thus far.

There was no mortality or persistent morbidity from the surgical procedure, and all surgery-related AEs were reversible and resolved without sequelae. One suicide occurred under GPI stimulation after 18 months. In this patient the GPI instead of the STN nucleus was chosen because of the patient’s past history of severe depression. Although suggested previously, more recently there has been doubt whether DBS increases the risk of suicide [22, 23]. Only 3 other non-reversible AEs were rated as severe or worse and at least possibly related to DBS involving gait and speech disorder, cognitive decline >2 years following surgery and weight gain in one patient each.

The majority of AEs was documented during ongoing DBS therapy covering a period of 578 patient-years (4.7 years mean/median follow-up). The list of AEs is headed by speech problems and gait disorders, and the most common psychiatric AEs were depression and cognitive decline. These AEs also represent cardinal symptoms and comorbidities of the underlying diseases (e.g. gait and speech problems and depression in Parkinson’s disease; gait and speech problems in essential tremor) [19, 20, 24–29]. For this reason alone it is difficult to assess their relatedness to DBS therapy. In Parkinson’s disease, we arbitrarily chose to attribute worsening of axial symptoms as probably related to DBS therapy when this occurred within 6 months. A period of 6 months provides a margin of safety as even long-latency therapeutic effects of DBS (for example, improvement of dystonia) usually evolve much earlier. In clinical
studies with follow-up periods of >6 months the presumed relatedness of AEs to DBS therapy should be reported, especially when there is no control group.

Voice and speech disturbances are preexisting in most PD patients prior to STN surgery. These deficits may deteriorate with the natural course of the disease and may worsen under STN stimulation [19, 20, 25, 27]. Our data suggest that the risk of non reversible mild or moderate impairment of speech within six months of STN stimulation is approximately 17%. Rates in monitored trials are very variable and range between <10% and >50% (Table 1). The exact phenotypic characteristics associated with impaired speech intelligibility and the actual functional impairments caused by DBS therapy still require further elucidation and exhibit high individual variability [30–39]. Whereas reduced volume is observed in almost all PD patients slurred speech has been regarded rather as a side effect of DBS therapy [38].

Although gait disturbances are usually pre-existent and progressive in PD, deterioration of gait (e.g. difficulties walking or freezing of gait) within the first days or weeks following DBS surgery may resolve with time (e.g. due to resolution of a microlesioning effect) and after stimulator settings and medication have been adjusted. In the long run preoperative gait disturbances may improve in STN-stimulated PD patients, in particular if these had proven to be levodopa-responsive [29, 40–46]. Nonetheless, gait problems may persist in a proportion of patients. Our data suggest that about 12% of STN-stimulated PD patients exhibit gait disturbances within the first 6 months of STN stimulation that were non reversible (or reversibility unknown). But even with an uneventful postoperative course and despite improvement of gait over a period of several years this does not prevent most PD patients from developing gait problems and falls later on due to disease progression [19, 20, 25, 27–29, 47–50]. A meta-regression performed by St. George et al. revealed that despite initial improvements in balance and gait compared to the preoperative state, the long-term application of STN stimulation (less with GPI stimulation) resulted in a progressive decline of balance and gait in PD patients [29]. In monitored trials the frequency of gait disturbances in PD patients ranges between 5% and >100% (Table 1). This illustrates the difficulties in gathering, rating and evaluating gait problems, in particular if these coincide with preexistent and progressive PD symptoms (Table 1).

In contrast to PD patients, in tremor and dystonia patients speech and gait problems were always mild. There were no other non reversible AEs that could at least possibly be related to DBS therapy indicating that GPI stimulation for dystonia is very well tolerated and could be applied virtually without side effects.

Bilateral stimulation in the ventrolateral thalamus and subthalamic area is associated with an increased risk of gait and speech disturbances (e.g. [51]). These only occurred in bilaterally stimulated patients in the present series, but not in patients receiving unilateral VIM stimulation (with the exception of 1 MS patient with preexisting gait disorder). The underlying mechanisms for the development of speech and gait disturbances under VIM stimulation have not been resolved yet. The development of tolerance (or habituation) associated with the need to increase stimulation amplitudes for the long-term suppression of tremor in some patients as well as the progression of pre-existing gait and speech abnormalities in ET and dystonic tremor patients appear to play a role [52–65].

In several studies it was found that average depression scores among STN-stimulated PD patients were improved compared to the preoperative state [66–70]. However, preoperative depression may temporarily be aggravated by the reduction of dopaminergic medication in the postoperative phase and depression may improve again after long-term adjustments of stimulation and medication have been made. This explains the fact that the reported rates of depression in monitored clinical trials covering the postoperative phase may be relatively high (up to 77%; Table 1). In the present study, for STN-stimulated PD patients the risk of non
reversible (or reversibility unknown) depression that was at least possibly related to DBS was 6.4%.

