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CLINICAL ARTICLE

Accuracy, precision, and safety of stereotactic, frame-based, intraoperative MRI-guided and MRI-verified deep brain stimulation in 650 consecutive procedures

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OBJECTIVE Suboptimal lead placement is one of the most common indications for deep brain stimulation (DBS) revision procedures. Confirming lead placement in relation to the visible anatomical target with dedicated stereotactic imaging before terminating the procedure can mitigate this risk. In this study, the authors examined the accuracy, precision, and safety of intraoperative MRI (iMRI) to both guide and verify lead placement during frame-based stereotactic surgery.

METHODS A retrospective analysis of 650 consecutive DBS procedures for targeting accuracy, precision, and perioperative complications was performed. Frame-based lead placement took place in an operating room equipped with an MRI machine using stereotactic images to verify lead placement before removing the stereotactic frame. Immediate lead relocation was performed when necessary. Systematic analysis of the targeting error was calculated.

RESULTS Verification of 1201 DBS leads with stereotactic MRI was performed in 643 procedures and with stereotactic CT in 7. The mean ± SD of the final targeting error was 0.9 ± 0.3 mm (range 0.1–2.3 mm). Anatomically acceptable lead placement was achieved with a single brain pass for 97% (n = 1164) of leads; immediate intraoperative relocation was performed in 37 leads (3%) to obtain satisfactory anatomical placement. General anesthesia was used in 91% (n = 593) of the procedures. Hemorrhage was noted after 4 procedures (0.6%); 3 patients (0.4% of procedures) presented with transient neurological symptoms, and 1 experienced delayed cognitive decline. Two bleeds coincided with immediate relocation (2 of 37 leads, 5.4%), which contrasts with hemorrhage in 2 (0.2%) of 1164 leads implanted on the first pass ($p = 0.0058$). Three patients had transient seizures in the postoperative period. The seizures coincided with hemorrhage in 2 of these patients and with immediate lead relocation in the other. There were 21 infections (3.2% of procedures, 1.5% in 3 months) leading to hardware removal. Delayed (> 3 months) retargeting of 6 leads (0.5%) in 4 patients (0.6% of procedures) was performed because of suboptimal stimulation benefit. There were no MRI-related complications, no permanent motor deficits, and no deaths.

CONCLUSIONS To the authors' knowledge, this is the largest series reporting the use of iMRI to guide and verify lead location during DBS surgery. It demonstrates a high level of accuracy, precision, and safety. Significantly higher hemorrhage was encountered when multiple brain passes were required for lead implantation, although none led to permanent deficit. Meticulous audit and calibration can improve precision and maximize safety.

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KEYWORDS stereotactic accuracy and precision; intraoperative MRI-guided and MRI-verified deep brain stimulation; functional neurosurgery

ABBREVIATIONS DBS = deep brain stimulation; GPi = globus pallidus pars interna; iMRI = intraoperative MRI; IPG = implantable pulse generator; MER = microelectrode recording; SAR = specific absorption rate; STN = subthalamic nucleus; VIM = ventral intermediate nucleus.

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MAXIMIZING safety, stereotactic accuracy, and precision is fundamental in functional neurosurgery.[1–4] Reliance on atlas targeting is vulnerable to individual anatomical variation, and most centers now use MRI sequences to visualize the intended anatomical target specific to the patient undergoing surgery. Nevertheless, analysis of 28,370 deep brain stimulation (DBS) procedures recorded in US national databases showed that 15.4% involved revision or removal of cranial DBS leads.[5] Over 48% of DBS revisions are due to suboptimal targeting, making this one of the most common and underreported complications of DBS surgery.[1,6,7]

Although initial target selection relies on imaging methods, clinical and physiological observations using methods such as macrostimulation and microelectrode recording (MER) have been used as surrogate verification techniques to compensate for the earlier lack of imaging techniques.[8–10] Despite good results in expert hands, these verification methods are not without their drawbacks.[11–13]

Surgery under local anesthesia, off medication, is an unpleasant experience for many patients and impossible to tolerate for some. Moreover, MER is associated with a higher risk of hemorrhage and may still be associated with suboptimal lead implantation.[5,11–16] Improvement in MR image quality has enabled a move to image verification.[17–19] Acceptance of this paradigm shift in functional neurosurgery is exemplified by the use of the Gamma Knife to place stereotactic lesions and the adoption of the ClearPoint system when performing "asleep" DBS procedures.[20,21]

However, image-based targeting techniques can be vulnerable to significant inaccuracy secondary to MRI distortion, the introduction of coregistration (or fusion) errors, and brain shift.[22] Therefore, when relying solely on imaging to both guide and verify the surgical procedure, a meticulous approach is warranted to minimize such errors.

