Gamma knife radiosurgery as a lesioning technique in movement disorder surgery

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Fifty-five patients underwent radiosurgical placement of lesions either in the thalamus (27 patients) or globus pallidus (28 patients) for treatment of movement disorders. Patients were evaluated pre- and postoperatively by a team of observers skilled in the assessment of gait and movement disorders who were blinded to the procedure performed. They were not associated with the surgical team and concomitantly and blindly also assessed a group of 11 control patients with Parkinson's disease who did not undergo any surgical procedures. All stereotactic lesions were made with the Leksell gamma unit using the 4-mm secondary collimator helmet and a single isocenter with dose maximums from 120 to 160 Gy. Clinical follow-up evaluation indicated that 88% of patients who underwent thalamotomy became tremor free or nearly tremor free. Statistically significant improvements in performance were noted in the independent assessments of Unified Parkinson's Disease Rating Scale (UPDRS) scores in the patients undergoing thalamotomy. Eighty-five and seven-tenths percent of patients undergoing pallidotomy who had exhibited levodopa-induced dyskinesias had total or near-total relief of that symptom. Clinical assessment indicated improvement of bradykinesia and rigidity in 64.3% of patients who underwent pallidotomy. Independent blinded assessments did not reveal statistically significant improvements in Hoehn and Yahr scores or UPDRS scores. On the other hand, 64.7% of patients showed improvements in subscores of the UPDRS, including activities of daily living (58%), total contralateral score (58%), and contralateral motor scores (47%). Ipsilateral total UPDRS and ipsilateral motor scores were both improved in 59% of patients. One (1.8%) of 55 patients experienced a homonymous hemianopsia 9 months after pallidotomy due to an unexpectedly large lesion. No other complications of any kind were seen. Follow-up neuroimaging confirmed correct lesion location in all patients, with a mean maximum deviation from the planned target of 1 mm in the vertical axis. Measurements of lesions at regular interals on postoperative magnetic resonance images demonstrated considerable variability in lesion volumes. The safety and efficacy of functional lesions made with the gamma knife appear to be similar to those made with the assistance of electrophysiological guidance with open functional stereotactic procedures.

Functional lesions may be made safely and accurately using gamma knife radiosurgical techniques. The efficacy is equivalent to that reported for open techniques that use radiofrequency lesioning methods with electrophysiological guidance. Complications are very infrequent with the radiosurgical method. The use of functional radiosurgical lesioning to treat movement disorders is particularly attractive in older patients and those with major systemic diseases or coagulopathies; its use in the general movement
disorder population seems reasonable as well.

**Key Words** *gamma knife* *thalamotomy* *pallidotomy* *Parkinson's disease* *radiosurgery*

Stereotactic lesioning in the thalamus and basal ganglia to treat movement disorders was one of the earliest functional stereotactic procedures to be performed. The advent first of computerized tomography (CT) and then magnetic resonance (MR) imaging improved the surgeon's ability to identify the desired target anatomically. The use of microelectrode stimulation and recording also provided the surgeon with the ability to identify the intended target for lesioning electrophysiologically.[1] In spite of these advances, functional stereotactic surgery for the treatment of movement disorders still requires the use of invasive techniques to provide a skull opening and to pass electrodes or probes through the brain to the proposed target. Some authors continue to use positive-contrast ventriculography for target localization.[4,5] These invasive techniques put the patient at risk of intracerebral or extracerebral hemorrhage, infection, seizures, brain displacement, tension pneumocephalus, and direct injury from probe placement, among others. Lars Leksell developed the concept of radiosurgery so that functional neurosurgery could be performed with less risk.[38,39] Leksell and colleagues used the gamma knife (Elekta Instruments, Atlanta, GA) to perform thalamotomies to treat chronic pain and psychiatric disorders and focused it on the trigeminal ganglion in attempts to treat trigeminal neuralgia.[14,38,40-42,58] More recently, others have reported on the use of the gamma knife to treat trigeminal neuralgia, psychiatric disorders, and epilepsy.[9,16,27,29,46,53,55,66,67] Some limited reports on the use of the gamma knife to treat movement disorders have also appeared.[12,18,20,31,43,47-49,52] In this report, we describe our experience in treating movement disorders using the gamma knife. Both thalamotomy and pallidotomy have been used to treat a variety of movement disorders, including those related to Parkinson's disease (PD), as well as essential tremor, tremor following stroke, and tremor following cerebral infection. Particular strengths of this report include independent assessment by observers not involved in the treatment of PD patients and the use of Hoehn and Yahr scores and Unified Parkinson's Disease Rating Scale (UPDRS) for comparison with a control group of PD patients who did not receive surgical treatment.

