Methods for microelectrode-guided posteroverentral pallidotomy

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Methods for localizing the posteroverental globus pallidus internus are described. The authors’ techniques include the use of microelectrodes to record single-unit activity and to microstimulate in human pallidum and its surrounding structures. This technique allows a precise determination of the locations of characteristic cell types in sequential trajectories through the external and internal segments of the pallidum. The location of the optic tract can be determined from microstimulation-evoked visual sensations and recordings of flash-evoked potentials. In addition, microstimulation-evoked motor and sensory responses allow the internal capsule to be identified. The data collected using this technique are an important adjunct to selecting optimum sites to place electrocoagulation lesions for stereotactic posteroverental pallidotomy for refractory Parkinson’s disease.

KEY WORDS • stereotaxy • microelectrode • visual evoked potentials • pallidum • microstimulation

PALIDOTOMY was used as a surgical treatment for Parkinson’s disease in the 1950s and 1960s. Various techniques were used to inactivate or ablate the globus pallidus (GP) such as procaine in oil, occlusion of the blood supply, deposition of radioactive material, cryolesions, or electrocoagulation. Pallidotomy was almost entirely replaced by the thalamotomy procedure of Hassler and Riechert, which was reported by these authors to be more effective for tremor reduction. The surgical treatment of parkinsonism declined in general with the introduction of L-Dopa pharmacotherapy.

For several reasons, there is a renewed interest in stereotactic posteroverental pallidotomy for the treatment of Parkinson’s disease. First, current therapy is not totally satisfactory, because certain patients do not tolerate available drugs, they are inadequately treated, or they develop motor and nonmotor complications. Second, there have been significant improvements in neuroimaging and surgical techniques in the last 30 years, making the stereotactic procedure safer and more accurate. Third, the effectiveness of pallidotomy has been recently reconfirmed, which has prompted a reexamination of this surgical treatment. Finally, advances in the understanding of the basal ganglia and the pathophysiology of parkinsonism have provided a scientific rationale to proceed with neurosurgical strategies to control the overactivity of the internal segment of the GP.

Recently, several groups have initiated microelectrode recordings in the human pallidum and reported the identification of cell types described in nonhuman primates. Our group has obtained extensive experience with thalamic recordings and localization techniques and has now gained experience with pallidal functional stereotactic localization. We examined the overall neuronal firing rates in the various segments of the GP and found evidence of elevated activity in the internal segments of the globus pallidus internus (GPI) that resembles the alterations reported in 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine–treated monkeys. We have also identified “tremor cells” in the GPI by means of spectral and autocorrelogram analyses.

In this study, we report using microelectrode recording and stimulation techniques to determine the optimum site for radiofrequency lesions. To a large extent the target depends on the location of the optic tract and internal capsule, which are in intimate relation to the lesion site and for which there is a risk of injury during pallidotomy.

Clinical Material and Methods

Patient Population

We have currently performed microelectrode-guided pallidotomy in 70 patients for refractory Parkinson’s dis-
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ease, and in four for striatoni gral degeneration. The main symptoms were rigidity and bradykinesia/akinesia, with some patients presenting with tremor of varying degree, and three with severe tremor. Patients gave informed consent prior to the procedure, and the protocol was reviewed and approved by The Toronto Hospital Committee for Research on Human Subjects.

Stereotactic Procedure

A Leksell model (D or G) stereotactic frame was applied after local anesthetic. Patients underwent magnetic resonance (MR) imaging to localize the anterior commissure (AC) and posterior commissure (PC). A Sigma 1.5-tesla magnet (General Electric, Milwaukee WI) was used to produce 1-mm thick nonoverlapping slices in axial, sagittal, and coronal planes. Images were acquired using the “spooled grass” sequence with a relaxation time of 43 msec and an excitation time of 13 msec. The stereotactic coordinates of AC and PC were calculated using the MR imaging console software. The calculated intercommissural line was transcribed onto a digitized sagittal stereotactic map from the Schaltenbrand and Wahren atlas. The atlas map was stretched or shrunk as a function of the relative length of the patient’s intercommissural line. The tentative target was chosen at a point 1 mm above the most ventral portion of the GPi in a plane 20 mm from the midline and in the center of the GPi in the anteroposterior plane.