Our approach has been to eliminate unnecessary steps where possible and systematically reduce inaccuracy in each step of the stereotactic process while auditing targeting precision. This is achieved by performing stereotactic MRI using dedicated and optimized sequences to maximize visibility of the patient-specific anatomical target and fiducials on the same image, without the need for image coregistration. Stereotactic MRI is also used to verify the coordinates of the implanted DBS lead and assess its final position in relation to the planned stereotactic coordinates as well as the MRI-visible target. Audit of the intended versus actual lead location determines the magnitude and direction of any systematic errors. This can then inform a calibration process during targeting for future procedures, improving first-pass accuracy.[5] This approach is entirely reliant on imaging and can therefore be performed under general anesthesia and without neurophysiological recording or clinical testing, reducing subjective assessments and inherent surgical risk, time, and cost. The availability of a dedicated intraoperative MRI (iMRI) facility, although not essential, can streamline workflow.

Here, we present the accuracy, safety, and precision of using iMRI as a tool to both guide and verify lead location during frame-based DBS surgery in a high-volume center.

Methods

A retrospective review was conducted that analyzed perioperative complications, targeting accuracy, and lead reimplantation of all DBS procedures at our institution for the 8-year period following installation of an iMRI facility prior to the outbreak of the COVID-19 pandemic (Supplementary Fig. 1). This audit was registered with our hospital board. Audits are not subject to ethics approval in the United Kingdom.

Inclusion and Exclusion Criteria

All DBS procedures were included for analysis of perioperative complications, intraoperative lead relocation, and delayed (> 3 months) revision procedures. Stereotactic accuracy analysis was performed for all immediate intraoperative relocations, targeting outliers (defined as more than 2 mm off the intended target), delayed retargeting procedures, all procedures after which postoperative adverse events had occurred, and a large subset of uneventful procedures for which reliable and complete imaging and data were available. Stereotactic ablative procedures were excluded.

Intraoperative Accuracy Verification

All patients underwent intraoperative stereotactic verification of final lead location prior to frame removal, enabling calculation of lead placement error using frame references identical to those used for planning. Postimplantion MRI was performed using a strict in-house safety protocol, limiting specific absorption rate (SAR) parameters to less than 0.4 W/kg.[19] For a smaller subset of procedures (n = 7) with prior implants in situ, low SAR iMRI was employed for planning and stereotactic CT for verification. Accuracy calculation of this subset, although within satisfactory criteria, was not included in the iMRI cohort analysis to ensure consistency of the study method.

Scalar error was calculated by comparing the cartesian coordinates of the intended target with the actual lead location by applying Heron's formula for the therapeutic lead implant,[22] allowing calculation of the shortest distance (h) between the lead and intended target (Supplementary Fig. 2). The vector error was also computed, providing the magnitude of the error in each of the three (x, y, and z) axes.

Image Optimization

The MRI transmitter-receiver head coil was verified daily for image quality, and the MRI machine was recalibrated for distortion errors at 90-day intervals. All patients underwent stereotactic iMRI using sequences optimized to visualize the planned anatomical target. This enabled patient-tailored direct planning to the visible anatomical target, replacing atlas coordinates, and avoiding well-described, but often ignored, coregistration errors.[22]

MRI acquisition was performed on a 1.5T machine (Espree, Siemens), and 3D distortion was corrected using the integrated Siemens algorithm.[23,24] Sequences included T2-weighted turbo spin-echo for the subthalamic nucleus (STN), proton density–weighted turbo spin-echo for the globus pallidus pars interna (GPi), and volumetric

T1-weighted isotropic volume for all procedures (Supplementary Table 1).

Target Selection and Planning

Target coordinates were calculated twice: manually from the 3D distortion-corrected sequence on the MRI console and separately using planning software (FrameLink, Stealth, Medtronic). Differences of more than 1 mm in any axis prompted close scrutiny to reevaluate and resolve planning discrepancy.

Fiducial registration was performed on the MRI slice where both the fiducial markers and anatomical target were visible. Coregistered T1-weighted images were only used to determine a gyral entry point and a trajectory avoiding sulci and ventricles. Adjustments were made to maximize the number of lead contacts within the target volume.[25] Therefore, entry point selection was susceptible to image coregistration error, but this was not the case for target selection.

Target Calibration

The mean vector error in each dimension calculated from a previous audit of 312 DBS implanted electrodes was used to generate a calibration protocol and was applied to all new 1201 targets of this cohort.[1] The Leksell frame (Elekta AB) was set at the calibrated coordinates to improve first-pass targeting accuracy. Targeting errors were regularly reviewed to ensure continued relevance of the calibration protocol.

Surgical Optimization

Each individual step, including frame placement, image acquisition, target planning, coordinate transcription, and stereotactic frame setup, was strictly cross-checked to minimize the risk of human error.