**CLINICAL MATERIAL AND METHODS**

**Patient Selection**

Fifty-five patients with movement disorders underwent thalamotomy (27 patients) or pallidotomy (28 patients) using the Leksell gamma unit. All patients who underwent pallidotomy were treated for bradykinesia, rigidity, or levodopa-induced dyskinesias related to PD. Thalamotomy was performed for treatment of tremor in 16 patients with PD, eight with essential tremor, two with tremor following cerebral infarctions, and one with tremor following a bout of encephalitis. Table 1 shows demographic data obtained in those patients who were evaluated independently by a movement disorder team. The team was blind to the patients' condition and were not involved in the selection of patients or the surgical procedures. There were no significant differences in the demographics of this subgroup compared with the entire treated population.

All surgically treated patients described in this report had previously been under the care of a neurologist and had exhausted pharmacological therapy or had experienced undesirable side effects of medical therapy that prevented effective treatment.

The minimum baseline, preoperative evaluation included physical and neurological examinations and
videotaping of abnormal movements. Patients with PD were also assessed by an independent team composed of a Ph.D. specialist in movement disorders (A.S.) and specially trained physical therapists who determined Hoehn and Yahr stage ratings as well as UPDRS scores.[37] Psychological assessment was performed by a psychologist using both standardized psychological tests and an interview. These results will be reported separately. Follow-up evaluation was performed at 6 and 12 months following the procedure. In some cases, follow-up clinical data were obtained by a trained nurse via telephone because distance or other factors prevented a return visit by the patient.

This report is relatively unique in that it incorporates a control group of 11 patients with PD who did not undergo surgery but were treated medically by their referring neurologists and studied using the same quantitative assessment methods. Demographic data for this group are also shown in Table 1.

![Fig. 1. Upper: Preoperative stereotactic MR image demonstrating the planned thalamic target. Lower: Postoperative MR image demonstrating the thalamotomy lesion. The patient experienced complete resolution of tremor by 6 months postoperatively.](image)

**Lesioning Technique**

Targets were localized by stereotactic MR imaging. Strict quality assurance was used to minimize MR image distortion.[71,72] A 1-tesla magnet (Magnetom; Siemens, Erlangen, Germany) was used that incorporated a specially tuned head coil with a field gradient of 15 mtesla/m. Alignment of the main
magnet was verified before each imaging session. The Leksell model G stereotactic frame (Elekta Instruments) was applied to the patient's head so as to position the intended target as close to the center of the stereotactic space as possible. A preliminary image was made to assure correct placement of the stereotactic frame, and measurements of the distances between the end fiducials were determined from the display monitor and compared to the known distances between the fiducial markers on the frame. Distances between the right and left intermediate fiducials and the end fiducials were also compared to assure that the frame was correctly aligned and that there was no distortion of the image from one side to the other.

Both $T_1$-weighted and short tau inversion recovery, as well as magnetization prepared rapid gradient echo images were used to maximize quality and to differentiate gray matter nuclei from white matter tracts. Finally, the phase and frequency encoding directions were reversed for identical images to take advantage of the reduced distortion of the phase encoded direction for all stereotactic measurements. The images were transported by fiberoptic link to the computer dose planning system (GammaPlan; Elekta Instruments) for the Leksell gamma unit. Targets were calculated by reference to the Schaltenbrand and Wahren Stereotactic Atlas[57] adjusted for the intercommissural (IC) distance, third ventricular width, and thalamic and basal ganglion anatomy.[53] For thalamotomy lesions, the intent was to place the lesions in the nucleus ventralis intermedius (VIM) and the posterior portion of the ventralis oralis posterior ventrolateral nucleus, contralateral to the side of the patient's more severe tremor.[15,19,23,47-49] The anteroposterior or $y$ coordinate was calculated from the atlas and adjusted as just described. The $x$ or lateral coordinate was determined from coronal images such that the lateral border of the lesion was calculated to coincide with the lateral thalamic border, that is, the junction between the thalamus and internal capsule (Fig. 1). The $z$ or vertical coordinate was calculated from coronal images such that the inferior edge of the lesion coincided with the inferior border of the thalamus (Fig. 1). The axial MR images were used to confirm the coordinates as well. Twenty-seven thalamotomy lesions were created in 27 patients. The general targeting coordinates reported by Laitinen were used for pallidotomy lesions.[29-32] The $y$ coordinate was again calculated by reference to the atlas, approximately 2 to 3 mm anterior to the IC point. The $x$ and $z$ coordinates were calculated by reference to coronal images so as to place the lesion in the medial globus pallidus just superior to the optic tract and just inferomedial to the internal capsule (Fig. 2). Both of the structures could be identified directly on the images. Axial images were also used to verify the targets.

