

Stereotactic pallidotomy performed without using microelectrode guidance in patients with Parkinson's disease: surgical technique and 2-year results

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Object. Pallidotomy for the treatment of medically refractory Parkinson's disease (PD) has enjoyed renewed popularity. However, the optimal surgical technique, lesion location, and long-term effectiveness of pallidotomy remain subjects of debate. In this article the authors describe their surgical technique for performing pallidotomy without using microelectrode guidance, and the clinical and radiological results of this procedure.

Methods. Patients were evaluated preoperatively by using a battery of validated clinical rating scales and magnetic resonance (MR) imaging of the brain. Individuals with severe treatment-refractory idiopathic PD who were believed to be good candidates for surgery underwent computerized tomography scanning- and MR imaging-guided stereotactic pallidotomy. Intraoperative macrostimulation was used to optimize lesion placement and to avoid injury to nearby structures. Lesion location and size were calculated from MR imaging sequences of the brain obtained within the first 24 hours after surgery and again 3 months later. Clinical examinations were conducted at 1.5, 3, 6, 12, and 24 months after surgery.

Seventy-five patients (mean age 61 years, range 38–79 years) underwent unilateral pallidotomy. Significant improvements were observed in the "off" period scores for the activities of daily living portion of the Unified Parkinson's Disease Rating Scale (UPDRS), the UPDRS motor scores, total "on" time, levodopa-induced dyskinesias, and contralateral tremor. These improvements were maintained 24 months postoperatively. The mean lesion volume measured on the immediate postoperative MR image was 73 ± 5.4 mm³. Radiological analysis suggests that initial lesion volume does not predict outcome. The only permanent major complication was a single visual field defect.

Conclusions. Pallidotomy performed without using microelectrode guidance is a safe and effective treatment for selected patients with medically refractory PD.

KEY WORDS • pallidotomy • Parkinson's disease • stereotaxis

LEITINEN and colleagues^{28,29} rekindled interest in the surgical treatment of PD in 1992 when they reported their successful experience performing Leksell's posteroventral pallidotomy⁴⁵ in patients with medically refractory PD. Since then, surgeons at numerous centers have reported achieving similarly good results when performing pallidotomy in selected patients with intractable PD.^{2,5,9–11,22–26,30,34–41,44,49,50,52}

Despite widespread acceptance of the procedure, several issues remain poorly defined and are the subject of much debate. These include what size to make the lesion and where to place it, the long-term benefits of the procedure, and the necessity of obtaining microelectrode recordings. At issue is whether the use of microelectrode recording enhances the efficacy or safety of pallidotomy

Abbreviations used in this paper: AC–PC = anterior commissure–posterior commissure; ADL = activities of daily living; CT = computerized tomography; GP = globus pallidus; GPi = GP internus; MR = magnetic resonance; PD = Parkinson's disease; SEM = standard error of the mean; UPDRS = Unified Parkinson's Disease Rating Scale.

or whether it increases the risk of perioperative complications. In this paper we describe in detail our surgical technique of pallidotomy performed using macrostimulation guidance and present the clinical and radiological results of this procedure.

Clinical Material and Methods

Patient Selection

Between June 1993 and July 1998, 213 patients with mid-to-late-stage PD (Hoehn and Yahr Stages III–V) were referred to the Massachusetts General Hospital as possible candidates for posteroventral pallidotomy. Of this group, 75 individuals were eventually chosen to undergo pallidotomy. All patients met the clinical criteria for idiopathic PD and had a history of clear-cut benefit from levodopa therapy. In addition, these patients were determined to be at Hoehn and Yahr Stage III or greater during the "off" period (average preoperative stage was 4 ± 0.1 [mean \pm SEM]) and were experiencing severe dyskinesias despite

having received appropriate pharmacotherapy. Patient age was considered on an individual basis (mean age 61 years, range 38–79 years). Patients whose overriding problem was postural instability or “on” period–related freezing of gait were deemed ineligible for surgery.

Clinical and Radiological Evaluation

Preoperative baseline neurological evaluations were conducted during the on state and the practically defined off state (no use of anti-PD medications overnight) by using modified versions of the UPDRS. Additional information was collected on the number of hours per day the patient spent in the on and off states, the number of hours spent suffering from dyskinesia, the severity of the dyskinesia, and the severity of tremor. Patients returned for follow-up evaluations at 1.5, 3, 6, 12, and 24 months after surgery, and the same clinical rating scales were applied. All evaluations were performed by two of the neurologists (L.A.S., T.J.C., or J.B.P.) and the patients’ scores were entered into a database. Statistical analysis was performed using the Wilcoxon signed-rank test for ordinal data and Student’s paired t-test for continuous data.

All patients underwent routine preoperative brain MR imaging so that gross structural abnormalities could be ruled out. Most patients underwent MR imaging within 24 hours after surgery and at the 3-month follow-up examination. An evaluation of lesion size and location based on postoperative MR images was performed using a workstation (Sun Microsystems, Inc., Palo Alto, CA) with image-analysis software. For each patient 60 images were available for review. Lesion volume on MR images obtained immediately postoperatively was calculated using the formula for an ellipsoid, $V = 4/3 \pi \times (a \times b \times c)$, where a, b, and c represent the radii of the lesion. Multiple regression analysis was used to determine whether lesion size and location had an effect on clinical outcome.