The patient received local anesthetic, and a single 3-mm twist-drill hole was made in the skull anterior to the coronal suture approximately 2 cm from the midline corresponding to the parasagittal plane of the intended series of electrode trajectories. The dura was penetrated with a sharp probe and the microelectrode guide tube, with an outer diameter of 1.1 mm, was stereotactically placed into the cerebrum so that the tip was 1.5 to 2.0 cm from the intended target location. A sterile microelectrode in a protective carrier tube was inserted into the guide tube so that the tip of the microelectrode was flush with the tip of the stereotactically placed guide tube. The microelectrode was fastened to the hydraulic microdrive that was carried on the arc car adaptor (or guide tube adaptor) of the stereotactic frame so that the tip could be advanced up to and beyond the intended target while recording neuronal activity. The initial target was approached in a parasagittal plane at an angle of 47° to 81° from the horizontal axis of the stereotactic frame (approximately 50°–60° from the AC–PC line). Usually three to six electrode trajectories were explored in each patient.

Microelectrodes and Signal Amplification

Electrodes were constructed using commercially available parylene-C–coated microelectrodes. The insulation of the parylene-C–coated electrodes is deposited by a “sputter” technique from a vapor phase, and the tips are exposed with a high-voltage arc pulse, techniques not performed in our laboratory. The length of exposed tip ranged from 15 to 40 µm and initial impedance from 1 to 2 Mohm. The shank of the electrode was stripped of insulation, crimped, and inserted into long thin 25-gauge stainless steel tubing insulated with a covering of 23-gauge polyimide tubing (Micro ML; Niemand Industries, New York, NY). Under microscopic control, the insulating tube was slid down toward the electrode to overlap and cover the insulated shank of the electrode, and epoxy resin glue was used to join the two insulators to make a contiguous seal. The impedance of electrodes was monitored before and after electrolytic plating of the exposed tip with gold and platinum black, which increases the microscopic surface area and results in a drop in impedance measurement to one-fifth to 1/20 the original measurements (from approximately 1 Mohm to < 0.2 Mohm). The plating at the electrode tip attracts free chloride ions when it comes into contact with saline to form a nonpolarizable Pt–PbCl₂ junction. This reduces the impedance at the electrode tip surface and decreases electrical noise at low frequencies. The patency of the insulation at the junction of the electrode shaft and polyimide tubing was tested by: immersion of the junction in 0.9% saline and observation of an impedance reading identical to that obtained with only the tip immersed; and/or application of a low DC voltage (5 V) to the electrode and observation of bubble formation only at the tip. Completed electrodes were inserted into labeled protective carrier tubes and placed in a perforated container for gas sterilization, along with leads for their attachment to the preamplifier. The electrode leads were shielded coaxial cable that was kept to the shortest length possible (approximately 10 cm) to reduce noise from stray capacitance. The hydraulic microdrive was sterilized by immersion in a 2% glutaraldehyde solution for at least 20 minutes, followed by a rinse in sterile water. In addition, a larger tipped electrode was constructed by insulating the 25-gauge stainless steel tubing to within 1.5 mm of the tip with polyimide tubing and beveling and polishing the tip to remove any sharp edges. This could be used for macrostimulation and for microinjection of lidocaine into the GP, as has been previously described for the thalamus.