Fig. 2. Upper: Preoperative stereotactic MR image demonstrating a planned pallidotomy target. Lower: Postoperative MR image demonstrating the pallidotomy lesion. The patient experienced complete cessation of contralateral
dyskinesias, marked reduction in ipsilateral dyskinesias, and significant improvements in bradykinesia and rigidity.

A total of 32 pallidotomy lesions were made in 28 patients. Three patients with severe akinesia received bilateral simultaneous lesioning and one patient underwent staged bilateral lesions 15 months apart. All other patients underwent unilateral lesioning, usually placed contralateral to the dominant hand, which in most patients exhibited the maximum functional disability due to bradykinesia and levodopa-induced dyskinesias.

All lesions were made using the 201-source $^{60}$Co Leksell gamma unit and the 4-mm secondary collimator helmet. The dose maximum varied between 120 and 160 Gy. Previous experience indicated that such doses would produce a spherical lesion that could be identified on follow-up contrast-enhanced MR images and that measured approximately 6 to 8 mm in diameter, that is, to approximately the 40 to 50% isodose line. Exposure times varied from 55 to 75 minutes and were dependent on the date on which the lesion was made, based on the radioactive half-life decay of the $^{60}$Co sources.

Patients were hospitalized overnight and discharged the following morning. Follow-up MR images were obtained every 3 months for the 1st year after treatment and then at intervals of 6 and 12 months.

**RESULTS**

The minimum follow-up time for patients reported here is 3 months (range 3-41 months) and the mean follow-up time is 14.1 months. Thirty-three patients have been followed for at least 1 year.

**Control Group**

Table 1 shows a comparison of the relevant demographic variables in the control, pallidotomy, and thalamotomy groups for those who were assessed by the independent team for determination of Hoehn and Yahr and UPDRS scores. There was no statistically significant difference between the groups on the basis of age or gender. The surgically treated patients, however, had a longer duration of illness ($p < 0.05$) and higher Hoehn and Yahr scores ($p < 0.05$) than the control patients. Follow-up testing 6 months after the initial evaluations showed no statistically significant overall changes in Hoehn and Yahr scores or UPDRS scores for the control group.

**Clinical Evaluation of Surgical Patients**

Clinical evaluations were performed by two independent, trained nurses as well as the senior author (R.F.Y.). Tremor was evaluated by patient self-assessment, direct observation, performance tests (such as
finger tapping), writing samples, and videotaped analysis. Tremor was classified as completely absent (excellent result), nearly completely absent (good result), or not significantly changed (failed). Notation was made of the patient's usual medication usage and of the most recent dosing to determine if patients were in the "on" or "off" states at the time of assessment. Every effort was made to perform the preoperative and follow-up assessments at the same time point in reference to medication usage. Levodopa-induced dyskinesias were evaluated in a similar way to tremor, as were bradykinesia, rigidity, and gait.

The clinical results of thalamotomy are presented in Table 2. Twenty-four (88.9%) of 27 patients who underwent thalamotomy experienced complete (19 patients) or nearly complete (five) resolution of tremor. These results were confirmed by direct observation and handwriting samples obtained by the senior author and by patient self-assessments obtained by the independent nursing team. Videotaped analyses were reviewed independently by both the senior author and the nursing team and there was uniform agreement on the effect of the procedures on tremor. Finger tapping speed was tested by the senior author and improved from 15 to 95% in the 24 patients who showed other evidence of improvement in tremor. There was no improvement in finger tapping in the three patients judged by other criteria to have no improvement in tremor. Usually within 2 to 3 months of the procedure the patients noted a gradual, progressive decrease in tremor that continued to decrease over the ensuing 3 to 6 months. A single patient showed little or no effect within 6 to 12 months of the procedure, but then over the next several months experienced progressive reduction in tremor. In three patients, follow-up MR imaging showed the development of well-placed lesions of the expected sizes; however, there was little or no reduction in tremor. These patients have been followed for 12, 18, and 36 months, respectively.