Surgery was performed inside the iMRI suite but outside the bore of the MRI magnet. Surgical factors that could impact targeting accuracy were routinely implemented, including ensuring adequate dural opening to avoid probe deflection while keeping its dimension and duration as small as possible. Tissue sealant (Evicel, Ethicon; or Tisseel, Baxter) was applied immediately after lead implantation to minimize CSF loss, pneumocephalus, and brain shift.

Stereotactic equipment used included the Leksell G frame (four sets) and Leksell Vantage frame (one set) (Elekta AB). Dynamic impedance monitoring was performed with a 1.5-mm-diameter radiofrequency probe (Elekta AB) along the trajectory path. Immediately after withdrawal of the radiofrequency probe, the DBS lead (model 3389 or 3387, Medtronic; or Cartesia, Boston Scientific) was introduced through the frame and brain track without a cannula. A depth-stop placed 190 mm from the center of the distal contact ensured depth control, and the lead was fixed to the skull after removing the stylet (Stimloc, Medtronic; or SureTek, Boston Scientific).

Anesthesia

Lead placement was performed under general anesthesia except for patients undergoing ventral intermediate nucleus (VIM) DBS and those participating in research for which local anesthesia was part of the protocol. Patients underwent lead and neurostimulator implantation either in one stage or as separate stages within 1 week. Patients participating in research studies underwent externalization of the DBS leads to allow for recording of local field potentials.

Target Errors and Intraoperative Relocation

Intraoperative stereotactic imaging to verify lead location was performed for all procedures. Lead placements > 1.5 mm from the intended target were subject to review. If placement was deemed anatomically suboptimal, the lead was immediately relocated via a second corticotomy a few millimeters away from the suboptimal lead and in the direction of the targeting error, ensuring that the second trajectory did not intersect with the first. The suboptimal lead was removed only after the replacement lead was implanted. The final location was then reverified during the same surgical session, prior to removal of the stereotactic frame.[3]

Perioperative Period

Anticoagulant and nonsteroidal anti-inflammatory medications were discontinued 2 weeks prior to and following implantation to minimize the risk of intracranial hemorrhage. Graduated elastic stockings and intermittent calf pneumatic compression devices were prescribed. Patient mobilization was encouraged from the 1st postoperative day. Pharmacological antithrombotic prophylaxis was not prescribed.

All patients routinely underwent preoperative methicillin-resistant *Staphylococcus aureus* and methicillin-susceptible *S. aureus* screening with suppression therapy when necessary (MRSA protocol). A preoperative chlorhexidine shower was advised. All new patients were given one preoperative dose of antibiotic (intravenous cephalosporin group) followed by two postoperative doses at 8-hour intervals. For externalized and revision procedures, vancomycin/saline wash (120 ml of 1 mg/ml) was applied prior to closure.

For procedures performed under general anesthesia, patients with Parkinson's disease did not completely stop their antiparkinsonian medication; however, preoperative reduction in dopamine agonists was implemented to avoid postimplantation dopamine dysregulation syndrome.

DBS screening was started on the 2nd or 3rd postoperative day while adjusting medication, except when the implantation "stun effect" was prominent. A low threshold was adopted for repeat imaging during the postoperative period. Surgical complications were investigated and recorded in our prospective database.

Statistical Analysis

Fisher's exact test was used for statistical analysis when relevant (p value set at 0.01).

Results

Demographics and Mode of Anesthesia

Indications and anatomical targets for 650 consecutive

TABLE 1. Indications for the procedure

Indication	No. of Procedures	%
PD	380	58
Dystonia	116	18
TAC	68	10
Tremor	46	7
GTS	17	3
Dementia*	12	2
OCD	6	1
Other	5	1
Total	650	

GTS = Gilles de la Tourette syndrome; OCD = obsessive compulsive disorder; PD = Parkinson's disease; TAC = trigeminal autonomic cephalalgia.
* Parkinson's disease dementia and Lewy body dementia.

TABLE 2. Anatomical targets for DBS

Target	No. of Leads	%
STN	626	52
PV GPi	322	27
VTA	93	8
VIM	68	6
AM GPi	28	2
NBM	24	2
AM STN	12	1
VC/VS	12	1
PPN	8	<1
Other	8	<1
Total	1201	

AM = anteromedial; NBM = nucleus basalis of Meynert; PPN = pedunculopontine nucleus; PV = posterior ventral; VC/VS = ventral internal capsule/ventral striatum; VTA = ventral tegmental area.

procedures with 1201 implanted DBS leads are presented in Tables 1 and 2. Apart from VIM DBS for tremor (n = 46, 7%), and some procedures included in research protocols (n = 11, 2%), lead placement for the remaining (91% [n = 593]) DBS procedures was performed under general anesthesia.

