Deep brain stimulation has become an established treatment for medically refractory Parkinson disease\(^1\),\(^2\),\(^3\) and essential tremor\(^4\),\(^5\),\(^6\),\(^7\) in adults. Deep brain stimulation has also been found to be effective for the treatment of medically refractory primary dystonia\(^8\),\(^9\),\(^10\),\(^11\) which often becomes symptomatic in childhood or early adolescence\(^1\)^. The success of DBS in these disorders inspired its application to secondary dystonias, including those associated with CP, stroke, and heredodegenerative conditions, with several groups reporting improved patient function (Witt JL, Starr PA, Ostrem JL: Use of pallidal deep brain stimulation in post-putaminal infarct hemidystonia. Abstract presented at the 15th International Congress of Parkinson Disease and Movement Disorders, Toronto, Canada, June 2011).\(^1\)^,\(^2\),\(^3\),\(^4\),\(^5\),\(^6\),\(^7\),\(^8\),\(^9\),\(^10\),\(^11\),\(^12\),\(^13\),\(^14\)

Although primary and secondary dystonias often affect children, very few DBS case series have focused

**Abbreviations used in this paper:** AC = anterior commissure; BADS = Barry-Albright Dystonia Scale; BFMDRS = Burke-Fahn-Marsden Dystonia Rating Scale; CP = cerebral palsy; DBS = deep brain stimulation; GPi = globus pallidus internus; IPG = implantable pulse generator; MER = microelectrode recording; NBIA = neurodegeneration with brain iron accumulation; PC = posterior commissure; STN = subthalamic nucleus; UPDRS-III = Unified Parkinson’s Disease Rating Scale, Part III (motor examination).

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**Object.** Deep brain stimulation (DBS) is an established technique for the treatment of several movement disorders in adults. However, the technical approach, complications, and results of DBS in children have not been well documented.

**Methods.** A database of DBS implantations performed at a single institution, prospectively established in 1998, was reviewed for patients who received DBS prior to the age of 18. Diagnoses, surgical technique, and complications were noted. Outcomes were assessed using standard rating scales of neurological function.

**Results.** Of 815 patients undergoing DBS implantation over a 12-year period, 31 were children (mean age at surgery 13.2 years old, range 4–17 years old). Diagnoses included the following: DYT1 primary dystonia (autosomal dominant, Tor1A DAG mutation, 10 cases), non-DYT1 primary dystonia (3 cases), secondary dystonia (11 cases), neurodegeneration with brain iron accumulation (NBIA, 3 cases), levodopa-responsive parkinsonism (2 cases), Lesch-Nyhan disease (1 case), and glutaric aciduria Type 1 (1 case). Six children ages 15–17 years old underwent awake microelectrode-guided surgery. For 25 children operated under general anesthesia, the surgical technique evolved from microelectrode-guided surgery to image-guided surgeries using real-time intraoperative MR imaging or CT for lead location confirmation. Complications included 5 hardware infections, all in children younger than 10 years old. At 1 year after implantation, patients with DYT1 dystonia had a mean improvement in the Burke-Fahn-Marsden Dystonia Rating Scale movement subscore of 75%, while those with secondary dystonia had only small improvements. Outcomes in the 3 children with NBIA were disappointing.

**Conclusions.** Results of DBS in children with primary and secondary dystonias were similar to those in adults, with excellent results for DYT1 dystonia in children without fixed orthopedic deformity and much more modest results in secondary dystonia. In contrast to reported experience in adults with NBIA, these results in children with NBIA were poor. Infection risk was highest in the youngest patients. (DOI: 10.3171/2011.8.PEDS11153)

**KEY WORDS** • dystonia • cerebral palsy • deep brain stimulation • neurodegeneration with brain iron accumulation • globus pallidus • functional neurosurgery
specifically on the pediatric population.1,14,24,28,40 Deep brain stimulation may have the largest impact in young patients, in areas such as social integration, completion of education, and ability to work. In this paper we describe our experience with DBS placement in children and adolescents with primary and secondary movement disorders. We share clinical and technical pearls we have learned from the care of these unique patients.