Imaging and Targeting

Patients were not given anti-PD medications for 8 to 12 hours before surgery. Medication was withheld to ensure that the patients were in a relatively off state so that involuntary movements could be minimized during imaging and to facilitate assessment of the clinical effects of pallidotomy during the surgical procedure. After placement of a stereotactic frame (CRW Stereotactic System; Radionics, Inc., Burlington, MA), a midsagittal T₁-weighted scouting image was obtained. This image was used to align the gantry of the imager so that axial images were parallel to the AC–PC plane. Next, axial T₁-weighted images (3-mm slices) were obtained through the basal ganglia. The patient was moved to the CT scanning suite, where we obtained oblique axial CT scans (1- to 1.5-mm thickness) through the area of interest, again parallel to the AC–PC plane.

The initial pallidal target was chosen to be 2 to 4 mm in front of the midcommissural point, 5 to 6 mm below the intercommissural line, and 19 to 22 mm lateral to the midline of the third ventricle in the posteroventral medial GP. Adjustments were made depending on the relative size and dimensions of the head, the width of the third ventricle, and the location of the posterior limb of the internal

capsule to ensure that the target was within the posteroventral medial GP. The eventual target was chosen to rest 2 to 3 mm superior to the lateral aspect of the optic tract at the level of the posterior mammillary line. Appropriate coordinates were obtained from results of both MR and CT studies and compared for accuracy.

Surgical Technique

After target coordinate calculation, a frontal burr hole was placed so that the electrode trajectory subtended an angle of 65 to 70° above the intercommissural plane and 5 to 10° lateral to the midsagittal plane. Stimulation and lesioning were performed using a radiofrequency lesion generator (Radionics, Inc.). A macroelectrode with a 2 × 1.8-mm uninsulated tip was introduced through a guide tube by using impedance monitoring. Impedance was often seen to drop when the gray matter of the basal ganglia was reached, but this outcome was not always reliable.

The electrode was stopped at a point 6 mm above the calculated target and macrostimulation was used to begin to delineate the optimal target location. Low-frequency stimulation (2-msec square-wave pulse, 2 Hz, 0–5 V) was used to obtain motor thresholds to ensure that lesion placement did not injure the internal capsule. High-frequency stimulation (2-msec square-wave pulses, 50–75 Hz, 0–5 V) was used to assess proximity to the optic tract, potential for speech dysfunction, and amelioration of symptoms. Stimulation was conducted at 6, 4, and 2 mm above the target and at the target. At each point, both low- and high-frequency stimulation were used. To obtain the motor thresholds, low-frequency stimulation (2 Hz) was used and the voltage was gradually increased until fine rhythmic contractions were seen in the upper extremity and the tongue. The voltage at which definite contractions of either the fingers or the tongue were first seen was defined as the motor threshold. As the electrode was advanced toward the target, the thresholds decreased. High-frequency stimulation (50–75 Hz) usually caused an improvement in contralateral rigidity and bradykinesia, which were assessed intraoperatively by passive manipulation of the contralateral limbs and by requiring the patient to perform voluntary movements such as finger tapping, rapid pronation and supination of the forearm, bicycling movements of the legs, and foot dorsiflexion and plantar flexion. Speech was carefully assessed during high-frequency stimulation by monitoring spontaneous output and by asking the patient to repeat several complex phrases and noting any difficulties with volume, articulation, or fluency. Once the electrode was 2 mm above the target, high-frequency stimulation was also used to ascertain visual thresholds. The operating room lights were dimmed and the minimal voltage that reproducibly elicited visual phenomenon was recorded as the visual threshold. The typical response was a transient perception of flashing white lights or phosphenes in the contralateral hemifield. The electrode was lowered to the target position and visual thresholds were again assessed. At final target coordinates, optimal motor threshold values were usually between 2 and 3 V. Visual thresholds were maintained at 2 V or greater to avoid injury to the optic tract.

Taken together the two sets of thresholds indicated the proximity of the electrode to the optic tract and the inter-