<table>
<thead>
<tr>
<th>Table 2: Clinical Results in 27 Patients Undergoing Thalamotomy</th>
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<tr>
<td>Result</td>
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<td>-------------------</td>
</tr>
<tr>
<td>Tremor free</td>
</tr>
<tr>
<td>Nearly tremor free</td>
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<tr>
<td>Failure</td>
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<td>Total</td>
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The clinical results following pallidotomy are shown in Table 3. Fourteen patients in this group originally demonstrated levodopa-induced dyskinesias and 12 (85.7%) experienced either complete or nearly complete resolution of this symptom as judged by the senior author and independently corroborated by the nursing team. Two other patients experienced significant improvements in dyskinesias. The effects were nearly always contralateral to the side of the lesion. Four patients showed ipsilateral reduction in dyskinesias; however, these ipsilateral effects were much less dramatic than the contralateral effects. As in the thalamotomy group, the reduction in dyskinesias usually began 2 to 3 months after the procedure with continued improvement noted over the next 3 to 6 months. All 28 patients who underwent pallidotomy experienced bradykinesia to varying degrees and 18 (64.3%) of 28 were thought to have significant clinical improvement following the procedures. Finger tapping speed was increased from 15 to 70% in the 18 patients who showed improvements in bradykinesia. There were no significant changes in the other 10 patients. The time course of improvement was similar to the time course for tremors and dyskinesias and again was strictly contralateral to the lesioned side.
Three severely akinetic patients who underwent bilateral simultaneous pallidotomies were not significantly improved after the procedures. One patient underwent staged bilateral pallidotomy with 15 months between procedures. This patient had undergone three prior radiofrequency thalamotomies for tremor at another institution without sustained relief. At the last follow-up review 41 months after the first procedure, he had complete relief of all tremor. Although he remains independently ambulatory, a progressive gait disturbance and reduced voice volume have developed over the past 12 to 18 months. Patients with severe gait disturbances and balance problems (Hoehn and Yahr stage IV) showed little or no improvement in gait, as judged clinically, although improvements in bradykinesia and levodopa-induced dyskinesias were noted in some of them.

**Quantitative Testing**

Thalamotomy. Eight of 16 patients with PD who underwent thalamotomy were evaluated preoperatively and again 6 months after lesioning. There was no overall change in Hoehn and Yahr scores. Evaluations of UPDRS scores (Table 4) showed statistically significant improvements in the activities of daily living (ADL) ($p = 0.008$), contralateral motor subscore ($p = 0.03$) and total UPDRS scores, both contralateral ($p = 0.05$) and ipsilateral ($p = 0.02$) to the side of the lesion when compared to the control group. Comparisons of UPDRS scores at the time of initial evaluations and 6 months after lesioning showed statistically significant improvements in the ADL subscores ($p = 0.02$) and in the total UPDRS scores ($p = 0.02$) contralateral to the lesions (Table 5). Total UPDRS scores ipsilateral to the lesions also showed improvement but the changes did not quite reach statistical significance ($p = 0.06$).

| TABLE 3  
| CLINICAL RESULTS IN 28 PATIENTS UNDERGOING PALLIDOTOMY |
| --- | --- | --- |
| Symptom | No. of Patients | Improved (%) |
| bradykinesia | 28 | 18 (64.3) |
| dyskinesias | 14 | 12 (85.7) |
| rigidity | 28 | 18 (64.3) |
| akinesia | 3 | 0 (0) |

**Pallidotomy.** Seventeen of 28 patients who underwent pallidotomy were evaluated preoperatively and again 6 months after lesioning. There were no significant changes in the overall population in any of the comparisons for Hoehn and Yahr or UPDRS scores whether the UPDRS scores were compared to the control group or compared pre- and postoperatively for the same patients (Tables 4 and 5). Examination
of the individual UPDRS scores indicated that 10 (58.8%) of 17 patients demonstrated improved scores for ADL (mean improvement 19.4%) and for total scores contralateral to the lesions (mean improvement 23.2%). Eight patients (47%) showed improvements in contralateral motor scores (mean improvement 32.2%). Interestingly, 10 patients (58.8%) also showed improvements in ipsilateral total UPDRS scores (mean 27.8%) and 10 (58.8%) showed improvements in ipsilateral motor scores (mean 37.7%). Overall, 11 (64.7%) of 17 patients showed improvement in at least one UPDRS score.