Methods

Data Collection

We searched a prospectively implemented database containing demographic and clinical data on all patients undergoing DBS for movement disorders by the senior author (P.A.S.) at the University of California, San Francisco, since the inception of its DBS program in 1998. All patients less than 18 years old at the time of implantation were identified and included in this series. Clinical data were abstracted from detailed chart review, including history, diagnosis, age of movement disorder onset, symptoms, prior treatments, medications, imaging findings, operative techniques, clinical results, and complications. This study was approved by the institutional review board of the University of California, San Francisco.

Indications for surgery in this population were as follows: 1) primary segmental or generalized dystonia causing significant disability that was not adequately responsive to a trial of trihexyphenidyl titrated up to the maximum tolerated dose (which may be > 10 mg/day in some children), oral baclofen titrated up to 20 mg 3 times a day or to the dose-limiting side effect, and to levodopa (to rule out the possibility of dopa-responsive dystonia); 2) secondary dystonia associated with severe trunk and/or upper-extremity hyperkinetic movements unresponsive to oral/intrathecal baclofen, trihexyphenidyl, benzodiazepines, or tetrabenazine; 3) heredodegenerative dystonias causing significant disability unresponsive to oral or intrathecal baclofen, trihexyphenidyl, or benzodiazepines; and 4) levodopa-responsive juvenile parkinsonism causing significant disability despite frequent levodopa dosing.

Stereotactic Targeting

Volumetric Gd-enhanced MR images, as well as axial inversion recovery fast-spin echo (GPI)30 or T2-weighted (STN) MR images, were obtained for target localization. These images were imported into a Stealth surgical planning station (Medtronic). Image fusion, reformatting, and target/trajectory planning were performed using FrameLink software (Medtronic).

In patients with primary dystonia, direct targeting of the GPI was performed by identifying the point 3–4 mm lateral to the pallidocapsular border, in the axial plane of the AC and PC, at the junction of the anterior two-thirds and posterior-third of the GPI (Fig. 1 left).39 This technique was adapted in patients with secondary dystonia as necessary to compensate for basal ganglia atrophy while maintaining sufficient distance from the pallidocapsular border (Fig. 1 right). Identification of the pallidocapsular border was routinely possible on inversion recovery fast-spin echo images performed on a Phillips Intera 1.5-T MR imaging machine (Best). The dorsolateral STN was targeted at the point 2–3 mm lateral to its medial border, along a line defining the anterior border of the red nuclei, 4 mm inferior to the axial plane passing through the AC and PC. Trajectories were planned to these targets to avoid the ventricles, sulci, and cortical veins.36

Operative Technique for Lead Placement

Children 15–17 years old with normal cognitive function, who did not have severe hyperkinetic movements (6 patients), underwent microelectrode-guided electrode placement in the awake state as described previously.38 These patients received conscious sedation only for frame placement, initial surgical exposure, and closure. The remaining 25 patients were placed under general anesthesia for the entirety of the procedure, including frame placement and planning MR imaging. Microelectrode recording was performed in 3 of these patients early in our practice, using noninhalational agents (propofol or ketamine/fentanyl) for the anesthetic technique. However, we subsequently abandoned the use of MER in patients undergoing DBS implantation under general anesthesia, for several reasons: 1) general anesthetics alter neuronal firing patterns and reduce movement-related neuronal responses, reducing the interpretability of the recorded signals; and 2) MER may increase the risk of hemorrhage, particularly when multiple brain penetrations are performed.11 For patients undergoing surgery in the awake state, this risk is partly mitigated by the ability to quickly identify new neurological deficits through frequent neurological examination, but general anesthesia precludes this important safety check.

All patients received the appropriate weight-based dose of cefazolin (or vancomycin if allergic to cephalosporin) within 30 minutes of incision. After the patient was positioned in the operating room and draped, coronally oriented incisions were made, and bur holes were drilled over the planned entry points. A recess was drilled around the bur hole to lower the profile of the lead anchoring device as permitted by the thickness of the patient’s skull. The
DBS lead (Medtronic 3387 or 3389) was lowered to the stereotactic target using the Leksell arc system (Elekta AB) and a micropositioner (Elekta or FHC). Fluoroscopy was used to confirm lead placement at arc center. When available, intraoperative CT was used (O-arm, Medtronic). Test stimulation was performed (contact 0–3, +185 Hz, 90–200 μsec) to determine the threshold for contraction of the tongue, contralateral face, or contralateral arm. One patient in this series underwent electrode placement using interventional MR imaging in a diagnostic MR imaging suite without any physiological testing. Leads were secured in place using methylmethacrylate, miniplate, and miniscrews (3 patients prior to September 2001) or a Stimloc cap (28 patients; Medtronic), and the distal ends were buried under the parietal scalp.