A preamplifier (model DAM 80; World Precision Instruments, Sarasota, FL) was used with the gold-plated headstage mounted on the arc car adaptor along with the hydraulic drive attached to the microelectrode assembly. Signals from the preamplifier were amplified and electrically isolated (brush model 11414310; Gould Inc., Valleyview, OH), filtered (model 3700; Krohn-Hite, Avon, MA), and led to oscilloscopes, a window discriminator (Winston Electronics, Millbrae, CA), and an audio monitor (Grass AM 8; Grass Instruments, Quincy, MA). The window discriminator used in the operating room has two variable voltage levels that can be set so that spikes of an intermediate voltage amplitude will trigger a logic pulse that is used to count and display firing frequencies. To better identify single-unit neuronal responses to active or passive somatic movements, this pulse was monitored on the audio amplifier. The audio monitor has a noise clipping circuit to remove high-amplitude portions of the spike signal so that the low-amplitude signal is not discriminated against by background noise. A digital recording device (VR-100-B; Instrutech Corp, Great Neck, NY) was combined with a high-fidelity video cassette recorder for storage of up to eight channels of data (microelectrode recording, 4 electromyographic (EMG) signals, accelerometer output, slow-wave) on individual video tapes. Another high-fidelity video cas-
sette recorder was used to film the patient’s movements simultaneously with the neuronal data (recorded on one of the two audio channels).

**Microstimulation and Photic Stimulation**

Electrical stimulation through the electrode tip was performed using a stimulus generator with a constant-current stimulus isolation unit (models A310 and A360; World Precision Instruments). A separate lead was manually clipped to the top of the electrode’s stainless steel shank. Stimulation was usually a 1-second train consisting of 0.2-msec negative-going monopolar pulses at 300 Hz.

**Fig. 1.** A reconstruction of a microelectrode trajectory that traversed external globus pallidus (GPe), internal globus pallidus (GPi), and optic tract (OT). A: The trajectory through the pallidum is demonstrated on the sagittal brain map (from Schaltenbrand and Wahren atlas27) 20 mm lateral to midline. The trajectory has been adjusted to approximate the physiological data as shown in B; however, note that the physiological data still do not completely match the 20-mm lateral map. B: Reconstruction of the trajectory in A is shown with results of microelectrode recordings and stimulation. Thick lines represent the cellular areas and thin lines represent the acellular (quiet) regions. Receptive fields (RFs) are shown to the left of the line along with the depth of the recordings along the trajectory. Receptive fields are shown on figurines. The joints around which movement elicited modulation of cellular activity are circled. Projected fields (PFs), or the effects of microstimulation, are shown to the right of the line along with the current used. Stimulation was performed only at the bottom of the trajectory to help identify the OT (V₁ = visual sensations). This example is somewhat unusual in that the patient did not have visual sensations with microstimulation at the depths at which recordings suggested the OT was present. C: Examples of typical cells recorded along this trajectory at each level of pallidum. One second of recording is shown for all except the OT recording that shows 0.1 second. For the OT, a single-pass recording is shown above the multisweep potential response to strobe light stimulation. The evoked potential is shown in the standard format of negative upward used for visual evoked potentials (VEPs). The stimulus artifact is the large vertical deflection at the beginning of the single-pass sweep. When this single-pass recording is amplified into an audible signal, the increase in baseline noise occurring at the 40-msec deflection of the VEPs can easily be heard. Note that the gain has been reduced in the lower GPe trace. AC = anterior commissure; PC = posterior commissure.
We recorded the axonal activity in the optic tract evoked by repetitive flashes of a strobe light with the room darkened. Photic stimulation was performed with a strobe light (Grass Instruments) normally at 1 Hz repetition. The filter was set for a wide-frequency bandpass from 0.1 Hz to 10 kHz, and signal averaging was performed with a digital oscilloscope (model DS6411-40 MHz; Iwatsu, Japan) with at least 16 sweeps per average. Offline analog filtering was performed with a low-frequency bandpass filter set at 0.2 Hz to 100 Hz and a gain of 20 dB and digitized at a rate of 200 Hz. Sampled latencies of biphasic peaks were calculated with a field potential computer program (see bottom trace in Fig. 1).