Immediate cognitive deficits after DBS procedures may be observed and the risk appears to be increased in PD patients already exhibiting cognitive impairments at baseline [71, 72]. Usually postoperative decline is worst in the first months following STN surgery and may improve in the ensuing months [73, 74]. Our data indicate that even with unsuspicious cognitive testings prior to STN surgery about 4% of patients may be affected by non reversible cognitive decline that was rated at least possibly related to DBS. It is unclear to what extent surgery or anesthesia as opposed to high-frequency stimulation of the STN contribute to cognitive decline [14, 73]. On the other hand, also improvements of cognitive aspects under STN stimulation have been observed [69, 75–77]. Cognitive impairments that have rather consistently been attributed to STN surgery and STN stimulation are disturbances of verbal fluency, memory and executive functioning [14, 28, 67, 69, 70, 73, 78–84], and also in our patients affected by cognitive deficits these represented the most common items.

Rather surprising was the frequency of postoperative (worsening of preexisting) urinary incontinence under STN stimulation occurring within the first 6 months following surgery. There may be underreporting of this AE in previous reports. Other patients, however, may also experience improved bladder control [85–87]. All our patients exhibiting postoperative urinary incontinence (2 female, 2 male) had peripherally received transurethral indwelling catheters involving uncomplicated catheterization. In all patients complaints or signs of urinary incontinence were already present prior to initiation of high-frequency stimulation of the STN. This is suggestive of microlesioning effects or residual effects of anesthesia.

Overall approximately 25% of the PD patients experienced non-reversible (or unknown reversibility) AEs that were at least possibly related to STN stimulation in the form of impaired speech or gait, depression, weight gain, cognitive disturbances or urinary incontinence. This number appears relatively high but seems to be in accordance with the clinical experience that approximately 1 in 4 STN-stimulated PD patients requires increased attention to one or several of these problems. However, one has to take into consideration that in the majority of cases those AEs were mild, most conditions were preexisting (e.g. impaired speech or gait, depression), and the overall quality of life in these patients may still be improved by DBS, and most patients would choose to undergo STN surgery again (different questionnaires about quality of life and satisfaction with therapy; CKEM, AG et al., unpublished data).

Strengths and limitations of the study

We investigated a non preselected (‘real world’) patient cohort involving the most common diseases treated by DBS in the most common surgical targets. Thus, this study is not charged with the unavoidable selection bias of prospective studies recruiting patients according to defined inclusion criteria. Our cohort is likely to represent patient populations similar to those of many DBS centers. All AEs were formally rated and presented in a transparent and relatable manner that, to the best of our knowledge, has not been performed for DBS patients to date.

The evaluation of AEs occurring under ongoing DBS therapy was facilitated by the fact that all AEs related to surgery were reversible. Only 2 patients showed transient neurological deterioration due to small intracerebral hemorrhages. In addition, none of the implanted electrodes had to be revised because of misplacement, lack of efficacy or intolerable side effects. Thus, almost all neurological and psychiatric AEs that were rated at least possibly related to DBS therapy can be attributed to ongoing stimulation performed in a standard manner as opposed to directly caused by the surgery itself (except for microlesioning effects that cannot be ruled out). In other words, a higher incidence of surgery- or lead-related complications with
neurological and psychiatric sequelae would have increased the actual rate of AEs and made it more difficult to determine to what extent these are related to DBS therapy or complications of surgery itself (e.g. suboptimal lead placement). AE rates in the present study are rather representative for uncomplicated postoperative courses.

Limitations of our study are its retrospective design and lack of a non-treated control group. Although the frequency of neurological and psychiatric AEs in the present series was higher than in several other—even monitored—studies (Table 1), an underreporting of, for example, sleep disturbances, pain, and obstipation in PD patients may be present in our series. The numerous factors responsible for variable reporting of AEs have been addressed in detail in the introduction, and it would be presumptuous to assume the present study was completely unaffected by those factors.

In the present study AEs were first collected in broader terms (e.g., speech or gait) and specified later in order to prevent diluted rates and to generate meaningful numbers that can be used for comparison, patient counseling and informed consent. Patient follow-up was comparably long (cf. Table 1). The longer the follow-up period the higher is the proportion of AEs that are not related to DBS therapy (e.g. disease progression and comorbidities) and the more important it is to properly assess the relatedness to DBS.