**Placement of Pulse Generators and Lead Extenders**

Implantable pulse generators were placed as part of the same procedure as lead implantation (in older, ambulatory children) or delayed by 2–4 weeks (in smaller or wheelchair-bound children). Implantable pulse generators were placed either in the chest or upper abdomen, depending on patient size and the need to avoid close proximity to tracheostomy, gastrostomy, or implanted baclofen pump, where applicable. The right and left systems were kept separate in the majority of patients using 2 single-pump, where applicable. The right and left systems were kept separate in the majority of patients using 2 single-pump, where applicable. The right and left systems were kept separate in the majority of patients using 2 single-pump, where applicable. The right and left systems were kept separate in the majority of patients using 2 single-pump, where applicable. The right and left systems were kept separate in the majority of patients using 2 single-pump, where applicable.

Postoperative MR imaging or CT was obtained for each patient to confirm lead location. These images were imported into a Stealth planning station (Medtronic) and reformatted in the commissural plane using Framelink software (Medtronic). In cases in which only postoperative MR imaging was obtained (3 cases), the CT scan was fused with each lead placed in a staged fashion 2–4 months apart. Unilateral leads were placed in 5 patients with unilateral-predominant disease, two of whom underwent second lead placement (1.5–2.5 years later) for treatment of progressive contralateral symptoms.

**Deep Brain Stimulation Lead Locations**

Consistent with the wide variation in size and position of basal ganglia nuclei in this patient population, there was considerable range in spatial coordinates of DBS lead tips (Table 1). Relative to the midpoint of the AC-PC line, the mean (range) coordinates for GPi placed leads were 19.5 mm for X (range 14.8–23 mm), 2.5 mm for Y (range –1.7 to 5.5 mm), and –5.9 mm for Z (range –3 to –8.6 mm). Of the 26 patients who underwent bilateral GPi lead placement, 9 showed greater than 1 mm difference in at least 2 of the coordinate planes between the left and right sides of the brain. On average, there was a 1 mm difference in each of the X, Y, and Z planes between the right and left sides with a maximum difference of 3.3 mm (X), 3.4 mm (Y), and 2.4 mm (Z) between sides.

**Clinical Outcomes**

**Primary Dystonia.** Clinical outcomes are provided in Table 1. Preoperative and postoperative BFMDRS scores were available for all patients with primary dystonia. The mean BFMDRS motor subscore improved (decreased) by 75% in the first year after surgery (baseline 57.2, follow-up 14.0). A similar decrease of 71% occurred in the BFMDRS disability subscore (baseline 13.2, follow-up 4.8). For patients with DYT1 dystonia without preexisting fixed orthopedic deformity (Cases 1–6, 8, and 9), BFMDRS improved 89% (motor subscore) and 82% (disability subscore), while those with fixed deformity (Cases 7 and 10) experienced a 61% and 55% improvement, respectively. Four patients with DYT1 dystonia who underwent awake, MER-guided surgery (Cases 6–9) experienced an improvement of 77% in the BFMDRS motor subscore, while 5 DYT1 patients who had surgery under general anesthesia (Cases 1–4 and 10) experienced an improvement of 87%.

Two patients with non-DYT1 primary dystonia (Cases 11 and 12) achieved excellent benefit from DBS treatment as reflected by the 100% and 83% decrease in BFMDRS motor subscore. Similar to the trend among DYT1 patients, the patient with a fixed foot deformity (Case 13) experienced only a 33% decrease in BFMDRS motor subscore.