Testing for Movement-Related Activity of Pallidal Neurons

Single units were tested for responses to active and passive movements about various joints. Stable units were tested with a comprehensive battery of passive and active movements of digits, wrist, elbow, shoulder, ankle, knee, and hip both ipsi- and contralateral to the operative side. In addition voluntary orofacial movements were requested: jaw opening and closing, tongue protrusion, and ocular movements. In cases of neurons with rhythmic discharges, irregular repetitions of the passive movements were tested to better distinguish movement-related activity. For research purposes, surface EMG activity was recorded from contralateral wrist flexors and wrist extensor muscles, ipsilateral wrist flexors as well as foot dorsiflexors (tibialis anterior). An EMG signal conditioner (model 2004-F; Intronix Technologies, Concord, Canada) was used to amplify and filter EMG signals using a low-pass filter (1 Hz–500 Hz) to avoid signal aliases during subsequent off-line digitization. An accelerometer (Entran Devices, Fairfield, NJ) was attached to the patient’s dorsal index finger (or sometimes under the chin to monitor jaw movements), and the output was amplified and recorded on tape for off-line analysis.

Typical Findings and Strategy

In most cases, penetrations passed successively through the external GP (GPe), the external and internal segments of the GPi, and the optic tract. Anteriorly, the external and internal segments of the GPi are separated by a lamina of white matter (approximately 1 mm wide from the stereotactic atlas), which can often be recognized as an area of diminished neuronal activity (Fig. 1B). Border cells were frequently recorded in the vicinity of this lamina. These regions could be identified on the basis of their differing neuronal characteristics as described below. In general the types of cells encountered in human pallidum are similar to those described in nonhuman primates.4,8,9

External Globus Pallidus. Two distinct patterns of spontaneous ongoing activity were usually observed. Some units had a slow-frequency discharge (10 Hz–20 Hz) punctuated by rapid bursts (Fig. 1C, GPe top trace). Other units discharged with an irregular pattern at a higher frequency (30 Hz–60 Hz) also with intervening brief pauses (Fig. 1C, GPe lower trace). However, we occasionally found neurons with high irregular firing rates localized to this region as well. Many of the GPe units fired in response to repetitive movements. Some units showed an inhibition of the baseline rate of discharge (see Fig. 2 upper), whereas the majority showed an increase in the discharge frequency with passive or active contralateral movements.

Internal Globus Pallidus. In patients with Parkinson’s disease, neurons in the internal segment of GPi generally had a baseline rate of firing that was higher than that found in GPe (82 ± 32 Hz vs. 60 ± 36 Hz, mean ± standard deviation).17 The range of discharge rates in GPi as a whole was 20 to 200 Hz with few of the brief pause periods described above for neurons in GPe. Typical GPi units are shown in Fig. 1C. Some GPi units responded to movements, and the majority of units responded exclusively to contralateral movements, although some units could be activated by movements of both right and left limbs, with a preference to either voluntary or passive movements. The most common finding with movement was an increase in the discharge rate of the GPi neuron, as illustrated in Fig. 2 lower. In addition some of the units fired in synchrony with tremor (Fig. 3). Microstimulation in the
GPi rarely evoked sensations or motor effects, but tremor reduction from microstimulation in GPi has been observed in some patients.

**Border Cells.** Border cells in nonhuman primates have been found at the borders of the internal and external pallidal segments\(^8,10\) and are thought to have neurophysiological properties similar to cells of the substantia innominata found at the ventral border of the GP.\(^4\) Recent reports from several groups have confirmed the existence of border cells in comparable locations in human pallidum.\(^17,28\) In 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine–treated monkeys showing Parkinson-like symptoms, border cells take on a slightly more irregular firing pattern than is found in untreated control animals.\(^8,9\) In humans with Parkinson's disease, border cells (Fig. 1C) are distinguishable from GP units by their regular firing pattern of 30 to 40 Hz. In contrast to neurons in the GPi and GPe, no border cells have been found to respond to repetitive limb movements.