**Complication Rate**

Only one patient (1.8%) experienced any complication due to a procedure. This 65-year-old man developed a complete left homonymous hemianopsia 9 months after a right pallidotomy performed at 120 Gy. Follow-up MR images at 3 and 6 months showed a normally developing lesion, but at 9 months the lesion was substantially larger than expected (volume 950 mm$^3$) and included the optic tract. Additional follow-up imaging showed a gradual decrease in the size of the lesion but there had been no clinical improvement as of 22 months after the procedure.

**Follow-Up MR Imaging**

At least one follow-up image was available in each of the 44 patients. Lesion volumes were measured to the outer edge of the contrast-enhanced ring. A total of 95 lesions were measured in 44 patients. For a variety of reasons, images were not available in 11 patients. Mean lesion volumes are shown in Table 6 at 3, 6, 9, and 12 months postoperatively. There were too few images obtained at 18 and 24 months from which to make meaningful calculations. The range of lesion volumes is also shown in Table 6. The small number of lesions available for measurement at 9 months (seven lesions) and 1 year (14 lesions) resulted in the mean values being skewed by two patients with relatively large lesions at those time intervals. Excluding those two patients, the mean volumes at 9 and 12 months were smaller than those at 3 and 6 months postoperatively (Table 6). In addition, the accuracy of lesion placement was estimated on follow-up images. Measurements of the stereotactic coordinates of lesions were obtained postoperatively. If possible, images were obtained at our institution by placing the patient's head within the stereotactic fiducial system but without skull fixation. The image data were then entered into the computer dose planning system for coordinate determination. Images obtained at other institutions were measured by hand to determine the stereotactic coordinates of the lesions. In addition to stereotactic coordinate determination, lesions were observed for their relationships to adjacent structures such as the internal capsule and optic tract. Repeated measurements on the same image indicated that the error in the

<table>
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<th>TABLE 5</th>
<th>RESULTS OF COMPARISON OF PREOPERATIVE AND 6-MONTH POSTOPERATIVE UPDRS SCORES IN EIGHT PATIENTS UNDERGOING THALAMOTOMY AND 17 PATIENTS UNDERGOING PALLIDOTOMY$^a$</th>
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<tbody>
<tr>
<td>Type of Test</td>
<td>Thalamotomy</td>
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<tr>
<td>mention</td>
<td>0.18</td>
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<tr>
<td>ADL</td>
<td>0.02$^*$</td>
</tr>
<tr>
<td>motor (con)</td>
<td>0.13$^*$</td>
</tr>
<tr>
<td>motor (ips)</td>
<td>0.36</td>
</tr>
<tr>
<td>total UPDRS (con)</td>
<td>0.02$^*$</td>
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<tr>
<td>total UPDRS (ips)</td>
<td>0.06</td>
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$^*$ Statistical significance was defined as $p < 0.05$. con = contralateral to lesion; ips = ipsilateral to lesion.
measurement technique alone, because of differences in estimates of lesion's centers, location of commissures, and other anatomical structures, averaged approximately 1 to 1.5 mm. Details of these measurements will be published later.

<table>
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<th>Table 6: Lesion Volumes at Various Postoperative Intervals</th>
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<tr>
<td>Factor</td>
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<td>--------</td>
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<tr>
<td>volume (mm$^3$)</td>
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<td>range (mm$^3$)</td>
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* Decreases to 163 if one lesion 700 mm$^3$ is excluded.
† Decreases to 191 if one lesion 520 mm$^3$ and one 700 mm$^3$ are excluded.

The maximum deviation from the calculated target in any of the coordinates (x, y, z) was 2.1 mm and the mean deviation was 0.5 mm for x, 0.8 mm for y, and 1 mm for z. No lesion unintentionally encroached on an adjacent structure except the one that resulted in a homonymous hemianopsia. In that case the lesion eventually became much larger than expected, but the lesion center was initially at the intended target coordinates.

**DISCUSSION**

Several controversies exist in the field of functional stereotactic neurosurgery for movement disorders. These include the accuracy of stereotactic planning using MR imaging, the role of microelectrode recording in target localization, and the efficacy of pallidotomy and thalamotomy, among others.