**Secondary Dystonia.** Outcomes in the remaining 18 patients were variable and much less marked than in those...
<table>
<thead>
<tr>
<th>Case No.</th>
<th>Diagnosis</th>
<th>Age at Op (yrs)</th>
<th>Target Anesthesia</th>
<th>Leads</th>
<th>Lead Tip Location (mm)†</th>
<th>Baseline Movement</th>
<th>Baseline Disability</th>
<th>FU Movement</th>
<th>FU Disability</th>
<th>FU (mos)</th>
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<td>12.4</td>
<td>GPi general</td>
<td>bilat</td>
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<td>2.5, 2.3</td>
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<td>10.7</td>
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<td>bilat</td>
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<td>bilat</td>
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<td>2.5, 3.3</td>
<td>4.6, 3.1</td>
<td>46</td>
<td>8</td>
<td>13</td>
</tr>
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<td>bilat§</td>
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<td>4</td>
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<td>bilat</td>
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<td>−5.8, −5.5</td>
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<td>28</td>
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<td>bilat</td>
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<td>−7.0, −6.3</td>
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<td>CP</td>
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<td>bilat</td>
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<td>−6.3, −5.9</td>
<td>25 (BADS)</td>
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<td>lt 19.5, rt 19.4</td>
<td>2.7, 2.3</td>
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<td>23 (BADS)</td>
<td>NA</td>
<td>18 (BADS)</td>
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<td>−8.1, −8.3</td>
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<tr>
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<td>bilat</td>
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<td>bilat**</td>
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<td>48.5</td>
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<td>bilat§</td>
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<td>unilat</td>
<td>lt 15.2</td>
<td>4.9</td>
<td>−6.9</td>
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<td>10.6</td>
<td>GPi general/iMRI</td>
<td>unilat</td>
<td>lt 14.8</td>
<td>2.7</td>
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<td>bilat**</td>
<td>lt 21.2, rt 20.7</td>
<td>4.8, 3.5</td>
<td>−5.7, −5.7</td>
<td>28 (BADS)</td>
<td>NA</td>
<td>23 (BADS)</td>
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<td>bilat</td>
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<td>4.1, 4.6</td>
<td>−5.4, −4.4</td>
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<td>bilat</td>
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<td>2.1, 3.4</td>
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<td>NBIA</td>
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<td>GPi general</td>
<td>bilat</td>
<td>lt 17.5, rt 17.3</td>
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<td>NBIA</td>
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<td>bilat</td>
<td>lt 19.4, rt 22.7</td>
<td>1.8, 1.5</td>
<td>−6.5, −4.8</td>
<td>64</td>
<td>25</td>
<td>87</td>
</tr>
<tr>
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<td>parkinsonism (PINK1 +/-)</td>
<td>8.8</td>
<td>STN general</td>
<td>bilat</td>
<td>lt 9.5, rt 8.3</td>
<td>−3.1, 2.5</td>
<td>−7.5, −7.7</td>
<td>43 (UPDRS-II)</td>
<td>30 (UPDRS-II)</td>
<td>50 (UPDRS-II)</td>
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<tr>
<td>31</td>
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<td>bilat</td>
<td>lt 11.2, rt 8.9</td>
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<td>−9.4, −6.2</td>
<td>64</td>
<td>25</td>
<td>87</td>
</tr>
</tbody>
</table>

* Scores reported are BFMDRS motor and disability subscores unless otherwise noted. Abbreviations: FU = follow-up; iMRI = intraoperative MR imaging; NA = scores not available or performed; PINK1 +/- = phosphatase and tensin homolog–induced putative kinase 1 heterozygous; UPDRS-II = UPDRS Part II (disability subscore).
† Lead tip locations measured relative to the midcommissural point.
‡ Indicates MER performed.
§ Indicates leads placed in staged fashion.
¶ Indicates contralateral lead implanted years after initial lead implanted.
** Indicates lead was located in the external pallidum, and was later repositioned in the internal pallidum.
†† Indicates scale scores obtained after unilateral lead placement.