**Optic Tract.** It is very important to identify the optic tract to localize the target and avoid possible visual complications of lesion making. It is usually quite apparent when the electrode emerges from the ventral and posterior border of the GP, because no further cellular activity is detected and the background noise in recordings diminishes. Action potentials arising from axons in the optic tract or capsule are not usually recorded by the electrode used; however, in some cases axonal spikes can be detected. Axons were tentatively identified by narrow (< 0.5 msec) monophasic spikes that were transiently recorded by the electrode tip. We have found that the most reliable way of detecting whether the electrode tip is in or near the optic tract is to use microstimulation. Stimulation in the optic tract should evoke visual sensations at currents of less than 20 μA, and thresholds can be as low as 2 μA. Patients report seeing lights or “stars” of various colors (most often blue, yellow, or white) or scotomata (clouds) in the contralateral visual field, and increasing the stimulation current produces a larger and brighter visual sensation. Some patients detect the stimulation-evoked visual sensations more readily if the ambient lighting is dimmed. With increasing distance away from the optic tract, the stimulation threshold increases. We do not use currents above 100 μA. The mean distance between the most ventral GPi unit and the visual responses evoked by stimulation of the optic tract was 1.6 mm ± 0.9 mm (23 cases).

For further confirmation of the location of the optic tract, we recorded strobe-evoked optic tract potentials from the appropriate portion of the trajectory. In most cases, optic tract potentials (see lower portion of Fig. 1C) could be obtained over the region corresponding to the lowest threshold for microstimulation-evoked visual reports. However this was not seen in all cases, and occasionally optic tract potentials were recorded where the patient did not report visual sensation from microstimulation.

**Internal Capsule.** The internal capsule lying medial and posterior to the GP is identified by the relative absence of somatodendritic action potentials and the occasional recording of axonal spikes. Stimulation in the capsule usually resulted in tetic contractions due to activation of corticospinal tract fibers and/or sensations of paresthesia (pulling, tugging, or tingling sensation). In eight of 23 cases sensorimotor responses (internal capsule) were found in tracks posterior to the GPi approximately 3 to 6 mm posterior to the evoked visual responses (optic tract).

**Lesion Making**

We did not perform lesioning until the ventral and posterior borders of the GPi were identified by recording and stimulation findings characteristic of the optic tract and internal capsule. Lesions, made in areas containing neu-
rons whose activity was modulated with movement, were at least 3 to 4 mm away from any point at which stimulation evoked a visual or motor response. Lesions were made by electrocoagulation using a high-frequency (100 kHz) sine wave current generator (OWL Universal RF System; Diros Technology, Inc., Toronto, Canada) with a 1-mm diameter probe whose last 3 mm was uninsulated. The heat generated during the lesioning process was monitored by a thermistor recording the temperature at the probe tip. After a test reversible lesion at 60˚C for 60 seconds, permanent lesions were made at 90˚C for 90 seconds. This procedure has been estimated to create a 5- to 6-mm diameter sphere of tissue destruction. Tomlinson, et al.\textsuperscript{31} found that a radiofrequency lesion in the thalamus at 78˚C for 60 seconds produces a stable lesion size of 3.3 mm diameter after 7 months. Patients had a single lesion or two overlapping lesions. Throughout the lesion-making process the patient’s speech and motor and visual functions were tested. Following the lesion making, patients resumed doses of anti-Parkinson medication as required.

Off-Line Data Analysis

Data stored on video cassettes were played back into a similar setup described above, except that a dual-window discriminator (model DDIDIS-1; Bak Electronics, Germantown, MD) was used, and in some cases computerized template matching was used to differentiate individual single units. Logic pulses from the window discriminator were used to trigger the digital storage oscilloscope (Iwatsu) with the spike signal delayed to superimpose waveforms and confirm their somatodendritic nature. The pulses were also fed into an event channel of a digital interface, and commercially available software (Spike2 Neurological Capture) was used to analyze and display data. Analog signals from the 4 EMG were digitized at 200 Hz and other markers (accelerometer; Entran Devices) were sampled at 40 Hz. Peri- and poststimulus time histograms and interval-time histograms were constructed for each neuron to examine baseline firing rates, characteristics of bursting, and movement-evoked activity.