Conclusion

Taken together, the present study provides a detailed and relatable analysis of AEs occurring in patients undergoing DBS surgery and long-term therapy. The assessment of neurological and psychiatric AEs, representing the most frequently recorded AEs, is limited by patient- and physician-related factors and also by the fact that there are no standardized procedures for the collection, evaluation and presentation of such data. This results in highly variable rates in the literature. AEs should be collected in rather broad terms and rated with regard to severity, reversibility and relatedness to DBS therapy as performed in the present study. It should be mandatory for clinical DBS studies to present actual details about critical AEs comprising those that are rated as severe or worse and at least possibly related to DBS in a comprehensive and relatable manner. In particular for axial symptoms in STN-stimulated PD patients the rating of relatedness and potential reversibility of AEs is equivocal. This is mainly due to gaps in knowledge (1) about the kinetics with which different AEs develop under DBS and (2) about the kinetics of the progression of different symptoms of the underlying (neurodegenerative) disease in a given patient. All serious adverse events (SAEs) that occurred within 4 weeks of surgery were reversible. DBS-related AEs that were severe or worse and non-reversible were only observed in PD affecting 4 of 82 patients (4.9%). PD patients exhibited a significant risk for non-severe AEs. Most of these were axial and non-motor symptoms that slightly preexist in all PD patients and also represent the most relevant long-term problems. Age and Hoehn&Yahr stage of STN-simulated PD patients, but not preoperative motor impairment or response to levodopa, showed a weak correlation (r = 0.24 and 0.22, respectively) with the number of AEs. Mild gait and/or speech disturbances were rather frequent complaints under VIM stimulation. GPI stimulation for dystonia could be applied with negligible DBS-related side effects.

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References

1. Deuschl G, Schade-Brittinger C, Krack P, Volkmann J, Schafer H, Botzel K, et al. A randomized trial of deep-brain stimulation for Parkinson’s disease. N Engl J Med. 2006; 355(9):896–908. https://doi.org/10.1056/NEJMoa060281 PMID: 16943402.

2. Weaver FM, Follett K, Stern M, Hur K, Harris C, Marks WJ Jr., et al. Bilateral deep brain stimulation vs best medical therapy for patients with advanced Parkinson disease: a randomized controlled trial. Jama. 2009; 301(1):63–73. https://doi.org/10.1001/jama.2008.929 PMID: 19126811;

3. Williams A, Gill S, Varma T, Jenkins C, Quinn N, Mitchell R, et al. Deep brain stimulation plus best medical therapy versus best medical therapy alone for advanced Parkinson’s disease (PD SURG trial): a randomised, open-label trial. Lancet Neurol. 2010; 9(6):581–91. https://doi.org/10.1016/S1474-4422(10)70093-4 PMID: 20434403;

4. Rehncrona S, Johne S, Widner H, Tornqvist AL, Hariz M, Sydow O. Long-term efficacy of thalamic deep brain stimulation for tremor: double-blind assessments. Mov Disord. 2003; 18(2):163–70. https://doi.org/10.1020/mds.10309 PMID: 12539209.

5. Schuurman PR, Bosch DA, Bossuyt PM, Bonsel GJ, van Someren EJ, de Bie RM, et al. A comparison of continuous thalamic stimulation and thalamotomy for suppression of severe tremor. N Engl J Med. 2000; 342(7):461–8. https://doi.org/10.1056/NEJM200002173420703 PMID: 10675426.

6. Volkman J, Wolters A, Kupsch A, Muller J, Kuhn AA, Schneider GH, et al. Pallidal deep brain stimulation in patients with primary generalised or segmental dystonia: 5-year follow-up of a randomised trial. Lancet Neurol. 2012; 11(12):1029–38. https://doi.org/10.1016/S1474-4422(12)70257-0 PMID: 23129071.

7. Mueller J, Skogseid IM, Benecke R, Kupsch A, Trottenberg T, Poewe W, et al. Pallidal deep brain stimulation improves quality of life in segmental and generalized dystonia: results from a prospective, randomized sham-controlled trial. Mov Disord. 2008; 23(1):131–4. https://doi.org/10.1002/mds.21783 PMID: 17973330.

8. Timmermann L, Jain R, Chen L, Maarouf M, Barbe MT, Allert N, et al. Multiple-source current steering in subthalamical nucleus deep brain stimulation for Parkinson’s disease (the VANTAGE study): a non-randomised, prospective, multicentre, open-label study. Lancet Neurol. 2015; 14(7):693–701. https://doi.org/10.1016/S1474-4422(15)00087-3 PMID: 26027940.

9. Volkman J, Mueller J, Deuschl G, Kuhn AA, Krauss JK, Poewe W, et al. Pallidal neurostimulation in patients with medication-refractory cervical dystonia: a randomised, sham-controlled trial. Lancet Neurol. 2014; 13(9):875–84. https://doi.org/10.1016/S1474-4422(14)70143-7 PMID: 25127231.
10. Schuepbach WM, Rau J, Knudsen K, Volkmann J, Krack P, Timmermann L, et al. Neurostimulation for Parkinson's disease with early motor complications. N Engl J Med. 2013; 368(7):610–22. https://doi.org/10.1056/NEJMoa1205158 PMID: 23406206.

11. Odekerken VJ, van Laar T, Staal MJ, Mosch A, Hoffmann CF, Nijsen PC, et al. Subthalamic nucleus versus globus pallidus bilateral deep brain stimulation for advanced Parkinson's disease (NSTAPS study): a randomised controlled trial. Lancet Neurol. 2013; 12(1):37–44. https://doi.org/10.1016/S1474-4422(12)70264-8 PMID: 23168021.