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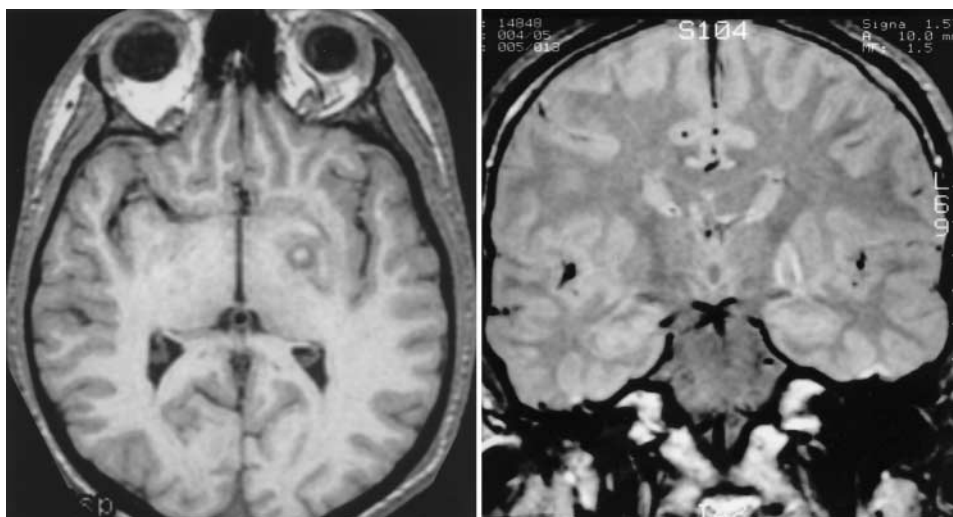


FIG. 1. Axial (left) and coronal (right) postoperative MR images revealing the typical location of posteroventral pallidotomy lesions.

nal capsule. For example, if the motor threshold values were lower than expected, but the visual threshold values were within range, the electrode was too close to the internal capsule and it was moved anteriorly or laterally 1 to 3 mm. If both the motor and visual threshold values were higher than expected, this typically indicated that the electrode needed to be advanced 1 to 2 mm deeper or more medially. Once the target coordinates were adjusted, the entire macrostimulation sequence was repeated until satisfactory target threshold values were obtained. In 75% of cases the initial stereotactic coordinates were accurate and no change was required in electrode location. In most of the remaining cases, only one instance of repositioning (usually 1–2 mm in a single direction) was required to obtain satisfactory threshold values.

Once the target location was verified, a test lesion was made at 46 to 48°C for 60 seconds. The patient was again evaluated for any evidence of motor, sensory, visual, or speech impairment. If there were no deficits, a permanent lesion was made at 70 to 80°C for 60 seconds. The electrode was withdrawn to 2 mm and 4 mm above the target, and a lesion was made at each site by using similar parameters (75–85°C for 60 seconds).

At the completion of surgery, the patients resumed their preoperative anti-PD medication regimens. A brain MR image was obtained within the first 24 hours to assess lesion location and to identify any clinically silent complications (Fig. 1). Most patients were discharged home the day after surgery.

Results

Patient Characteristics

Between June 1993 and July 1998, 91 pallidotomies were performed in 75 patients with idiopathic PD. All 75 patients initially underwent unilateral pallidotomies (39 on the left side and 36 on the right side). Sixteen patients subsequently underwent pallidotomy on the opposite side at a later date. In this series, we describe the clinical re-

sults of unilateral pallidotomy in 68 of the 75 patients for whom follow-up data were available. A more detailed analysis of the 16 patients who underwent bilateral pallidotomy will be the subject of future reports. Not all patients were available at each of the follow-up examinations.

Macrostimulation Thresholds

The relationship between the motor threshold and the height of the electrode relative to the target was quite reliable and very nearly linear. The average motor threshold for the tongue at 6 mm above target was 4.7 ± 0.2 V (mean \pm SEM; 62 patients). This value declined to a mean of 2.85 ± 0.14 V at the target (Fig. 2A). Values for the upper extremity were similar (4.8 ± 0.2 V and 2.98 ± 0.1 V, respectively; Fig. 2B). The mean visual threshold at the target was 2.42 ± 0.1 V. After some experience and given the predictable relationship of electrode location and motor and visual thresholds, determining whether the electrode was placed at the correct location became a straightforward process.

Clinical Global Improvement Scale

A clinical global improvement scale was used to evaluate subjectively the overall effectiveness of pallidotomy. Outcome was rated as excellent, good, moderate, unchanged, or worse compared with the patient's preoperative condition. Patients were assigned to a given category by the neurologists and the attending neurosurgeon. Overall, 67% of patients had a good or excellent outcome, 22% of patients experienced moderate improvement, 9% had no improvement, and 2% experienced a worsening of symptoms following the procedure.

Assessment According to the UPDRS

All three components of the UPDRS were assessed both pre- and postoperatively (ADL [maximum score 52], mentation [maximum score 16], and motor function [maximum score 108]). The mean UPDRS ADL score during