Targeting Accuracy

We performed a detailed accuracy analysis for all procedures necessitating immediate intraoperative relocations (n = 37), targeting outliers (defined as more than 2 mm off the intended target; n = 2), and delayed retargeted leads (n = 6) and for all procedures with postoperative adverse events (n = 47). Detailed accuracy analysis was performed in a total of 449 leads (252 patients) for whom reliable and complete imaging and data were available at the time of this study. Recruitment of uncomplicated procedures to the detailed accuracy analysis was stopped when it became evident that the addition of further cases did not have an appreciable effect on the overall population statistics.

The mean (± SD) final targeting error was 0.9 ± 0.3 mm (range 0.1–2.3 mm). Intraoperative verified first-pass accuracy was achieved for 1164 (97%) of 1201 leads. Intraoperative stereotactic MRI-verified accuracy was submillimeter in 68% and within 1.5 mm in 92% of analyzed leads (Figs. 1 and 2).

Immediate relocation was performed for 37 leads (3% of leads, 5.7% of procedures), as they had not satisfied intraoperative quality assessment. Eleven of these were ≥ 2

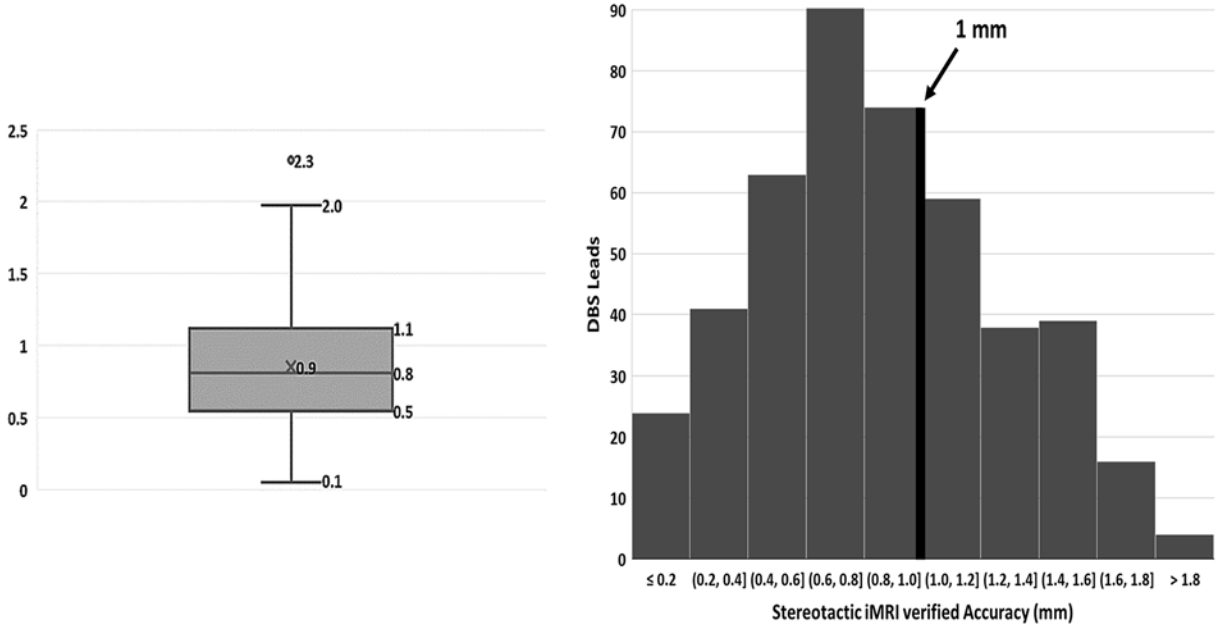

FIG. 1. Left: Box-and-whisker plot showing the median targeting error of final lead placement from the intended target. The mean error, denoted by the *x*, is 0.9 mm. **Right:** Distribution histogram showing final targeting error of analyzed leads (n = 449).