12. Okun MS, Gallo BV, Mandybur G, Jagid J, Foote KD, Revilla FJ, et al. Subthalamic deep brain stimulation with a constant-current device in Parkinson's disease: an open-label randomised controlled trial. Lancet Neurol. 2012; 11(2):140–9. https://doi.org/10.1016/S1474-4422(11)70308-8 PMID: 22239915.

13. Follett KA, Weaver FM, Stern M, Hur K, Harris CL, Luo P, et al. Pallidal versus subthalamic deep-brain stimulation for Parkinson's disease. N Engl J Med. 2010; 362(22):2077–91. https://doi.org/10.1056/NEJMoa0907083 PMID: 20519680.

14. Okun MS, Fernandez HH, Wu SS, Kirsch-Darrow L, Bowers D, Bova F, et al. Cognition and mood in Parkinson's disease in subthalamic nucleus versus globus pallidus interna deep brain stimulation: the COMPARE trial. Ann Neurol. 2009; 65(5):586–95. https://doi.org/10.1002/ana.21596 PMID: 19288499.

15. Vidalhêt M, Vercueil L, Houeto JL, Krystkowiak P, Lagrange C, Yelnik J, et al. Bilateral, pallidal, deep-brain stimulation in primary generalised dystonia: a prospective 3 year follow-up study. Lancet Neurol. 2007; 6(3):223–9. https://doi.org/10.1016/S1474-4422(07)70035-2 PMID: 17935298.

16. Kupsch A, Benecke R, Muller J, Trottenberg T, Schneider GH, Poewe W, et al. Pallidal deep-brain stimulation in primary generalised or segmental dystonia. N Engl J Med. 2006; 355(19):1978–90. https://doi.org/10.1056/NEJMoa063618 PMID: 17093249.

17. Vesper J, Chabardes S, Fraix V, Sunde N, Ostergaard K, Kineta Study G. Dual channel deep brain stimulation system (Kineta) for Parkinson's disease and essential tremor: a prospective multicentre open label clinical study. J Neurol Neurosurg Psychiatry. 2002; 73(3):275–80. https://doi.org/10.1136/jnnp.73.3.275 PMID: 12185158.

18. Deep-Brain Stimulation for Parkinson's Disease Study G. Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease. N Engl J Med. 2001; 345(13):956–63. https://doi.org/10.1056/NEJMoa000827 PMID: 11575287.

19. Hariz MI, Rehncrona S, Quinn NP, Speelman JD, Wensing C, Mulder C. Multicenter Advanced Parkinson's Disease Deep Brain Stimulation G. Multicenter study on deep brain stimulation in Parkinson's disease: an independent assessment of reported adverse events at 4 years. Mov Disord. 2008; 23(3):416–21. https://doi.org/10.1002/mds.21888 PMID: 18067188.

20. Krack P, Batir A, Van Blercom N, Chabardes S, Fraix V, Ardouin C, et al. Five-year follow-up of bilateral stimulation of the subthalamic nucleus in advanced Parkinson's disease. N Engl J Med. 2003; 349(20):1925–34. https://doi.org/10.1056/NEJMoa035275 PMID: 14614167.

21. Moll CK, Payer S, Gulberti A, Sharrott A, Zittel S, Boelmans K, et al. STN stimulation in general anaesthesia: evidence beyond ‘evidence-based medicine’. Acta Neurochir Suppl. 2013; 117:19–25. https://doi.org/10.1007/978-3-7091-1482-7_4 PMID: 23652652.

22. Voon V, Krack P, Lang AE, Lozano AM, Dujardin K, Schupbach M, et al. A multicentre study on suicide outcomes following subthalamic stimulation for Parkinson's disease. Brain. 2008; 131(Pt 2):1925–34. https://doi.org/10.1093/brain/awn214 PMID: 18941146.

23. Weintraub D, Duda JE, Carlson K, Luo P, Sagher O, Stern M, et al. Suicide ideation and behaviours after STN and GPi DBS surgery for Parkinson’s disease: results from a randomised, controlled trial. J Neurol Neurosurg Psychiatry. 2013; 84(10):1113–8. https://doi.org/10.1136/jnnp-2012-304396 PMID: 23667214.

24. Hariz GM, Lindberg M, Bergenheim AT. Impact of thalamic deep brain stimulation on disability and health-related quality of life in patients with essential tremor. J Neurol Neurosurg Psychiatry. 2002; 72(1):47–52. https://doi.org/10.1136/jnnp.72.1.47 PMID: 11784825.

25. Schupbach WM, Chastan N, Welter ML, Houeto JL, Mesnage V, Bonnet AM, et al. Stimulation of the subthalamic nucleus in Parkinson's disease: a 5 year follow-up. J Neurol Neurosurg Psychiatry. 2005; 76(12):1640–4. https://doi.org/10.1136/jnnp.2005.063206 PMID: 16291886.