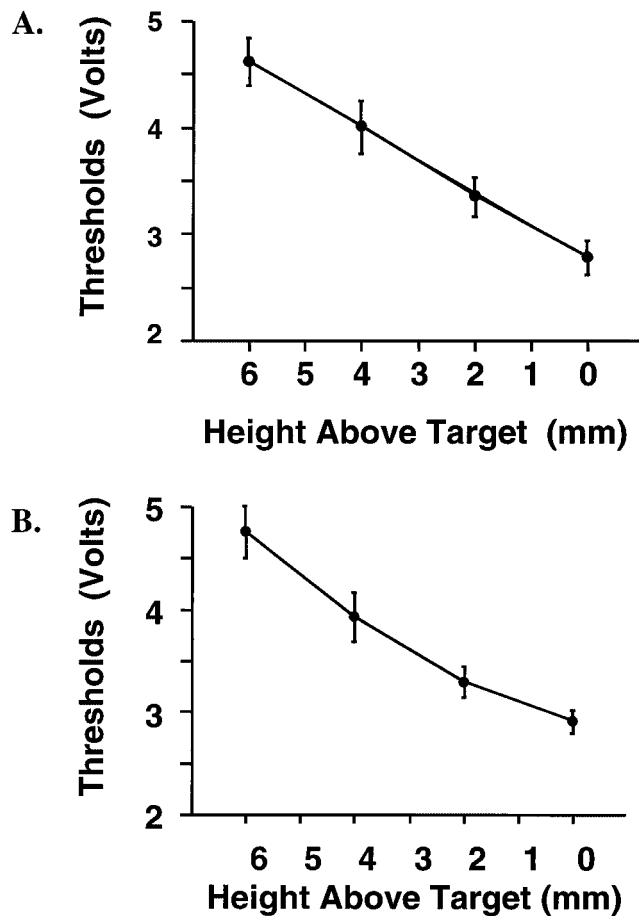


FIG. 2. Graphs showing face (A) and upper-extremity (B) macrostimulation motor thresholds in volts as the electrode is advanced toward the target.

the off periods decreased by 34% 6 weeks after pallidotomy and reached a plateau at approximately 20% below the preoperative level at 3, 6, 12, and 24 months postoperatively (Fig. 3). These changes were all statistically significant ($p < 0.05$, Wilcoxon's signed-rank test) up to 24 months. The UPDRS ADL on scores were not significantly changed in patients who had undergone pallidotomy. There were no significant changes in UPDRS mentation scores in patients after pallidotomy. Total UPDRS motor scores were obtained postoperatively; however, statistically reliable conclusions were difficult to reach because it was not possible to examine all patients during the clinically defined worst off period (> 12 hours without receiving any anti-PD medication) at the follow-up examinations. When the analysis was limited to those patients who had been examined preoperatively during the worst off state and later at follow-up review (17 patients), we found a 25% improvement in motor scores from a mean of 46 ± 4.6 to a mean of 34 ± 4.1 , which was statistically significant (Wilcoxon's signed-rank test, $p < 0.05$). For the entire group of patients, there was a significant improvement in contralateral motor scores (subset 20–26 of the UPDRS motor examination [maximum score 36], Wilcoxon's signed-rank test, $p < 0.05$), which was maintained up to 24 months; however, there was no significant

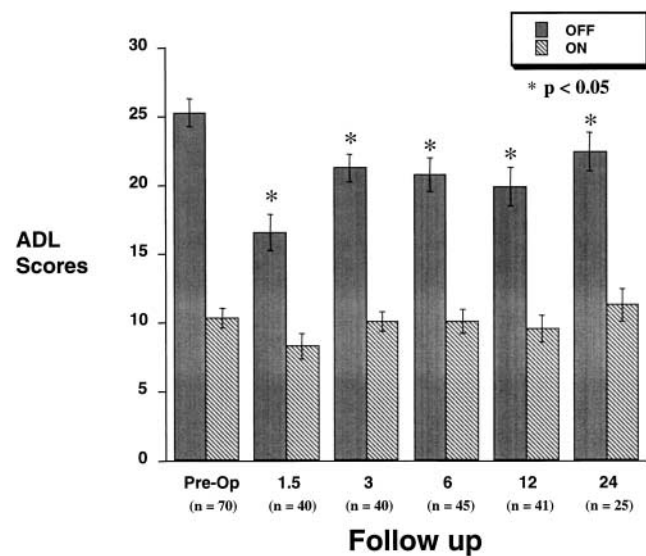


FIG. 3. Bar graph depicting the mean UPDRS ADL scores obtained in patients during on and off periods. The scores were obtained preoperatively (pre-op) and at 1.5, 3, 6, 12, and 24 months postoperatively. N = number of patients.

improvement in ipsilateral motor scores (Fig. 4). There was no significant change in medication regimens (dopa equivalents) postoperatively.

On- and Off-Period Changes

Pallidotomy increased the number of hours per day that patients were in the on state by 24%, from an average of 9.5 hours preoperatively to an average of 11.8 hours postoperatively. This change was statistically significant and was maintained at 1.5, 3, 6, 12, and 24 months (paired t-test, $p < 0.05$) (Fig. 5). There was a corresponding 41% decrease in the number of hours patients spent in the off state per day, from 7.8 to 4.6 hours, which was significant at 1.5, 3, 6, 12, and 24 months (paired t-test, $p < 0.05$).