TABLE 1: Patient characteristics, lead locations, and clinical outcomes*
with primary dystonia. Clinical scores were obtained in the majority of patients in this group, although only subjective evaluation was documented for a few patients. Six patients were treated for hyperkinetic movements due to CP and experienced a small benefit from DBS. Preoperative and postoperative BFMDRS scores available for 3 of the 6 patients (Cases 16, 17, and 19) demonstrated small improvements in motor and disability (10% and 20%, respectively). Similarly, Case 15 had a 22% decrease in BADS score. One of the remaining patients with CP (Case 14) experienced some improvement realized as greater ease of patient care due to decreased severity and frequency of opisthotonic movements. Finally, 1 patient (Case 18) received sufficient benefit to warrant replacement of his IPG 2.5 years after initial implantation.

Both patients (Cases 23 and 24) treated with unilateral DBS for poststroke dystonia experienced minimal motor improvement (13% and 5%, respectively), although both reported subjective improvements in ease of movements.

Three patients were treated for heredodegenerative dystonia associated with NBIA. One patient received a robust initial benefit from treatment, especially in severe oromandibular dystonia, allowing him to speak and eat for the first time in over a year. However, this marked improvement disappeared 6 months after surgery despite multiple reprogramming attempts. The BFMDRS score changed minimally in the remaining 2 patients with NBIA, although 1 patient experienced a worsening of leg control following inadvertent deactivation of the IPG that recovered with stimulation, indicating some response to DBS.

Five additional patients were treated for other dystonias of various origins: 1 with glutaric aciduria Type 1, 1 with autoimmune inflammatory disease of the basal ganglia, 1 with Lesch-Nyhan syndrome, and 2 with unknown, probable secondary dystonias. The patient with glutaric aciduria experienced reduced dystonia and improved functionality in his left arm following unilateral right DBS placement, reflected in an 18% reduction in the BADS. He subsequently underwent a left DBS placement for progressive dystonia of the right arm. Little improvement was noted in the patient suffering from dystonia secondary to autoimmune basal ganglia disease, but full benefit may not have been achieved as he required early device removal due to infection (discussed below). After bilateral lead placement, the patient with Lesch-Nyhan syndrome experienced a decrease in self-injurious behavior as measured by the Behavior Problems Inventory, with decreases in frequency and severity of 80% and 75%, respectively. However, his improvement in dystonia was modest (16% decrease in BFMDRS motor subscore).

A clear cause could not be identified for the remaining 2 patients. One of them (Case 20) developed dystonia in early adolescence after a normal childhood, similar to the course experienced in primary idiopathic dystonia. However, she had experienced febrile seizures and possible encephalitis as a child, precluding classification as primary idiopathic dystonia. She received significant motor benefit (5%) from unilateral stimulation and later underwent placement of a contralateral lead for symptom progression on the previously untreated side, also with benefit. The remaining patient (Case 21) presented with rapidly progressive dystonia at a young age (2 years old) after normal early development, most consistent with a metabolic origin, although the specific etiology could not be pinpointed. This patient did not experience benefit from DBS and ultimately the entire system was removed. Finally, 2 patients were treated with STN DBS for childhood-onset parkinsonism. One of these patients (Case 30) demonstrated mild improvement as documented by a small decrease in total UPDRS score (from 85 to 81). The second patient (Case 31) experienced early postoperative complications (discussed below) that impaired early recovery. However, he did experience significantly decreased medication-related motor fluctuations and had improved from being wheelchair-bound to walking independently 2 years after surgery.

Complications

Device infection was the most common complication in this cohort, with 5 infections occurring in 4 patients, each requiring hardware removal. Details of infectious complications are provided in Table 2. Hardware infection occurred in 57% of the children younger than 10, while the infection rate for children over 10 years old was 0% (p = 0.001, Fisher exact test), regardless of diagnosis. Three of the 5 infections presented within 3 months of surgical implantation. Two of these patients (Cases 20 and 21) were initially treated with partial device removal and intravenous antibiotics in an effort to preserve the intracranial leads.4,34 This strategy failed in both patients; therefore, the remainder of each system was removed. Two infections occurred in a delayed manner, many months after complete wound healing. One of these presented as an epithelialized cystic lesion growing from the frontal lesion (Fig. 2). Although this patient (Case 14) also experienced an early infection of the contralateral system, the long time interval between infections and differing organisms indicate they are separate events.