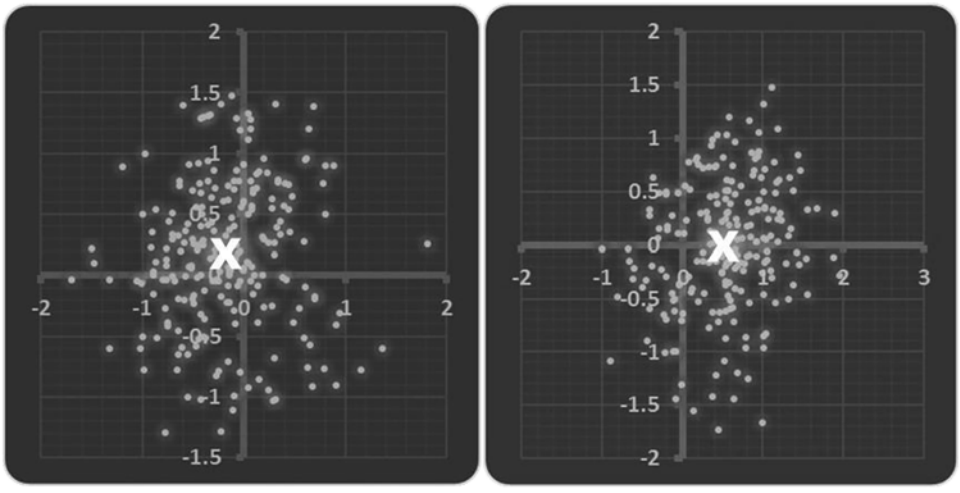

FIG. 2. Scatterplots of axial targeting error in millimeters calculated by comparing the cartesian coordinates of the intended target in the left (**left**) and right (**right**) hemispheres with the actual lead location employing Heron's formula. The *x* marks the average targeting error.

mm off target, and in the remaining (n = 26), the targeting error was > 1.5 but < 2.0 mm. Identifiable causes were lead migration along the track due to a faulty skull fixation mechanism (n = 4), transcription error of the intended coordinate to the frame (n = 1), and loose depth-stop on the lead (n = 1).

Postoperative Adverse Events

Postoperative adverse events are summarized in Table 3.

Hemorrhage Events

Four patients experienced hemorrhage (0.6% of procedures). Three of these patients (0.5% of all procedures) had transient neurological symptoms (transient postoperative confusion in one; temporary memory problems and seizure in another; and transient dysphasia and seizure in the third patient), and 1 (0.2%) had cognitive decline (Fig. 3). The patient with cognitive decline had a small hemorrhage distal to the tip of the right STN DBS lead; at the 1-year follow-up, neuropsychometry findings revealed moderate cognitive impairment, mostly implicating anterior and subcortical regions that were in keeping with progression of PD, and he remains dependent. All hemorrhages were small (< 3 cm^3) and were managed conservatively. Two of the bleeds coincided with immediate relocation (2 of 37 leads, 5.4%). This contrasts with hemorrhage in 2 of 1164 leads implanted on the first pass (0.17%) (p = 0.0058).

Seizure Events

Three patients (0.5%) had postoperative seizures. In 2 of these patients, seizures coincided with radiological hemorrhage, but neither patient developed epilepsy. One of the seizures coincided with second-pass targeting.

Behavioral Events

Transient behavioral changes in patients within 3 months of implantation were observed after 27 procedures (4.2% of procedures). Confusion or delirium was exhibited after 16 procedures (2.5%), low mood after 7 procedures (1.1%), and suicidal ideation after 4 procedures (0.6%), including 1 patient who attempted self-harm. At the 1-year follow-up, objective cognitive decline according to the Wechsler Adult Intelligence Scale, Third Edition, was noted in 3 patients. In one of these patients, the decline was mild, and in the other 2 patients, the decline was moderate. MRI did not demonstrate any surgical complications in 2 of these patients, and they remained self-caring on follow-up.

Other

There were no MRI-related complications, no motor deficits, and no incidents of perioperative deep vein thrombosis, and no patient died.

TABLE 3. Postimplantation adverse events

	No. of Procedures	%
Transient behavioral change	27	4.2
Confusion/delirium	16	
Low mood	7	
Suicidal ideation	4	
Explanted, early infection (<3 mos)	10	1.5
ICH	4	0.6
Seizure	3	0.5
Cognitive decline (WAIS-III)	3	0.4
Moderate	2	
Mild	1	
Deep vein thrombosis	0	
MRI-related implant damage	0	
Permanent limb deficit	0	
Mortality	0	

ICH = intracerebral hemorrhage; WAIS-III = Wechsler Adult Intelligence Scale, Third Edition.