26. Schuurman PR, Bosch DA, Merkus MP, Speelman JD. Long-term follow-up of thalamic stimulation versus thalamotomy for tremor suppression. Mov Disord. 2008; 23(8):1146–53. https://doi.org/10.1002/mds.22059 PMID: 18442104.

27. Gervais-Bernard H, Xie-Brustolin J, Mertens P, Polo G, Klinger H, Adamec D, et al. Bilateral subthalamic nucleus stimulation in advanced Parkinson’s disease: five year follow-up. J Neurol. 2009; 256(2):225–33. https://doi.org/10.1007/s00415-009-0076-2 PMID: 19242649.
28. Fasano A, Romito LM, Daniele A, Piano C, Zinno M, Bentivoglio AR, et al. Motor and cognitive outcome in patients with Parkinson's disease 8 years after subthalamic implants. Brain. 2010; 133(9):2664–76. https://doi.org/10.1093/brain/awq221 PMID: 20802207.

29. St George RJ, Carlson-Kuhta P, Burchiel KJ, Hogarth P, Frank N, Horak FB. The effects of subthalamic and pallidal deep brain stimulation on postural responses in patients with Parkinson disease. J Neurosurg. 2012; 116(6):1347–56. https://doi.org/10.3171/2012.2.JNS11847 PMID: 22424564;

30. Rousseaux M, Krystkowiak P, Kozlowski O, Oszasncak C, Blond S, Desteel A. Effects of subthalamic nucleus stimulation on parkinsonian dysarthria and speech intelligibility. J Neurol. 2004; 251(3):327–34. https://doi.org/10.1007/s00415-004-0327-1 PMID: 15015014.

31. Pinto S, Gentil M, Krack P, Sauleau P, Fraix V, Benabid AL, et al. Changes induced by levodopa and subthalamic nucleus stimulation on parkinsonian speech. Mov Disord. 2005; 20(11):1507–15. https://doi.org/10.1002/mds.20601 PMID: 16037917.

32. Hammer MJ, Barlow SM, Lyons KE, Pahwa R. Subthalamic nucleus deep brain stimulation changes speech respiratory and laryngeal control in Parkinson's disease. J Neurol. 2010; 257(10):1692–702. https://doi.org/10.1007/s10072-010-1569-x PMID: 20582431;

33. Frost E, Tripoliti E, Hariz MI, Pring T, Limousin P. Self-perception of speech changes in patients with Parkinson's disease following deep brain stimulation of the subthalamic nucleus. Int J Speech Lang Pathol. 2010; 12(5):399–404. https://doi.org/10.3109/17549507.2010.497560 PMID: 20602580.

34. Tripoliti E, Zrinzo L, Martinez-Torres I, Frost E, Pinto S, Foltynie T, et al. Effects of subthalamic stimulation on speech of consecutive patients with Parkinson disease. Neurology. 2011; 76(1):80–6. https://doi.org/10.1212/WNL.0b013e318203e7d0 PMID: 21068426;

35. Schulz GM, Hosey LA, Bradberry TJ, Stager SV, Lee LC, Pawha R, et al. Selective left, right and bilateral stimulation of subthalamic nuclei in Parkinson's disease: differential effects on motor, speech and language function. J Parkinsons Dis. 2012; 2(1):29–40. https://doi.org/10.3233/JPD-2011049 PMID: 23939406.

36. Skodda S, Gronheit W, Schiegel U, Sudmeyer M, Schnitzler A, Wojtceck I. Effect of subthalamic stimulation on voice and speech in Parkinson's disease: for the better or worse? Frontiers in neurology. 2014; 4:218. https://doi.org/10.3389/fneur.2013.00218 PMID: 24453405;

37. Tripoliti E, Limousin P, Foltynie T, Candelario J, Aviles-Olmos I, Hariz MI, et al. Predictive factors of speech intelligibility following subthalamic nucleus stimulation in consecutive patients with Parkinson's disease. Mov Disord. 2014; 29(4):532–8. https://doi.org/10.1002/mds.25816 PMID: 24532491.

38. Wertheimer J, Gottuso AY, Nuno M, Walton C, Dubois A, Tuchman M, et al. The impact of STN deep brain stimulation on speech in individuals with Parkinson's disease: the patient's perspective. Parkinsonism Relat Disord. 2014; 20(10):1065–70. https://doi.org/10.1016/j.parkreldis.2014.06.010 PMID: 25048615.

39. Tsuboi T, Watanabe H, Tanaka Y, Ohdake R, Yoneyama N, Hara K, et al. Distinct phenotypes of speech and voice disorders in Parkinson's disease after subthalamic nucleus deep brain stimulation. J Neurol Neurosurg Psychiatry. 2015; 86(8):856–64. https://doi.org/10.1136/jnnp-2014-308043 PMID: 25280914.