Severity of Dyskinesia

The severity of dyskinesias was evaluated using a five-point scale (0 = no dyskinesia, 1 = mild dyskinesia, 2 = constant dyskinesia with no interference with ADL, 3 = dyskinesia that interferes with ADL, and 4 = incapacitating dyskinesia). The severity of contralateral dyskinesias was decreased by 84% from an average score of 2.7 to a score of 0.41 (Fig. 6 upper). This change was significant and was maintained at 1.5, 3, 6, 12, and 24 months (Wilcoxon's signed-rank test, $p < 0.05$). In contrast, ipsilateral dyskinesias were not significantly changed in patients after pallidotomy. Virtually all patients also reported considerable improvement in the number of hours per day during which dyskinesias were prominent. Preoperatively, patients reported a mean of 4.8 hours of severe dyskinesia per day. Postoperatively, that number dropped to a mean of 2.3 hours/day. This decrease was maintained and was significant at 1.5, 3, 6, and 12 months after surgery (paired t-test, $p < 0.05$) (Fig. 5).

Severity of Tremor

The severity of tremor was also rated using a five-point

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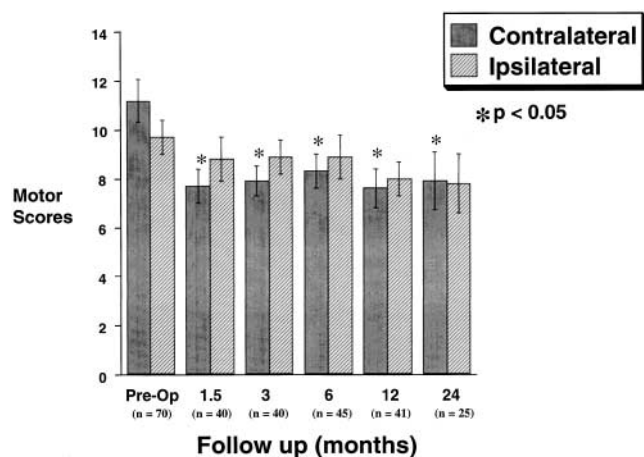


FIG. 4. Bar graph showing the mean UPDRS motor scores for contralateral and ipsilateral limb function obtained preoperatively and at follow-up examinations.

scale similar to that used for evaluating dyskinesia. The severity of contralateral tremor was significantly decreased postoperatively at 1.5, 3, 6, 12, and 24 months (Wilcoxon's signed-rank test, $p < 0.05$), whereas ipsilateral tremor was not significantly modified by pallidotomy (Fig. 6 lower).

Lesion Size and Location

On average, the center of the lesions was 21.1 ± 0.2 mm (mean \pm SEM) lateral to the midline and 4.1 ± 0.26 mm anterior to the middle of the AC-PC line. The most inferior aspect of the lesions was 5.2 ± 0.28 mm below the AC-PC plane. The average volume of the middle zone of the lesions, indicating the area of hemorrhagic necrosis demonstrated on immediate postoperative images, was 73 ± 5.4 mm³.^{27,47} When the outer zone (indicating the surrounding ring of edema) was included, the average lesion volume was 355 ± 24 mm³. The average lesion volume was significantly reduced to 40 ± 4.8 mm³ at 3 to 6 months after surgery (paired t-test, $p < 0.001$).

Multiple regression analysis was used to determine whether lesion size or location correlated significantly with clinical outcome. Lesion volume and location were analyzed with respect to the changes in dyskinesia, tremor, and UPDRS scores 3 months postoperatively. We found no obvious correlation between the lesion volume and any of the aforementioned outcome parameters. The location of the lesion along the anteroposterior and inferosuperior dimensions also had little clear correlation with outcome. On the other hand, there was a significant correlation between the lateral location of the lesion and improvement in tremor, with a more lateral lesion resulting in a greater improvement in contralateral tremor (analysis of variance, $p < 0.05$). There also appeared to be a relationship between lateral location and dyskinesia, with a more medial lesion resulting in a greater decrease in dyskinesia, although the correlation did not reach statistical significance (analysis of variance, $p < 0.10$).

Complications of Surgery

Of the 75 unilateral pallidotomies performed during this

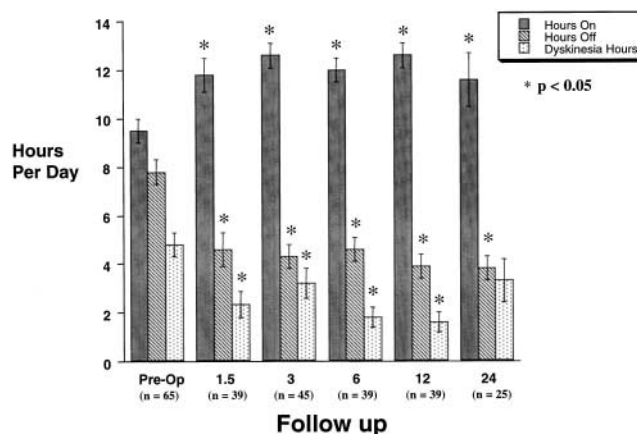


FIG. 5. Bar graph showing the mean numbers of hours patients spent in on and off states as well as the number of hours patients experienced dyskinesia preoperatively and at 1.5, 3, 6, 12, and 24 months postoperatively.

period, only one patient suffered a major complication, which was homonymous hemianopsia. This occurred approximately 36 to 48 hours after surgery and was thus believed to be due to a delayed ischemic event. Delayed infarctions of the internal capsule following placement of radiofrequency lesions have been described previously by other authors.³² Two clinically silent cortical hemorrhages, 2 to 3 cm in diameter, were detected on postoperative imaging. No specific intervention was required in either case. Two patients experienced prolonged confusion, one patient a transient dysarthria, four patients mild contralateral hemiparesis, and two patients a single generalized tonic-clonic seizure in the early postoperative period. No patient in this series died.