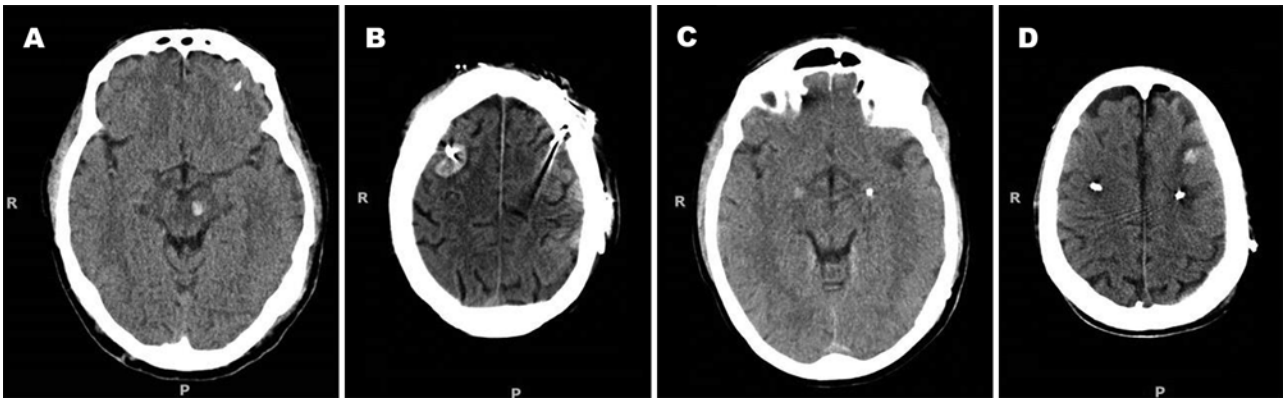

FIG. 3. Axial CT scans obtained through largest diameter of hemorrhages. All hemorrhages were small (< 3 cm^3) and were managed conservatively. **A:** CT scan obtained 1 day postoperatively in a patient who underwent immediate relocation of the lead twice during surgery and subsequently collapsed on the ward. The patient experienced delayed cognitive decline over the next year. **B:** CT scan obtained on postoperative day 2 in a patient who had intraoperative high blood pressure and a period of postoperative confusion. **C:** CT scan obtained 20 days postoperatively in a patient who experienced postoperative seizures and temporary memory problems. The hemorrhage was not visible on several earlier postoperative CT scans. **D:** CT scan obtained 3 days postoperatively in a patient who had high intraoperative blood pressure and immediate relocation of the lead during surgery. The patient experienced postoperative seizures and transient dysphasia.

Infection

There were 21 infections in 16 patients, resulting in hardware removal following lead implantation (3.2% of 650 procedures: 1.5% presenting within 3 months and 1.7% presenting more than 3 months from surgery). Some of these occurred in patients who experienced repeat infection after lead reimplantation. The indications for DBS and percentage risk per indication were as follows: Gilles de la Tourette syndrome in 2 patients (11.8%), trigeminal autonomic cephalgia in 2 patients (2.9%), dystonia in 3 patients (2.6%), Parkinson's disease in 8 patients (2.1%), and tremor in 1 patient (2.2%). The site of infection was cranial in 7 procedures (6 patients). Two of these patients were immunosuppressed, and another was poorly compliant with the MRSA protocol (Tables 4 and 5). Infection started distally (implantable pulse generator [IPG] or extension cables) after 14 procedures (2.2%). For 2 of these procedures, the entire system was immediately explanted. In the remaining 12 procedures, removal of the IPG and cables and antibiotic therapy only allowed "rescue" of cranial leads in 2 cases, with delayed explantation of the whole system in the remaining 10 procedures. In this small cohort, 83% of attempted rescues ultimately failed.

TABLE 4. Infection pattern

	No. of Infections
Total	21
Cranial	7
Distal	14
Presentation	
Early (<3 mos)	10
Late (>3 mos)	11

Infections led to explantation in 16 patients.

Unexpected DBS Maintenance Procedures

Other than end-of-service neurostimulator replacements, the most frequent delayed-reoperations (> 3 months) were IPG or cable revisions (3.1%, n = 20) due to hardware failure (n = 10) or local discomfort or concerns of possible erosion (n = 10).

Delayed Lead Retargeting Procedures

Retargeted placement of electrodes was performed in 31 patients. Eleven had undergone their primary DBS procedure at another center. Twelve patients had undergone implantation at our center prior to this study, of whom 9 required replacement of malfunctioning or infected leads and 3 required retargeting following disease progression. Delayed (> 3 months) retargeting of 6 leads (0.5%; 4 in the STN and 2 in the GPi) was performed in 4 patients (0.6%) from the early phase of the current cohort, following suboptimal stimulation benefit. On review, the originally planned target was suboptimal. In 4 other instances, suboptimal tremor control/tolerance to DBS led to patients being offered a subsequent thalamotomy.

Surgical Time

The MRI-guided and MRI-verified approach to DBS

TABLE 5. Infection risk by indication

	Total No.	No. Affected	%
GTS	17	2	11.8
Cephalgia	68	2	2.9
Dystonia	116	3	2.6
Tremor	46	1	2.2
PD	380	8	2.1

GTS = Gilles de la Tourette syndrome.

surgery enables two patients to undergo implantation of complete DBS systems (leads, cables, and IPG) on the same day, without the need to stage the procedure, unless required for research. Single-stage DBS was performed in 84% (n = 71 of 85) of implantations during the last year of this study.