Additional device complications included inaccurate lead placement (Cases 5 and 31), lead fracture (Case 26), and lead extender fracture (Case 8). Each of these was addressed with surgical revision. One patient (Case 31, STN target) had their lead repositioned the same day after postoperative MR imaging revealed poor lead location. The second patient (Case 5, pallidal target) experienced stimulation-induced dyskinesias associated with a lead that was excessively lateral (in the globus pallidus externus rather than the GPi). Repositioning of this lead 3 years later resolved the dyskinesia. Both cases of suboptimal initial lead placement occurred in patients having implantation under general anesthesia, with MER, but without intraoperative CT or MR imaging. Both cases of fracture occurred several years after initial implantation, presenting clinically as return of preoperative symptoms, with subsequent surgical revision of the lead/extender.

Two patients developed CSF collections that tracked along the device from the bur hole site to the IPG pocket. Both of these patients suffered from severe hyperkinetic movements and had the IPGs and intracranial leads implanted on the same day. These collections were treated with pressure dressings.

One patient (Case 31) suffered a small capsular in-
farct and associated left-sided hemiparesis. With rehabilitation, he recovered to full strength with the exception of persistent foot drop.

Discussion

In this report we document our experience with implantation of deep brain stimulators in 31 children with movement disorders, managed in a large referral-based surgical movement disorders clinic that offers DBS for both adults and children. Despite growing interest in the use of DBS in children, few prior published clinical series have focused specifically on this population.\textsuperscript{1,14,24,28,40} Our series illustrates both the benefits and challenges of DBS placement in children.

Clinical Benefits and Diagnosis

In children with \textit{DYTI} dystonia without fixed orthopedic deformity, GPi stimulation consistently produced a dramatic and, in some cases, near-elimination of dystonic movements and dystonia-related disability, without perioperative complications. This is consistent with prior reports.\textsuperscript{5,9,14,17}

The only children who did not experience profound resolution of symptoms were those with a fixed orthopedic deformity before surgery. This is consistent with findings in mixed pediatric and adult clinical series showing that in primary dystonia, duration of symptoms and orthopedic deformity both correlate inversely with outcome.\textsuperscript{5,9,14,17} These results strongly argue for performing DBS in children with \textit{DYTI} dystonia at the onset of disability that cannot be alleviated with medications or injection of botulinum toxin.

A recent meta-analysis indicated that in primary dystonia, the presence of the \textit{DYTI} mutation correlated positively with degree of improvement.\textsuperscript{5} We found GPi DBS highly beneficial in a small number of patients with non-\textit{DYTI} primary dystonia, but the small numbers in our series did not allow for direct statistical comparison with our \textit{DYTI} dystonia patients.

The functional benefit was far more variable among patients with dystonia secondary to CP, stroke, or other causes. A modest response was observed in patients with CP, consistent with prior reports.\textsuperscript{19,45} Particularly for these patients with CP, the caregivers reported meaningful benefit despite the small absolute change in rating scale scores. Traditional dystonia rating scales do a poor job of distinguishing small but meaningful improvements in levels of function (such as wheelchair control and activities of daily living) that are important in this population of patients. For example, 1 patient (Case 14) suffered from severe opisthotonic posturing that was reduced significantly following surgery. This change was not reflected in the rating scales, but it was functionally important with respect to mobilization (ability to sit in a wheelchair) and care (such as bathing). Similarly, both patients with hemidystonia secondary to stroke reported subjective improvement not reflected by the BFMDRS.

Although previous studies have found that older children and young adults with NBIA receive benefit from DBS,\textsuperscript{7,41} we did not find this to be the case for the 3 children (ages 11–14 years) in this cohort. Unlike in primary dystonia, in NBIA the duration of disease has been positively correlated with improvement following DBS.\textsuperscript{41} Our children with NBIA developed symptoms at a young age, which may reflect a more malignant disease phenotype that progresses rapidly and is less amenable to DBS.

Both patients with childhood-onset parkinsonism had shown a response to levodopa therapy prior to DBS.