40. Faist M, Xie J, Kurz D, Berger W, Maurer C, Pollak P, et al. Effect of bilateral subthalamic nucleus stimulation on gait in Parkinson's disease. Brain. 2001; 124(PT 8):1590–600. PMID: 11459750.

41. Stolze H, Klebe S, Poepping M, Lorenz D, Herzog J, Hamel W, et al. Effects of bilateral subthalamic nucleus stimulation on parkinsonian gait. Neurology. 2001; 57(1):144–6. PMID: 11445647.

42. Xie J, Krack P, Benabid AL, Pollak P. Effect of bilateral subthalamic nucleus stimulation on parkinsonian gait. J Neurol. 2001; 248(12):1068–72. PMID: 12013584.

43. Krystkowiak P, Blatt JL, Bourriez JL, Duhamel A, Perina M, Blond S, et al. Effects of subthalamic nucleus stimulation and levodopa treatment on gait abnormalities in Parkinson disease. Arch Neurol. 2003; 60(1):80–4. PMID: 12533092.

44. Ferraye MU, Debuc B, Fraix V, Xie-Brustolin J, Chabardes S, Krack P, et al. Effects of subthalamic nucleus stimulation and levodopa on freezing of gait in Parkinson disease. Neurology. 2008; 70(16 Pt 2):1431–7. https://doi.org/10.1212/01.wnl.0000310416.90757.85 PMID: 18413568.

45. McNeely ME, Earhart GM. Medication and subthalamic nucleus deep brain stimulation similarly improve balance and complex gait in Parkinson disease. Parkinsonism Relat Disord. 2013; 19(1):86–91. https://doi.org/10.1016/j.parkreldis.2012.07.013 PMID: 22885253;

46. Vercruysse S, Vandenberghue W, Munks L, Nuttin B, Devos H, Nieuwoerdt A. Effects of deep brain stimulation of the subthalamic nucleus on freezing of gait in Parkinson's disease: a prospective controlled study. J Neurol Neurosurg Psychiatry. 2014; 85(8):871–7. https://doi.org/10.1136/jnnp-2013-306336 PMID: 24396010.
47. Maurer C, Mergner T, Xie J, Faist M, Pollak P, Lucking CH. Effect of chronic bilateral subthalamic nucleus (STN) stimulation on postural control in Parkinson’s disease. Brain. 2003; 126(Pt 5):1146–63. PMID: 12690054.

48. Guehl D, Dehail P, de Seze MP, Cuny E, Faux P, Tison F, et al. Evolution of postural stability after subthalamic nucleus stimulation in Parkinson’s disease: a combined clinical and posturometric study. Exp Brain Res. 2006; 170(2):206–15. https://doi.org/10.1007/s00221-005-0202-z PMID: 16328820.

49. van Nuenen BF, Esselink RA, Munneke M, Speelman JD, van Laar T, Bloem BR. Postoperative gait deterioration after bilateral subthalamic nucleus stimulation in Parkinson’s disease. Mov Disord. 2008; 23(16):2404–6. https://doi.org/10.1002/mds.21986 PMID: 18951532.

50. Blomstedt P, Hariz MI. Are complications less common in deep brain stimulation than in ablative procedures for movement disorders? Stereotact Funct Neurosurg. 2006; 84(2–3):72–81. https://doi.org/10.1159/000094035 PMID: 16790989.

51. Hariz MI, Shamsgovara P, Johansson F, Hariz G, Fodstad H. Tolerance and tremor rebound following long-term chronic thalamic stimulation for Parkinsonian and essential tremor. Stereotact Funct Neurosurg. 1999; 72(2–4):208–18. PMID: 10853080.

52. Stolze H, Petersen G, Raethjen J, Wenzelburger R, Deuschl G. The gait disorder of advanced essential tremor. Brain. 2001; 124(11):2278–86. PMID: 11673328.

53. Sydow O, Thobois S, Alesch F, Speelman JD. Multicentre European study of thalamic stimulation in essential tremor: a six year follow up. J Neurol Neurosurg Psychiatry. 2003; 74(10):1387–91. https://doi.org/10.1136/jnnp.74.10.1387 PMID: 14570831.

54. Kumar R, Lozano AM, Sime E, Lang AE. Long-term follow-up of thalamic deep brain stimulation for essential and parkinsonian tremor. Neurology. 2003; 61(1):1601–4. PMID: 14663050.

55. Pappavassiliou E, Rau G, Heath S, Aboch A, Barbaro NM, Larson PS, et al. Thalamic deep brain stimulation for essential tremor: relation of lead location to outcome. Neurosurgery. 2004; 54(5):1120–6. https://doi.org/10.3171/2008.10.JNS08330 PMID: 15113466.

56. Putzke JD, Whaley NR, Baba Y, Wszolek ZK, Ultitz RJ. Essential tremor: predictors of disease progression in a clinical cohort. J Neurol Neurosurg Psychiatry. 2006; 77(11):1235–7. https://doi.org/10.1136/jnnp.2006.086579 PMID: 17043291.