Discussion

This retrospective analysis of 1201 DBS leads in 650 consecutive procedures over an 8-year period assessed targeting accuracy, precision, and safety of intraoperative stereotactic MRI to both guide and verify lead implantation before removal of the stereotactic frame, thus allowing immediate lead relocation and verification when necessary. Audit and calibration to improve precision led to a mean final targeting error of 0.9 mm and enabled single-pass insertion in 97% of leads, with 92% within 1.5 mm of the intended target and 68% within 1.0 mm. General anesthesia was used in 91% of procedures. Adverse effects included 4 small, conservatively managed hemorrhages, 3 with transient seizures, and 2 patients with moderate cognitive decline, and no instances of permanent motor deficit or mortality. To our knowledge, this is the largest report to date on the use of iMRI to both guide and verify DBS procedures, with encouraging levels of surgical safety.[14,26] This approach allows safe, precise stereotactic targeting and is reproducible across a variety of targets and patients.

Accuracy is a measure of the error between the intended and final achieved target, while precision is the consistency of targeting accuracy. DBS surgery requires high levels of both, ideally providing reproducible submillimeter accuracy safely.[22] A meticulous protocol for stereotactic MRI verification, with constant audit to allow calibration, was essential in ensuring high accuracy, precision, and safety. Such calibration strategies have subsequently been adopted successfully by other groups.[27]

Safety Considerations

A meta-analysis of risk for surgical delivery to deep nuclei (109 studies, 6237 patients, and 9890 tracks) noted that the risk per trajectory for intracerebral hemorrhage was 1.6% (95% CI 1.26%–1.95%), 0.5% for seizures, and 2.4% for neurological deficit. MER procedures were associated with a significantly higher risk of intracerebral hemorrhage and its consequent neurological deficits.[14] Excluding psychiatric changes, the risk of serious or permanent neurological deficit or death was 0.8% per trajectory. This would equate to 10 instances in our series of 1201 DBS leads. Since none were observed, a high rate of safety with the MRI-guided and MRI-verified DBS surgical technique is suggested.

A literature review on hemorrhage risk in functional neurosurgery procedures reported an incidence of 5.0%, leading to death or disability in 1.1% of procedures.[28] In the current series, this would equate to 33 bleeds leading to death or disability in 7 patients. The observed incidents of 4 and 0, respectively, compare favorably. Despite the small number of hemorrhages in this cohort, the hemorrhage rate associated with immediate retargeting was significantly higher than that for leads implanted on the first pass (5.4% vs 0.17%, p = 0.0058).

The most recent systematic review of infection after DBS surgery found a summary prevalence of early-onset infection (within 90 days of DBS placement) of 5.0% (95% CI 4.0%–6.0%) in 57 studies. The summary prevalence of late-onset hardware infections, with presentation over 90 days, was also 5.0% (95% CI 3.0%–6.0%) (n = 18).[29] In our study, both early-onset and late-onset infection rates (1.5% and 1.7%, respectively) are considerably lower than the 95% CIs reported in the literature, suggesting that the approach used may be associated with lower than usual infection rates.

Verification Technique and Clinical Outcome

Trials comparing the outcome after surgical validation with MER versus image-verified approaches have noted that initial targeting accuracy and precision is an essential prerequisite in obtaining reliable MER recording and a significant decisive factor in the final choice of the appropriate channel.[16] A number of systematic reviews, meta-analyses, and prospective studies have examined differences in Unified Parkinson's Disease Rating Scale scores, levodopa equivalent drug dosage, and surgical adverse events between the two techniques.[26,30–32] There was no significant difference in the long-term neuromodulation outcome, but the image-verified approach performed under general anesthesia was associated with a lower complication rate (hemorrhage, seizure, and infection).

Method of Anesthesia

In a survey of 95 consecutive patients who had undergone frame-based DBS surgery under local anesthesia, 8.8% were fearful of undergoing surgery "awake," and 14% found it a "difficult experience."[15] Good communication and surgeon rapport can alleviate some of the issues with awake surgery; however, performing the entire procedure under general anesthesia is a much less traumatic experience for patients and shorter in duration.[26,31,33]

Accuracy

Coregistering preoperative MRI to stereotactic CT on the day of surgery for DBS planning is susceptible to potential "fusion" errors averaging 1 mm or more, with errors of over 3 mm being reported in individual patients.[34] Maximizing data points available to the algorithm by using contrast-enhanced high-resolution MRI and CT can reduce coregistration errors. However, coregistration errors can be avoided entirely by obtaining a stereotactic MR image on the day of surgery, such that the visible target and fiducials are visible on one image without the need for exposure to CT or contrast medium. Sometimes, less is more.

It is accepted that DBS leads with targeting errors of more than 2 mm can result in suboptimal clinical outcome.[35–37] Unless the error is promptly diagnosed, it can lead to months or even years of unsatisfactory neuromodulation before surgical retargeting is offered, potentially with marked improvement.[37] Therefore, stereotactic imaging of the implanted leads prior to termination of the procedure, allowing opportunity for immediate correction, should be considered a standard of care in DBS surgery.