Results

The site of lesion making was confirmed within 7 days of the surgery by postoperative MR imaging. A typical example is shown in Fig. 4. In all cases the center of the lesion was in the internal segment of the GP and had dimensions that averaged $4 \times 4 \times 6$ mm corresponding to a volume of 80 to 150 mm$^3$. In some patients a second lesion was made in the same trajectory 3 to 4 mm above the first lesion and occasionally in a different trajectory. Using the present method of functional localization of target sites in GP\textsubscript{i} based on mapping physiological results, the final lesion site is almost always revised from the stereotactic target used by Laitinen, et al.\textsuperscript{19} In fact, in only four of 26 cases was there little revision of the original stereotactic target. The final lesion site has tended to be in a location more dorsal and anterior to the recommended target (Fig. 5). We do not currently have sufficient follow-up data to know whether more dorsal or more extensive lesions give superior results.

At the time of scanning 1 week after the operation, edema was usually widespread around the lesion sites. Postlesion edema is well known in the clinical literature and is absent in scans from 6-month follow ups. There were few immediate adverse effects of the operation, although some patients complained of headache due to loss of cerebrospinal fluid. In one of 70 patients, a hemorrhage developed, signaled by progressive dysphasia and hemiparesis. A craniotomy was performed to evacuate an intracerebral hematoma from the path of the guide tube. The patient showed some improvement but still had speech and motor deficits at 3 months postsurgery. Most significantly, none of the 27 patients treated has shown any visual field deficits due to inadvertent damage to the optic tract.

Discussion

The introduction by Albe-Fessard, et al.,\textsuperscript{1} and Guiot and Brion\textsuperscript{2} of microelectrode recording to localize targets for stereotactic thalamotomy yielded much information on thalamic neuronal activity. These original studies were performed with larger tipped bipolar electrodes (50 \mu m) that recorded mainly multiunit activity and local field potentials.\textsuperscript{13} Bertrand, Jasper and coworkers\textsuperscript{2,16} reported using 2- to 3-\mu m tipped electrodes and were, therefore, probably the first to record predominantly single units in
the human thalamus. Compared to numerous thalamic microelectrode studies, there have been only isolated reports of recordings of human pallidal neurons. In 1965, Umbach and Ehrhardt \cite{32} recorded pallidal single- and multiunit activity using lacquer-insulated microelectrodes with tip sizes of either 1 to 2 \( \mu \text{m} \) or 20 \( \mu \text{m} \). They used a hydraulic microdrive and guide tube assembly adapted to Riechert and Wolff’s stereotactic frame \cite{32} and concurrently measured neuronal activity, deep electroencephalography and surface EMG of contralateral leg and shoulder. Studies by Raeva \cite{25} identified units responding to commands to prepare for movement in the lateral segment of GP (GPe) and identified cells with rhythmic oscillations in firing activity in synchrony with limb tremor in the medial segment of GP (GPI). Although primarily concerned with thalamic recording, Jasper and coworkers did tentatively identify single units recorded in medial pallidum in the anteroinferior portion of long curved trajectories originating in thalamus. Units responding to joint and digit movements as well as “tremor cells” were described.

The combined approach of recording and microstimulation has been used to an advantage in studies of human thalamus in stereotactic procedures for movement disorders and pain control (see Dostrovsky, et al. \cite{5}). We have used similar procedures to record from the human pallidum and described characteristic cell types and results from stimulation that provide neurophysiological “landmarks” to aid in the identification of optimum lesion sites for pallidotomy.

The criteria for making lesions in the GP of patients with Parkinson’s disease were: 1) identification of the somatosensory portion of GPI by recording single units with movement-related activity; 2) identification of the ventral and posterior borders of GPI to ensure that the optic tract and internal capsule could be spared. Using these physiological criteria, all the information was integrated from the trajectories to reconstruct the boundaries of GPI and determine the anatomical deviation from the calculated stereotactic maps.