57. Blomstedt P, Hariz GM, Hariz MI, Koskinen LO. Thalamic deep brain stimulation in the treatment of essential tremor: a long-term follow-up. Br J Neurosurg. 2007; 21(5):504–9. https://doi.org/10.1080/02686690701552278 PMID: 17922323.

58. Illitissi JG, Metman LV, Toleikis JR, Hughes LE, Sani SB, Bakay RA. Factors involved in long-term efficacy of deep brain stimulation of the thalamus for essential tremor. J Neurosurgery. 2008; 109(4):640–6. https://doi.org/10.1002/jns.22557 PMID: 19526587.

59. Kronenbueger M, Konczak J, Ziegler W, Buderath P, Frank B, Coenen VA, et al. Balance and motor speech impairment in essential tremor. Cerebellum. 2009; 8(3):389–98. https://doi.org/10.1007/s12311-009-0111-y PMID: 19452239.

60. Zhang K, Bhatia S, Oh MY, Cohen D, Angel C, Whiting D. Long-term results of thalamic deep brain stimulation for essential tremor: disease progression versus tolerance. Brain. 2012; 135(5):1455–62. https://doi.org/10.1093/brain/aws026 PMID: 22344584.

61. Shi LC, LaFever K, Lim C, Pappavassiliou E, Tarsy D. Loss of benefit in VIM thalamic deep brain stimulation (DBS) for essential tremor (ET): how prevalent is it? Parkinsonism Relat Disord. 2013; 19(7):676–9. https://doi.org/10.1016/j.parkreldis.2013.03.006 PMID: 23582712.

62. Louis ED, Hernandez N, Ionita-Laza I, Ottman R, Clark LN. Does rate of progression run in essential tremor families? Slower vs. faster progressors. Parkinsonism Relat Disord. 2013; 19(3):363–6. https://doi.org/10.1016/j.parkreldis.2012.10.005 PMID: 23121728.

63. Funkiewiez A, Ardouin C, Crack P, Fraix V, Van Blencom N, Xie J, et al. Acute psychotrophic effects of bilateral subthalamic nucleus stimulation and levodopa in Parkinson’s disease. Mov Disord. 2003; 18(5):524–30. https://doi.org/10.1002/mds.10441 PMID: 12722166.
67. Funkiewiez A, Ardouin C, Caputo E, Krack P, Fraix V, Klinger H, et al. Long-term effects of bilateral subthalamic nucleus stimulation on cognitive function, mood, and behaviour in Parkinson's disease. J Neurol Neurosurg Psychiatry. 2004; 75(6):834–9. https://doi.org/10.1136/jnp.2002.009803 PMID: 15145995.

68. Witt K, Daniels C, Herzog J, Lorenz D, Volkmann J, Reiff J, et al. Differential effects of L-dopa and subthalamic stimulation on depressive symptoms and hedonic tone in Parkinson's disease. J Neuropsychiatry Clin Neurosci. 2006; 18(3):397–401. https://doi.org/10.1176/npn.2006.18.3.397 PMID: 16963590.

69. Castelli L, Perozzo P, Zibetti M, Crivelli B, Morabito U, Lanotte M, et al. Chronic deep brain stimulation of the subthalamic nucleus for Parkinson's disease: effects on cognition, mood, anxiety and personality traits. Eur Neurol. 2006; 55(3):136–44. https://doi.org/10.1159/000093213 PMID: 16682797.

70. Combs HL, Folley BS, Berry DT, Segerstrom SC, Han DY, Anders on-Mooney AJ, et al. Cognition and long-term cognitive outcome of bilateral subthalamic deep brain stimulation of the Subthalamic Nucleus and Globus Pallidus Pars Interna in Parkinson’s Disease: A Meta-Analysis. Neuropsychol Rev. 2015; 25(4):439–54. https://doi.org/10.1007/s11065-015-9302-0 PMID: 26459361.

71. Kim HJ, Jeon BS, Yun JY, Kim YE, Yang HJ, Paek SH. Initial cognitive dip after subthalamic deep brain stimulation in Parkinson’s disease. J Neurol. 2014; 261(6):1090–6. https://doi.org/10.1007/s00415-014-7321-z PMID: 24687897.

72. Merola A, Rizzi L, Artusi CA, Zibetti M, Rizzone MG, Romagnolo A, et al. Subthalamic deep brain stimulation: clinical and neuropsychological outcomes in mild cognitive impaired parkinsonian patients. J Neurol. 2014; 261(9):1745–51. https://doi.org/10.1007/s00415-014-7414-8 PMID: 24952619.

73. Daniele A, Albanese A, Contarino MF, Zinzzi P, Barbier A, Gasparini F, et al. Cognitive and behavioural effects of chronic stimulation of the subthalamic nucleus in patients with Parkinson’s disease. J Neurol Neurosurg Psychiatry. 2003; 74(2):175–82. https://doi.org/10.1136/jnnp.74.2.175 PMID: 12531943.