Discussion

The resurgence of interest in the use of pallidotomy is attributable to simultaneous advances in clinical neurosurgery and basic neuroscience. Initial reports by Laitinen and colleagues^{28,29} empirically showed that many of the symptoms of PD could be successfully alleviated by creating lesions in the posteroventral pallidum. At nearly the same time, Albin, et al.,¹ proposed a model of basal ganglia connections and their role in movement disorders that provided a rational basis for performing pallidotomy in patients with PD. In this model, the decrease of dopamine in patients with PD ultimately results in increased inhibitory output from the GPi to the ventrolateral thalamus. Pallidotomy abolishes the excessive output from the GPi, thereby releasing the thalamus from abnormal inhibition.⁴

Although pallidotomy has become a widely accepted treatment for medically refractory PD, several areas of controversy remain regarding its use. These relate to the long-term benefits of the procedure, the optimal location and size of the lesions, and the necessity of using intraoperative microelectrode recordings. Despite these controversies, authors of existing studies seem to agree on several points. The primary benefit of pallidotomy during the on state is a dramatic reduction in contralateral dyskinesias. Following pallidotomy, virtually all patients expe-

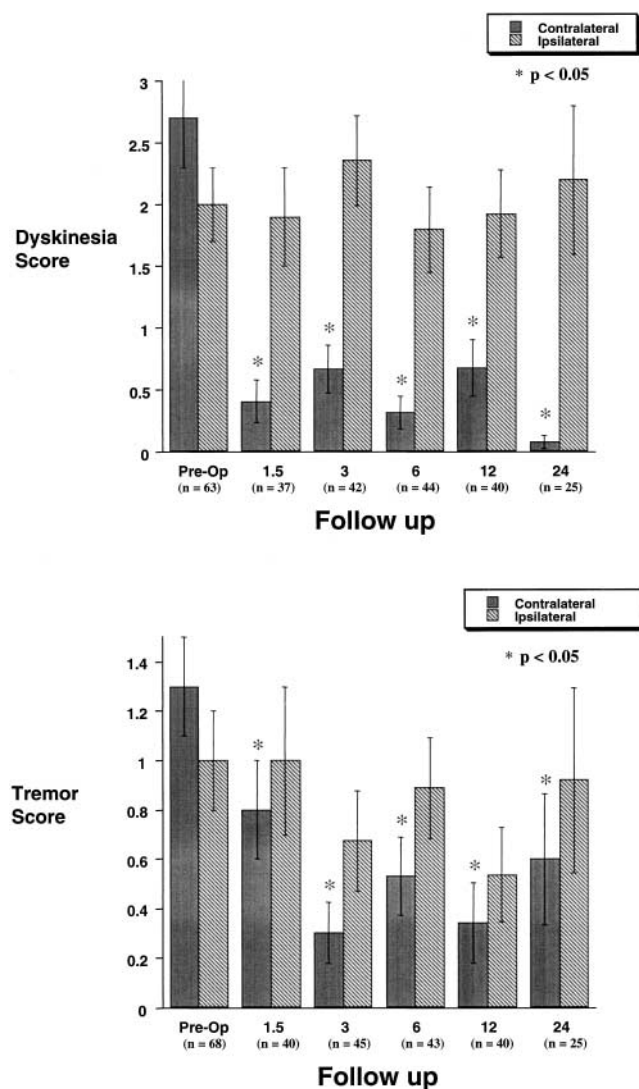


FIG. 6. Bar graphs depicting mean dyskinesia (*upper*) and tremor (*lower*) scores in the contralateral and ipsilateral sides of patients preoperatively and at 1.5, 3, 6, 12, and 24 months postoperatively.

experience a significant improvement or abolition of contralateral dyskinesias.^{5,22-24,28,29,34,39} Pallidotomy also improves many of the off-state symptoms, including rigidity and bradykinesia.^{5,10,22,24,26,28-30,34} Although thalamotomy has traditionally been the surgical treatment of choice for tremor, it is becoming increasingly clear that pallidotomy can improve contralateral tremor in many patients.^{5,10,22,24,26,30,34,39,46} In addition, most patients experience a decrease in the severity of on/off period fluctuations.^{5,10,23,26} Although few long-term studies are available, the effects of pallidotomy appear relatively long lasting, with most patients retaining at least some benefit 2 years postoperatively and, as documented in at least one report, for up to 4 years.^{11,30,37,52}