The placement of lesions based on stereotactic coordinates determined from anatomical and clinical criteria was insufficient to guide lesion placement. Indeed, in our series we found that the stereotactic target was often too posterior and inferior to the best placement, as determined by the results obtained with microelectrode recording and microstimulation. In fact, in only four of 26 cases was there little revision of the coordinates. The deviations also suggest that in the absence of physiological confirmation of lesion sites more complications from optic tract damage may have arisen. In the study by Laitinen, et al. \cite{19} lesions were made 2 mm superior to sites at which macrostimulation induced visual sensation, or in later cases lesions were placed in trajectories 2 mm more lateral;\cite{19} despite these precautions, these investigators reported permanent partial homonymous hemianopsia in six (14\%) of 42 patients.

A further source of error may derive from the use of an anatomical or functional map of the human brain. In our method, the AC and PC coordinates are used to generate a customized sagittal map based on the Schaltenbrand and Wahren’s atlas. The orig-
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inal edition of this atlas by Schaltenbrand and Bailey is remarkably different and appears to be in error with respect to several structures in the region of the GP. First, the 18.5-mm lateral map in the original edition is identical to the 20-mm lateral map in the later edition. Second, the location of the AC as shown on the sagittal maps in 1959 (Schaltenbrand and Bailey) is 2 to 3 mm dorsal to that shown in the original atlas. Third, in the original atlas a white matter tract anterior to the optic tract is labeled “cerebral nerve II/optic tract.” In fact this white matter is more likely to be lateral olfactory stria. We have found the physiological map of the pallidum to match more closely the Schaltenbrand and Wahren edition of the atlas, and we use it exclusively in the selection of our target. The computer program uses these maps and modifies them to fit each individual’s AC–PC length and draws the mid-commissural line on the map. Our initial target is selected on this map as the most posteroventral part of GPi and in general corresponds to the target recommended by Laitinen, et al., that is, 2 to 3 mm anterior to the mid-commissural line and 3 to 6 mm ventral to the AC–PC line.

The use of both microelectrode recording and stimulation is highly recommended because specific instances have arisen when patients have reported visual sensations with microstimulation; however no visual evoked potentials were recorded over the same segment of the trajectory. Less frequently, no electrically evoked visual sensations were found despite good recordings of flash potentials from the optic tract. We have no certain explanation for why this would occur in an apparently attentive and comprehending patient.

Although microstimulation within the GP itself did not evoke somatosensory sensation, preliminary findings in two patients have shown tremor reduction and tremor arrest from stimulation at sites in which tremor cells were recorded. Further work may yield beneficial effects of electrical stimulation (especially with larger tipped electrodes) of GPi on motor performance. One preliminary report involving six patients has noted significant improvement in bradykinesia and rigidity with chronic electrical stimulation of the GP.

A preliminary analysis of the clinical outcome in 14 patients indicates that pallidotomy produces significant improvements in bradykinesia and drug-induced dyskinesia in our patients. Using the microelectrode recording and stimulation techniques, we had specifically no incidence of visual loss related to injury to the optic tract, but some patients experienced transient facial paresis that resolved with time.

It is still unclear what constitutes the best target or the optimum lesion size. Whether disruption of pallidofugal fibers at the ventral portion of GPi is also important for the optimum lesion benefit remains to be determined. Our usual pallidotomy lesions are 6 mm in diameter and centered at the most ventral portion of GPi and include the efferent axonal projections. These lesions are sufficient to produce a significant clinical benefit.

The present work shows that neurophysiological techniques can increase the accuracy and safety of the posteroventral pallidotomy. The results show that significant intraoperative modifications of target sites, selected on the basis of imaging procedures alone, can be made that avoid visual and motor complications. Furthermore, important information can be obtained concerning the physiological properties of the human GP. Further analysis and quantitation of these and subsequent data will be an important step toward establishing the optimum lesion placement in the GP of patients with akinetic rigid syndromes.

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