74. Kim HJ, Jeon BS, Yun JY, Kim YE, Yang HJ, Paek SH. Initial cognitive dip after subthalamic deep brain stimulation in Parkinson disease. J Neurol 2013; 260(8):2130–3. https://doi.org/10.1007/s00415-013-6959-2 PMID: 23681647.

75. Funkiewiez A, Ardouin C, Cools R, Krack P, Fraix V, Batir A, et al. Effects of levodopa and subthalamic nucleus stimulation on cognitive and affective functioning in Parkinson’s disease. Mov Disord. 2006; 21(10):1656–62. https://doi.org/10.1002/mds.21029 PMID: 16930317.

76. Witt K, Pulkowski U, Herzog J, Lorenz D, Hamel W, Deuschl G, et al. Deep brain stimulation of the subthalamic nucleus improves cognitive flexibility but impairs response inhibition in Parkinson disease. Arch Neurol. 2004; 61(5):697–700. https://doi.org/10.1001/archneur.61.5.697 PMID: 15148146.

77. Contarino MF, Daniele A, Sibilia AH, Romito LM, Bentivoglio AR, Gainotti G, et al. Cognitive outcome 5 years after bilateral chronic stimulation of subthalamic nucleus in patients with Parkinson’s disease. J Neurol Neurosurg Psychiatry. 2007; 78(3):448–52. https://doi.org/10.1136/jnnp.2005.068660 PMID: 16690696.

78. Dujardin K, Defebvre L, Krystkowiak P, Blond S, Destee A. Influence of chronic bilateral stimulation of the subthalamic nucleus on cognitive function in Parkinson’s disease. J Neurol. 2001; 248(7):603–11. PMID: 11518003.

79. Alegret M, Junque C, Valdeorrosa F, Vendrell P, Pillier M, Rumia J, et al. Effects of bilateral subthalamic nucleus stimulation on cognitive function in Parkinson disease. Arch Neurol. 2001; 58(8):1223–7. PMID: 11493162.

80. Gironell A, Kulisevsky J, Remi L, Fortuny N, Garcia-Sanchez C, Pascual-Sedano B. Effects of pallidotomy and bilateral subthalamic stimulation on cognitive function in Parkinson disease. A controlled comparative study. J Neurol. 2003; 250(8):917–23. https://doi.org/10.1007/s00415-003-1109-x PMID: 12928909.

81. Parsons TD, Rogers SA, Braaten AJ, Woods SP, Troster AI. Cognitive sequelae of subthalamic nucleus deep brain stimulation in Parkinson’s disease: a meta-analysis. Lancet Neurol. 2006; 5(7):578–88. https://doi.org/10.1016/S1474-4422(06)70475-6 PMID: 16781988.

82. York MK, Duly M, Macias A, Levin HS, Grossman R, Simpson R, et al. Cognitive declines following bilateral subthalamic nucleus deep brain stimulation for the treatment of Parkinson’s disease. J Neurol Neurosurg Psychiatry. 2008; 79(7):789–95. https://doi.org/10.1136/jnnp.2007.118786 PMID: 17965146.

83. Saez-Zea C, Escamilla-Sevilla F, Katami MJ, Minguez-Castellanos A. Cognitive effects of subthalamic nucleus stimulation in Parkinson’s disease: a controlled study. Eur Neurol. 2012; 68(6):361–6. https://doi.org/10.1159/000341380 PMID: 23095782.

84. Yaguez L, Costello A, Moriarty J, Hulse N, Selway R, Clough C, et al. Cognitive predictors of cognitive change following bilateral subthalamic nucleus deep brain stimulation in Parkinson’s disease. J Clin Neurosci. 2014; 21(3):445–50. https://doi.org/10.1016/j.jocn.2013.06.005 PMID: 24231557.
85. Herzog J, Weiss PH, Assmus A, Wefer B, Seif C, Braun PM, et al. Subthalamic stimulation modulates cortical control of urinary bladder in Parkinson’s disease. Brain. 2006; 129(Pt 12):3366–75. https://doi.org/10.1093/brain/awl302 PMID: 17077105.

86. Winge K, Nielsen KK, Stimpel H, Lokkegaard A, Jensen SR, Werdelin L. Lower urinary tract symptoms and bladder control in advanced Parkinson’s disease: effects of deep brain stimulation in the subthalamic nucleus. Mov Disord. 2007; 22(2):220–5. https://doi.org/10.1002/mds.21253 PMID: 17133504.

87. Herzog J, Weiss PH, Assmus A, Wefer B, Seif C, Braun PM, et al. Improved sensory gating of urinary bladder afferents in Parkinson’s disease following subthalamic stimulation. Brain. 2008; 131(Pt 1):132–45. https://doi.org/10.1093/brain/awm254 PMID: 17977862.