Flash visual evoked potential monitoring of optic tract function during macroelectrode-based pallidotomy

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Posteroventral pallidotomy (PVP) has received renewed interest as an ablative procedure for the symptomatic treatment of Parkinson's disease. In previous reports, the proximity of the optic tract to the lesion target in the globus pallidus internus has resulted in the occurrence of visual field deficits in as much as 14% of patients. The authors have used intraoperative visual evoked potentials (VEPs) during PVP to reduce this risk. All procedures were performed in awake patients. Flash stimuli were delivered to each eye via fiberoptic sources. Baseline flash VEPs were recorded at O1/Cz (left visual cortex to vertex), Oz/Cz (midline visual cortex to vertex), and O2/Cz (right visual cortex to vertex) for OS, OU, and OD stimulation. Epochs were acquired before and after localization, after macroelectrode stimulation, after temporary thermal lesioning, and after permanent thermal lesioning. Forty-seven patients underwent a total of 59 procedures. Visual evoked potentials were recorded reproducibly in all patients. In 11 procedures, VEP changes were reported, including six amplitude changes (10-80%), six latency shifts (3-10 msec), and one report of "variability." In four procedures, VEP changes prompted a change in target coordinates. One false-positive and one false-negative VEP change were encountered. The only confirmed visual deficit was a superior quadrantanopsia, present on formal fields, but clinically asymptomatic. The authors conclude that VEPs may be useful for procedures performed in the awake patient because of the lack of anesthetic-induced variability. The 1.7% visual morbidity reported here (one in 59 patients) compares favorably with other series using microelectrodes. Visual evoked potentials may be a useful monitoring technique to reduce the incidence of clinically significant visual morbidity during pallidotomy, especially during formal lesioning of the ventral pallidum adjacent to the optic tract.

Key Words * visual evoked potentials * pallidotomy * Parkinson's disease * intraoperative monitoring

Posteroventral pallidotomy (PVP) is currently advocated for the treatment of symptomatic advanced Parkinson's disease (PD).[14] Studies using macroelectrode techniques,[21] microelectrode techniques,[4,11,23] or a combination of both,[17] have shown that PVP may improve all three cardinal manifestations of PD: rigidity, bradykinesia, and tremor. Statistically significant improvements have been documented in Unified Parkinson's Disease Rating Scale (UPDRS) scores, an objective measure of motor performance in patients who have undergone PVP.[4,11,17]

The proximity of the optic tract to the ablative target, the globus pallidus internus (GPi), accounts for the association of PVP with postoperative visual field deficits. Previous studies have reported visual morbidity between 0% and 14%. [4,11,17,21,23] These prior reports have not used intraoperative cortical visual evoked potential (VEP) monitoring. During microelectrode-monitored pallidotomy Lozano, et al., [22] have described the use of directly recorded potentials in the optic nerve evoked by flash stimulus.

Visual evoked potential monitoring has been described by several groups as helpful in assessing the status of the visual pathways during surgery. [1,10,12,16,28,30-32] In contrast, other investigators have concluded that intraoperative flash VEPs are unreliable. [2,8,15,25] Previous problems with intraoperative VEPs in other settings have often stemmed from unacceptable anesthetic-induced variability [13] unrelated to actual optic pathway injury. In this pilot study, we have used VEPs to minimize visual morbidity in awake patients undergoing PVP.

CLINICAL MATERIAL AND METHODS

Patient Selection

All patients in whom pallidotomy was performed at the University of Pittsburgh Medical Center between April 1993 and April 1996 are included in this study. Patients with unilateral or bilateral rigidity and/or bradykinesia due to idiopathic PD were offered pallidotomy. The presence of levodopa-induced dyskinesias was also an indication for surgery. Patients with predominantly unilateral tremor were offered thalamotomy. Prior to surgery, medical therapy was maximized, usually with multiple agents. The majority of patients were evaluated pre- and postoperatively by a neurologist specializing in movement disorders (S.B.). The presence of a preexisting visual field deficit was an exclusion criterion. Other exclusion criteria were coagulopathy, uncontrolled hypertension, age older than 85 years, and patients with "Parkinson's plus" syndromes. [18]

The study group included 30 men and 17 women. The mean age was 66.1 years $\pm$ 8.1 standard deviation (SD), the average duration of illness was 13.8 years $\pm$ 6.3 SD, and the median preoperative Hoehn and Yahr score was 4 (range 2.5-5).

Pallidotomy Technique

A macroelectrode technique was used and has been described elsewhere. [18] Throughout PVP patients were awake and cooperative; a mild anxiolytic or narcotic agent was used sparingly. Gadolinium-enhanced magnetic resonance (MR) imaging was performed using a T₁-weighted sagittal localizing sequence, a volume acquisition fast gradient echo, and a fast inversion recovery sequence in both the coronal and axial planes. A radiofrequency probe (Radionics, Inc., Burlington, MA) with a 1.1-mm diameter and 3-mm exposed tip was used for both stimulation and lesion production. Initial targets were based on the coordinates described by Laitinen, et al.: [21] 2 to 3 mm anterior to the anterior commissure-posterior commissure midpoint, 18 to 22 mm lateral, and 5 to 6 mm inferior. Initial lateral coordinates varied for women (19 mm) and men (21 mm). Lateral coordinates were increased in patients in whom the third ventricle was dilated more than 4 mm. Targets were modified based on imaging that relied heavily on the coronal inversion recovery images. Targets that encroached on the optic nerve were moved superiorly, whereas those that encroached on the internal capsule were moved laterally. The GPi and GP externus (GPe) were typically well visualized on the coronal inversion recovery sequence, and targets were moved medially out of GPe and into GPi in several patients.