The current report addresses these and other controversial issues. Our prior reports show that MR imaging alone is sufficiently accurate to provide localization for stereotactic lesioning. A number of authors have addressed the issue of magnetic field inhomogeneity resulting in distortion in MR imaging. Alexander and colleagues described a method to correct MR image distortion using a formula based on CT scanning. We replied then and we reiterate now, that with a meticulous quality assurance program, MR image distortion can be minimized so that the test is sufficiently accurate for stereotactic coordinate determination. The important elements of MR image quality assurance include regular alignment of the main magnet, use of a high magnetic field gradient, placement of the stereotactic frame to locate the intended target close to the center of the stereotactic space where distortion is at a minimum, and use of the minimal distortion in the phase encoded direction of the imager. With such measures, accuracy in the 1-mm range can be achieved.

The value of electrophysiological localization to refine the targets for stereotactic lesioning for movement disorders has been generally accepted. Yet in 1985, Laitinen reported that 12 different, well-respected, stereotactic neurosurgeons throughout the world identified a variety of thalamic lesion sites as their ideal target for treatment of the movement disorders of PD. The same is true of pallidotomy. These observations belie the idea that there is some magical tiny cluster of cells within the basal ganglia that can only be identified by electrophysiological localization and that, when lesioned, produces the best results in movement disorder surgery. A recent survey of practice techniques indicated that only approximately 50% of neurosurgeons performing pallidotomy used microelectrode recording for target localization, although another 25% were considering adding that capability to their procedures. Although there are strong advocates for the microelectrode approach, there is in reality no documentation that such methods improve either the
efficacy or safety of functional stereotactic procedures. Our own experience with microelectrode techniques for clinical and research purposes indicates that procedures performed with such guidance are probably no more effective and may be associated with more complications than those that are not. In fact, Ohye, et al., a group with extensive experience in microelectrode-guided functional stereotactic procedures for movement disorders, have recently described their experience with gamma knife thalamotomy using methods similar to those described in our report.

The use of an open surgical technique may account for the apparent need for electrophysiological localization because of brain shifts that may result from loss of cerebrospinal fluid or because even microelectrodes may displace rather than penetrate brain tissue. Certainly if techniques such as ventriculography or CT scanning are used for stereotactic localization, electrophysiological corroboration is needed to identify functional targets accurately. The ability of MR imaging to demonstrate the actual target for lesioning as well as anatomical reference points such as the commissures makes the need for electrophysiological target localization questionable.

More important than these theoretical considerations, however, is the safety and efficacy of the procedures. Our success rates based on clinical evaluations for thalamotomy for tremor control and pallidotomy for control of bradykinesia, rigidity, and levodopa-induced dyskinesias are very similar to those reported for open stereotactic procedures of a similar type. Our success rate of 88.9% in controlling tremor by gamma knife thalamotomy compares favorably with the 91% reported by Fox, et al., and 90% reported by Jankovic, et al. for open thalamotomy. Quantitative, blinded assessment of Hoehn and Yahr and UPDRS scores produced some different results from those of the clinical evaluations. For thalamotomy the efficacy of the procedure as assessed clinically was confirmed by the UPDRS scores without a change in Hoehn and Yahr scores. These improvements were verified in comparisons made of the same patients before and at 6 months after surgery and in comparisons made with a control group of PD patients who did not receive surgical treatment. The efficacy rates for pallidotomy remain controversial, with some authors reporting very good results and others reporting little overall effectiveness. Using clinical assessment, gamma knife pallidotomy controlled levodopa-induced dyskinesias in 85.7% of patients with PD who exhibited this symptom, and there were significant reductions in dyskinesias in the other 14.3%. Thus, all patients with dyskinesias experienced improvement after pallidotomy. Bradykinesia and rigidity were improved in 64.3%.