### TABLE 2: Details of hardware infections\textsuperscript{*}

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs)</th>
<th>Time to Clinical Presentation</th>
<th>Location</th>
<th>Organism</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>6.9</td>
<td>1 mo</td>
<td>rt connector site</td>
<td>MSSA</td>
<td>removal of rt-sided system, nafcillin</td>
</tr>
<tr>
<td>14</td>
<td>6.9</td>
<td>22 mos</td>
<td>lt bur hole site</td>
<td>\textit{S. epidermidis}</td>
<td>removal of lt-sided system, TMP/SMX</td>
</tr>
<tr>
<td>21</td>
<td>4.8</td>
<td>9 days</td>
<td>connector site</td>
<td>\textit{S. epidermidis}</td>
<td>lead extender removed, cephalixin; persistent infection at blind cranial end, rest of system removed</td>
</tr>
<tr>
<td>22</td>
<td>8</td>
<td>1 mo</td>
<td>IPG site</td>
<td>MSSA</td>
<td>IPG &amp; extenders removed, nafcillin; persistent infection at blind cranial end, rest of system removed</td>
</tr>
<tr>
<td>26</td>
<td>5.4</td>
<td>18 mos</td>
<td>rt bur hole site</td>
<td>\textit{S. epidermidis}</td>
<td>removal of rt-sided system, TMP/SMX</td>
</tr>
</tbody>
</table>

\textsuperscript{*} MSSA = methicillin-sensitive \textit{Staphylococcus aureus}; \textit{S. epidermidis} = \textit{Staphylococcus epidermidis}; TMP/SMX = trimethoprim/sulfamethoxazole.

**Fig. 2.** Photograph of delayed infection of the DBS system in Case 14 presenting as an epithelialized cyst over the intracranial lead insertion site. The cyst grew over a 3-week period from a previously well-healed incision line, 22 months after implantation.
One patient (Case 31) experienced significant motor fluctuations and, similar to adults with PD, DBS treatment decreased these motor fluctuations. However, the degree of response was modest compared with that typically observed among adults.41 In addition, the capsular infarct occurring in this patient negatively impacted the degree of response to DBS. To our knowledge, only 1 case report has previously documented the use of DBS for the treatment of childhood-onset parkinsonism.42

The mixed outcome among patients with secondary movement disorders raises the question of utility of DBS implantation for these patients. The benefit for some patients, as scored on validated measures of function and disability, is minimal. However, the improvements that have been reported by the parents or caregivers are not reflected in scoring tools. There is a need for the development of additional and more sensitive outcome measures specifically designed for the pediatric population, especially those with secondary dystonia. Future prospective studies should also include a quality of life measurement scale such as the Pediatric Quality of Life Inventory or possibly motor rating scales specifically developed for the evaluation of patients with cerebral palsy, such as the Gross Motor Function Measure.31,43 In addition, the modest results of GPi DBS in secondary and heredodegenerative dystonias suggest future consideration of new targets outside the basal ganglia for these disorders.

Evolution of Operative Technique

Pediatric patients undergoing DBS present unique technical challenges. Older children (> 15 years old) with normal cognition and without severe spontaneous hyperkinetic movements are able to participate in an awake MER-guided procedure, as typically performed in adults. However, young age and severe hyperkinetic movements limit the ability of many children to tolerate such a procedure. Other groups have described the use of MER in children sedated with dexmedetomidine, an agent with less effect on basal ganglia neuronal discharge than propofol or inhalational agents.14,25 Early in our experience we used MER in 3 patients under general anesthesia, although these recordings did not significantly contribute to the final lead placement and may have even been misleading, as 2 of these patients required subsequent lead repositioning. In adults in the awake state, MER is a precise technique for localization of the GPi or STN, but is not necessarily associated with improved outcome from DBS surgery.12,15,16 The increasing availability of intraoperative imaging,6,33,35,37 along with the availability of image-based criteria for optimal lead placement,26,27,38 have informed our change of technique from MER-guidance to the use of real-time imaging (either intraoperative CT or intraoperative MR imaging) for those patients who must undergo surgery under general anesthesia. For GPi DBS in children, imaging that is adequate for direct visualization of GPi borders is especially critical, due to the high variability in the spatial coordinates of the posterolateral GPi in this population.