Our results demonstrate that pallidotomy performed without microelectrode guidance can provide a marked improvement in many features of PD and that these improvements are comparable in magnitude to those reported in previously published studies. It was not possible to

obtain routine follow-up motor examinations during the clinically defined worst off periods in many cases. However, in the cases in which these assessments were obtained pre- and postoperatively, there was significant improvement following pallidotomy. In addition, an analysis of limb motor function across all patients revealed a significant improvement in contralateral but not ipsilateral UPDRS scores. Furthermore, other quantifiable measures were in close accordance with those reported in the literature. The most marked improvements occurred in the reduction of contralateral dyskinesias, which were either completely abolished or significantly improved in most patients. In addition, there was a significant reduction in the severity of contralateral tremor. Overall, patients experienced a reduction in the severity of on/off period fluctuations through a combination of increased on hours, decreased dyskinesias during on hours, and decreased signs and symptoms during off hours. These effects combined to generate a marked improvement in the patients' functional independence and in their quality of life. Furthermore, these improvements appeared to be relatively durable, lasting up to 2 years in patients for whom adequate follow-up evaluation was available.

The ideal target location for pallidotomy lesions remains to be clearly defined. Target locations have been reported to be between 17 and 25 mm lateral to the midline, 3 and 8 mm below the intercommissural line, and 2 to 3 mm anterior to the midcommissural point.^{5,10,11,22,23,27-29,33,34,44} Our analysis of early postoperative MR images supports the contention that the posteroventral medial pallidum is the optimal site for lesions in the treatment of PD. The lesion we make appears to be 21 mm lateral to the midline, 2 to 4 mm anterior to the midcommissural point, and 5 to 6 mm inferior to the AC-PC plane. The relatively consistent lesion location in our series supports the concept that the reproducible and linear reduction in macrostimulation of motor and visual thresholds as the electrode approaches the final target can provide reliable intraoperative confirmation of proximity to the internal capsule and the optic tract.

Microelectrode recordings of human pallidal neurons in patients with PD are beginning to yield information that may be helpful in rationally choosing pallidal targets. For example, several studies have shown that neurons in the medial and lateral GP differ in their frequency and pattern of activity.^{33,43} The description of a sensorimotor area with at least partial somatotopical organization located in the posteroventral GPi has been used to support the contention that the optimal lesion target lies in the posteroventral medial pallidum.^{5,30,34}

Although it seems prudent to create the smallest effective lesions, there have been no definitive studies in which lesion size has been related to clinical outcome. The range of reported lesion volumes extends from 50 to 181 mm³.^{5,10,17,27-29,34} Authors of some studies have implied that a poor response was secondary to small lesion size with an improvement after repeated pallidotomy, although the precise location and size of the initial small lesions has not been specified.^{23,44} Repeated pallidotomy was performed in six patients in our series because their clinical response had been equivocal. Four of the patients had received initial pallidotomy lesions considered to be in a good location; none of these patients experienced im-

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provement after repeated surgery and enlargement of the lesion. After the death of one of these patients of unrelated causes, an autopsy was performed and, despite the fact that the patient had a clinical history of PD with modest levodopa responsiveness, a neuropathological diagnosis of Lewy bodies disease was determined. In two cases in which the initial pallidotomy lesion was believed to be in a suboptimal location, reoperation with placement of the lesion at the ideal location imparted substantial and long-lasting benefit (in one of these cases the initial pallidotomy was performed while the patient was at another institution). In these two cases of failed pallidotomy, initial lesions were only 2 to 3 mm anterior and lateral to the optimal target location, but they were surprisingly ineffective.¹² In both cases, the repeated lesions, as measured on MR images obtained immediately postoperatively, were relatively small (90 and 105 mm³, respectively), but were ultimately successful in bringing about impressive, long-lasting benefit, particularly in alleviating the levodopa-induced dyskinesias.

Hariz¹⁷ examined postoperative CT scans in 19 patients who had undergone either thalamotomy or pallidotomy for PD. The small number of patients did not allow for statistically significant conclusions to be drawn, although larger lesions appeared to be associated with the occurrence of more complications. The technique used at our institution permits us to create lesions with a diameter of 4 to 6 mm, a height of 6 to 9 mm, as measured on immediate postoperative MR images, and a corresponding mean volume of approximately 73 mm³ (range 40–150 mm³). A significant reduction in lesion volume is evident at 3 months.³¹ This lesion volume is smaller than those reported in most series in which pallidotomy is guided by microelectrode techniques, but appears to be associated with good clinical outcome and few complications. Our finding that lesion volume does not appear to be correlated with short-term outcome is in agreement with those of other investigators in which no clear relationship was found between lesion size and outcome.^{15,19,27} This implies that smaller lesions, if well placed, may be adequate to bring about significant clinical benefit. Determining whether larger lesions produce a better long-term effect will require comparing different lesion sizes at later follow-up examinations. Our findings that more medial lesions were associated with a greater improvement in dyskinesias and more lateral lesions resulted in a greater improvement in tremor are in agreement with the findings in the recent report by Gross, et al.¹⁵ This suggests that, with greater understanding of the circuitry of the basal ganglia, it may be possible to tailor lesion location to specific PD signs.