Quantitative, blinded assessment gave different results depending on the evaluation method and such differences have been discussed previously by Pernat, et al. Considering the pallidotomy population as a whole, neither Hoehn and Yahr nor UPDRS scores confirmed the clinical improvements. When examined individually, however, nearly 60% of patients showed improvements in ADL scores and in total scores contralateral to the lesions. In addition, nearly half (47%) showed improvements in contralateral motor scores, whereas ipsilateral total UPDRS scores and ipsilateral motor scores were improved in 59%. The greater improvement in ipsilateral than in contralateral scores is puzzling but may be accounted for, at least in part, by the relatively small number (17) of patients assessed and the large impact of changes in only a few patients. The results do point out, however, that ipsilateral as well as contralateral benefit may be obtained by unilateral pallidotomy. Overall, 11 (64.7%) of 17 patients showed improvement in one or more of the UPDRS scores. Thus, we confirm that pallidotomy can improve performance in approximately two-thirds of patients. Currently we are seeking to determine...
what factors may precipitate favorable outcomes to refine our selection process. It appears that our overall clinical assessments and the blinded UPDRS evaluations correlate reasonably well and indicate that although useful, at least in our hands, pallidotomy is not a cure-all for PD. The reason for the differences in the pooled UPDRS scores for the thalamotomy group versus the pallidotomy group is unclear. The significant improvements in pooled UPDRS scores for thalamotomy patients confirmed the clinical results, whereas for pallidotomy patients the pooled data did not show any overall change. The follow-up images confirmed the accuracy of lesion placement for both groups; this tends to reduce the likelihood that targeting errors accounted for the less favorable results in the pallidotomy group. The pallidotomy group had higher beginning Hoehn and Yahr scores, perhaps indicating that patients with more advanced stages of the disease do not fare as well as with surgical intervention. Another possible interpretation is that pallidotomy is a less effective procedure than thalamotomy. It does not appear to ameliorate all symptoms and the factors that predict a favorable outcome have not been fully determined.

Only one complication, a homonymous hemianopsia following pallidotomy, has been observed in 55 patients in our experience. Jankovic, et al.[23] recently reported a 58% immediate complication rate following stereotactic radiofrequency thalamotomy and a 23% persistent complication rate. Additionally, Jankovic, et al., reported that an initial thalamotomy failed to give lasting relief of tremor in nine of 60 patients and these lesions were enlarged during second procedures performed an average of 2 months after the initial procedures. Thus the failure rate for the first procedure was 15%, virtually identical to our failure rate of 11.1%. [23] Laitinen, et al.[34] reported a 15% incidence of visual field defects after radiofrequency pallidotomy, but in more recent reports such field defects are rare.[11,22,33,35,36,44] Lozano, et al.[44] reported an intracerebral hemorrhage that required craniotomy for evacuation following a microelectrode-guided pallidotomy.

The primary problem with functional stereotactic procedures using the gamma knife has been accuracy in identifying or attaining appropriate targets. The primary problem has been variability in lesion volumes using identical radiosurgical parameters.[17,27,72] Leksell and colleagues have described medial thalamic lesions made using the gamma knife with dose maximums of 180 to 200 Gy.[14,38,40,58] These lesions were made to control cancer-related pain. Only a few autopsy descriptions of such lesions were obtained, usually after patient survival times of just a few months.[65] Imaging techniques to study such lesions were not available at that time. Although the lesions in the early reports were made with a single isocenter, the secondary collimator helmet used at that time is not currently available. We and others have reported the variability in volumes of lesions made with the gamma knife.[17,27,72] Tomlinson, et al.[64] also described MR imaging following radiofrequency thalamotomy for tremor control. We have gradually decreased the dose maximums we used to make functional lesions with the gamma knife.[72] In addition, we no longer make multiisocenter lesions with the gamma knife because this technique appears to result in even more variability in lesion size.[72] Using dose maximums in the 120- to 140-Gy range and the 4-mm collimator helmet, lesion volumes are relatively reproducible. Dose maximums below 120 Gy may not produce lesions identifiable on follow-up MR images. Whether changes in brain function may be induced by gamma knife radiosurgery without an identifiable lesion is unproven. There is some evidence, however, that such functional changes may indeed occur.[54] Interestingly, our single complication occurred with a lesion made using only 120 Gy, which may indicate the unpredictable nature of functional radiolesions even at lower dosage levels. It is clear from our earlier work, however, that lower dosage and single isocenter lesions are more predictable in size than are lesions made at higher doses with multiple isocenters.[72] Even with this variability, however, we found only one clinical complication in 55 patients (1.8%). This compares very favorably to the
complication rate for radiofrequency lesioning procedures.

We believe that radiosurgical lesions made with the gamma knife may be used successfully and safely to treat movement disorders. The efficacy and safety of the procedure compares favorably to that of open, electrophysiologically controlled, radiofrequency lesioning procedures and is a viable alternative technique that may be particularly suitable for older patients, those with significant systemic diseases other than their movement disorders, and those with coagulopathies caused by disease or the use of anticoagulant agents. Its use in the general movement disorder population also appears reasonable.

Acknowledgments

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