Higher Complication Rate in Young Children

In this series, the overall incidence of hardware infection requiring device removal was 13% on a per patient basis. This is higher than typical hardware infection rates for adults (4%–8%),13,34 although similar to that of a recently published pediatric DBS series (14%).11 However, in our series, all infections occurred in severely debilitating, wheelchair-bound children under the age of 10, with a diagnosis other than primary dystonia. Thus, young age and severe disability probably increase the risk of infection. To reduce this infection risk, we systematically instituted a protocol (beginning in 2004) consisting of chlorhexidine wash the night prior to surgery, clipper (not razor) hair removal, and minimal handling of implants such that the implants are removed from the sterile package and immediately inserted into the patient by 1 implanting surgeon. An interesting aspect of 2 device infections in our series was delayed occurrence many months after complete healing of incisions, which we have not observed in our adult series.34

Special Considerations for Wheelchair-Bound and Severely Hyperkinetic Patients

In wheelchair-bound children with severe dystonic spasms, placement of the intracranial lead, lead extenders, and IPGs on the same day sometimes resulted in “wick-ing” of CSF along the lead and lead extender, with tense accumulation of CSF in the IPG pocket. This was treated with pressure dressings. For this reason, in these children we now stage the placement of the electrodes and the pulse generators to be at least 2 weeks apart to allow tissue healing over the bur-hole cap, reducing the likelihood of leakage from the intracranial to the subgaleal space. Children with hyperkinetic head movements (choreoathetoid CP and some primary dystonia patients) are at high risk for postoperative wound breakdown, especially of incisions near the parietal boss that cover the lead extender connection. For these children, we now maintain a full head wrap, changed at least 1 time per week, for 3 weeks following any cranial hardware implantation. Further, hyperkinetic head movements may result in excessive force transmission from the lead extenders in the neck to the DBS electrodes, even when the proximal connector of the lead extender is anchored to the underlying parietooccipital fascia with permanent sutures. This can be prevented by anchoring the lead extender connector closer to the vertex of the head and drilling a partial skull-thickness bone trough for the connector at the time of placement. In adults undergoing bilateral DBS placement, we often connect both leads to 1 dual-channel pulse generator. However, in children, we prefer to attach each lead to a separate, single-channel IPG placed on either side of the chest or abdomen. The resulting lower profile of each system allows for better wound healing, as well as preservation of the contralateral system in the case of device infection.

Conclusions

The application of DBS to the pediatric population is rapidly evolving. Excellent results with a low complication rate can be achieved in children with primary generalized dystonia who are offered surgery prior to onset of orthopedic deformity. The indications for surgery in other
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movement disorders in children are less clear but merit further detailed study, the development of more sensitive rating scales to assess modest but potentially important functional changes, and rigorous attention to technical aspects that minimize wound-related complications.

Disclosure

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Author contributions to the study and manuscript preparation include the following. Concept and design: Starr, Ostrem. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Starr, Air. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Starr. Statistical analysis: Air.

References

32. Schuurman PR, Bosch DA, Bossuyt PM, Bonsel GJ, van Someren EJ, de Bie RM, et al: A comparison of continuous tha-
lamic stimulation and thalamotomy for suppression of severe
33. Shahlaie K, Larson PS, Starr PA: Intraoperative computed
34. Sillay KA, Larson PS, Starr PA: Deep brain stimulator hard-
35. Smith AP, Bakay RA: Frameless deep brain stimulation using intraoperative O-arm technology. Clinical article. J Neuro-
surg 97:370–387, 2002
39. Starr PA, Vitek JL, DeLong M, Bakay RA: Magnetic reso-
40. Thompson TP, Kondziolka D, Albright AL: Thalamic stimu-
41. Timmermann L, Pauls KA, Wieland K, Jech R, Kurlemann
44. Vidailhet M, Vercueil L, Houeto JL, Krystkowiak P, Benabid
AL, Cornu P, et al: Bilateral deep-brain stimulation of the glo-
46. Zhang JG, Zhang K, Wang ZC, Ge M, Ma Y: Deep brain stimu-
lization in the treatment of secondary dystonia. Chin Med J
(Engl) 119:2069–2074, 2006

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