Some type of intraoperative physiological confirmation of lesion location is required; however, the necessity of microelectrode recordings is the subject of continued debate.^{8,16} The use of microelectrode recordings during pallidotomy to guide placement of lesions has been strongly advocated by some groups.^{3,5,6,10,11,14,30,34,42,44,48,51} Potential benefits of microelectrode recordings include more precise localization of the GP externus, the GPi, the inferior margin of the GP, and the optic tract, which theoretically should lead to more accurate lesion placement and fewer complications. Furthermore, microelectrode recordings have yielded important research information and have the potential to continue to yield data that may be useful in ra-

TABLE 1

Summary of larger series in which microelectrodes or macrostimulation alone were used to assist pallidotomy

Authors & Year	No. of Patients	No. of Optic Tract Injuries (%)	No. of Hemorrhages/Infarctions (%)
<i>microelectrode-guided surgery</i>			
Baron, et al., 1996	15	1 (7)	2 (13)
Dogali, et al., 1996	33	0 (0)	0 (0)
Burns, et al., 1997	23	0 (0)	2 (9)
Kopyov, et al., 1997	29	0 (0)	0 (0)
Krauss, et al., 1997	36	0 (0)	1 (3)
Lang, et al., 1997	40	0 (0)	2 (5)
Uitti, et al., 1997	20	0 (0)	0 (0)
Vitek, et al., 1997	160	4 (3)	2 (1)
Alterman & Kelly, 1998	160	1 (1)	2 (1)
Ondo, et al., 1998	34	0 (0)	0 (0)
Samuel, et al., 1998	26	2 (8)	4 (15)
Shannon, et al., 1998	26	1 (4)	4 (15)
Dalvi, et al., 1999	20	2 (10)	0 (0)
totals	622	11 (1.8)	19 (3.1)
<i>surgery w/ macrostimulation only</i>			
Laitinen, et al., 1992	38	6 (16)	0 (0)
Iacono, et al., 1995	126	2 (2)	3 (2)
Hariz & De Salles, 1997	132	1 (1)	2 (2)
Johansson, et al., 1997	22	1 (5)	0 (0)
Kishore, et al., 1997	24	3 (13)	1 (4)
Schuurman, et al., 1997	19	1 (5)	1 (5)
Giller, et al., 1998	47	0 (0)	0 (0)
Scott, et al., 1998	20	1 (5)	0 (0)
Kondziolka, et al., 1999	58	0 (0)	0 (0)
totals	486	15 (3.1)	7 (1.4)

tionally modifying target location and size. Nonetheless, surgeons at many centers around the world rely completely on stereotactic localization and intraoperative macrostimulation to localize the lesions.^{13,18,20,21,23–25,28,39,40} It has been argued that microelectrode recordings require more operating time and a larger operating room staff and that multiple electrode passes place the patient at additional risk for hemorrhage or other injuries.

A review of some of the larger series in which either microelectrode guidance or macrostimulation alone was used suggests that microelectrode recordings reduce the risk of injury to the optic tract, but are associated with a higher rate of complications (Table 1). In 13 published studies in which microelectrodes were used, the average incidence of optic tract complications was 1.8% (range 0–10%, 622 patients), whereas in nine studies in which only macrostimulation was used, the average incidence was 3.1% (range 0–16%, 486 patients). In contrast, the average incidence of hemorrhage or infarction in series in which microelectrodes were used was 3.1% (range 0–15%), whereas in series in which macrostimulation was used the incidence was 1.4% (range 0–5%). Furthermore, three reported deaths, which were directly attributable to the procedure, occurred when microelectrode recordings were used.^{38,41} Complications in our series included one visual field defect (1.3%) and two cortical hemorrhages (2.7%). This rate of optic tract complications compares favorably with other series and is certainly no higher than that obtained with microelectrode-guided localization.

The extra risk incurred by the use of microelectrode recording might be justified if it resulted in greater accuracy in lesion placement; however, even authors at centers

that rely on microelectrode recordings report some variability both in lesion location and clinical results.^{15,50} Moreover, it appears that both microelectrode-guided pallidotomy and pallidotomy performed using macrostimulation only have similarly good clinical outcomes. At the present time, the best conclusions that can be reached are that, in experienced hands, both techniques appear to offer comparable results and that an unequivocal endorsement of one technique over the other is not warranted.

Conclusions

Pallidotomy can impart to selected patients with PD useful functional improvement by abolishing contralateral dyskinesias and tremor while significantly improving off period, ADL, and motor function. Using surgical techniques that rely on macrostimulation alone can produce an accurate and consistent lesion in the GP with clinical results that compare favorably to published results of studies in which microelectrode techniques were used. Furthermore, with the careful use of stereotactic imaging and intraoperative macrostimulation, it is possible to have complication rates that are the same or better than those published in previous reports. Thus, pallidotomy performed without using microelectrode guidance appears to be a safe and effective treatment for selected patients with PD. Whether alternative surgical treatments, such as long-term deep brain stimulation or neural transplantation, can ultimately improve on these results and provide a long-lasting cure for PD remains to be seen.

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