Intraoperative stereotactic CT verification is increasingly popular because of its speed and ease of use. However, this modality cannot visualize the targeted anatomy, and it may not provide reliable verification when there is significant pneumocephalus and associated brain shift. Stereotactic MRI is therefore the gold standard for verification.

Meticulous planning and final assessment of contact placement and lead trajectory, combined with knowledge of the relevant anatomy observed on MRI, is essential for this approach. In the current cohort, 4 patients from the earlier years of this cohort (0.6% of 650) underwent delayed retargeting of 6 leads (0.5% of 1201). In these instances, the contacts were too close to the STN borders and caused motor or speech side effects, with current spread to the internal capsule or cerebellothalamic tract (4 STN leads). In 1 patient, bilateral pallidal leads had encroached on the globus pallidus pars externa. A greater appreciation of how suboptimal contact location can lead to unwanted side effects has resulted in tightening of our tolerance for misplaced leads over the years. We now consider immediate lead relocation for leads that are as little as 1.5 mm off the target in some cases.

Precision

In this series, 37 leads (3%) were deemed suboptimally placed after the initial postimplantion MRI. A new lead was implanted through the same burr hole but via a new corticotomy, with frame coordinates adjusted to offset the observed error before removal of the suboptimal lead. Additional MRI was performed after implantation to ensure an optimal lead location before frame removal. Of these suboptimally placed leads, 11 were thought to be due to lapses in surgical technique, emphasizing the importance of a meticulous approach.

When a cluster of intraoperative relocations occurred over a short time period, without identifiable surgical lapses, a systematic problem with one of our older Leksell frames was suspected. Decommissioning the frame terminated the cluster. This incident emphasizes the need for ongoing audit and vigilance.

Some important considerations in improving accuracy and precision were optimizing stereotactic MRI sequences to ensure visualization of the anatomical target and MRI fiducials on the same image; addressing MRI distortion using well-established algorithms (provided by the MRI unit manufacturer); avoiding coregistration of images used for targeting, thereby eliminating such errors; target calibration based on audit of prior targeting errors; adopting a protocol and template to eliminate transcription errors; and performing surgery under general anesthesia in a supine position (with a 5°–10° upward tilt to encourage venous drainage) that avoids pneumocephalus and brain displacement from its location on preoperative stereotactic MRI. Crucially, stereotactic MRI verification and direct visual anatomical assessment of DBS leads in situ reassures the surgeon of optimal placement before the procedure is terminated. Reimplantation, when necessary, is optimally performed immediately, avoiding patient discomfort, and the logistical challenges of a repeat procedure months later, when gliosis around the lead may interfere with repeat targeting.

Neuroimaging is of fundamental importance, and the functional neurosurgeon must have an in-depth appreciation of its nuances and potential pitfalls to achieve accurate and precise targeting.

Safety of MRI With Implanted DBS Hardware

MRI with DBS hardware in situ has safety implications, but implementing strict precautions is associated with an excellent safety record.[1] Our low SAR protocol did not result in any MRI-related problems for these 1201 leads.

Limitations

This study focuses on surgical accuracy and precision. It includes a wide range of targets and indications, and we did not report on the efficacy of DBS stimulation. However, our group has already published clinical outcomes using this technique for a variety of DBS indications.[38–42]

A dedicated iMRI suite is a luxury that helps with workflow logistics but is not essential for the MRI-guided and MRI-verified protocol. Indeed, the senior author implements this protocol in Malta, where there is no iMRI facility. This requires transport of the patient from the MRI suite to the operating room and back, and comparable results after DBS have been reported.[43]

Conclusions

An iMRI-guided and MRI-verified approach to DBS under general anesthesia is safe, accurate, and efficient, allowing precise and reproducible results across a variety of targets and indications. Nevertheless, this method is not a shortcut to performing DBS, and a meticulous approach with constant audit is required to ensure optimal results.

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Conception and design: Rajabian, Hariz, Zrinzo. Acquisition of data: Rajabian, Vinke, Candelario-Mckeown, Milabo, Salazar, Nizam, Salloum. Analysis and interpretation of data: Rajabian. Drafting the article: Rajabian, Zrinzo. Critically revising the article: Rajabian, Vinke, Hyam, Akram, Joyce, Foltynie, Limousin, Hariz. Reviewed submitted version of manuscript: Rajabian. Approved the final version of the manuscript on behalf of all authors: Rajabian. Statistical analysis: Rajabian. Administrative/technical/material support: Rajabian, Candelario-Mckeown, Milabo, Salazar, Nizam, Salloum. Study supervision: Rajabian, Zrinzo.

Supplemental Information

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