Motor, speech, and cognitive function were monitored clinically throughout the procedure. Macroelectrode stimulation was performed at 0.5 to 3 V and 5, 50, and 100 Hz. Target adjustment was indicated if any of the following occurred at thresholds of 2 V or less: visual symptoms, VEP changes, contralateral limb weakness or hypotonia, or a "capsular response" (marked rigidity and dysarthria or speech arrest). Also, if the patient's rigidity, tremor, or dyskinesia could not be modulated at all by stimulation, the target was moved. Test lesions (temporary thermal lesions) were performed at 40°C for 30 seconds. Permanent lesions were made at 70 to 78°C for 60 seconds. (The slight variability in temperature relates to the manual feedback control of the radiofrequency generator thermocouple.)

Visual Evoked Potentials

Preoperative baseline flash VEPs used a light source positioned 100 cm from the patient's nasion for monocular and binocular stimulation. Intraoperatively, flash stimuli were delivered through closed eyelids via fiberoptic light sources with attached reflective shields. Ambient light was minimized and maintained constant during recording. Intraoperative baseline flash VEPs were recorded while the patient was on the operating table using 128 trials per epoch at a stimulus frequency of 1.1 Hz, a 200 to 400-msec observation interval, an amplifier bandwidth of 1 to 300 Hz, and a gain of 10 to 50 k. Recordings were made from O1/Cz (left visual cortex to vertex), Oz/Cz (midline visual cortex to vertex), and O2/Cz (right visual cortex to vertex).

For intraoperative recording, monocular stimulation was used exclusively, usually alternating epochs between the ipsilateral and contralateral eyes. Epochs were acquired immediately before and after GPi localization, GPi stimulation, test thermal lesioning, and permanent GPi lesions. Patients were questioned regarding visual phenomena (phosphenes, blurring) and sensory disturbances (paresthesias, dysesthesias).

Visual Field Assessment

Pre- and postoperative confrontational field tests were performed by both the surgeon and a neurologist in all patients. The initial six patients underwent preoperative and postoperative formal visual field studies. Subsequently, visual field tests were no longer performed routinely, and no additional patients had visual complaints or deficits on examination that would have justified formal visual field mapping.

RESULTS

We reviewed 47 patients who underwent a total of 59 procedures.

Baseline VEPs

Pre-operative baseline VEPs obtained in a subset of 30 patients in this study have previously been reported (unpublished data). Responses were similar to those previously described,[3] with the N75 and P100 peaks (also termed peak III and IV) being identified most consistently. Significant prolongation of latencies of the N75 and P100 peaks compared to historical controls was noted. Average latencies for these two waves were approximately 100 msec and 140 msec respectively. Using binocular stimulation, the amplitude of the midline response (Oz/Cz) was typically larger, by 10 to 20%, than either of the lateral responses, which themselves were symmetrical. Using monocular stimulation, the midline responses were also typically larger than the lateral responses. Symmetrical responses, lateralization ipsilateral to the stimulus, and lateralization contralateral to the stimulus were all observed. The waveform morphology and peak latencies did not differ significantly between preoperative baselines and

intraoperative baselines (Fig. 1).

Fig. 1. Left: Baseline recordings of flash VEPs in a patient with PD obtained 1 day prior to surgery. An N75 peak and P100 peak (also termed peak III and IV) are consistently identified, and significantly delayed compared to normal subjects. Right: Baseline recordings of flash VEPs in the same patient, obtained in the operating room after sedation, frame placement, and MR imaging. Prior to surgical manipulation, wave morphologies and latencies are not significantly different from levels obtained 1 day before surgery.

Intraoperative VEP Changes

Visual evoked potentials were recorded reliably and reproducibly in all patients before surgical manipulation. In 48 procedures (81%), variability in amplitude was less than 10%, and latency shifts lasted less than 3 msec throughout the entire operative procedure (Fig. 2 upper left). Operative times averaged 95 minutes (excluding stereotactic frame placement and imaging). The parameters monitored were the amplitudes and latencies of the N75 and P100 peaks, with amplitude reductions of 10% or more, and latency shifts of 3 msec or more reported to the surgeon by the neurophysiologist. In 11 procedures (19%), VEP changes were reported after stimulation, temporary lesioning, or permanent lesioning. These changes included six amplitude changes (10-80%), six latency shifts (3-10 msec) and one report of "increased variability." Two patients showed both decreased amplitude and increased latency (Table 1, Fig. 2).

TABLE 1
INTRAOPERATIVE VEP CHANGES*

Case No.	VEP Change	Timing	Visual Symptoms	Action Taken	VEP Result	Visual Deficit	Operative Side	Stimulated	Recorded Changes
1	dec amp 80%	stimulation	yes	move 1 mm sup	resolved	yes	rt	OD	O1/Cz, Oz/Cz, O2/Cz
2	dec amp 30%	temp lesion	no	move 1 mm sup	persisted	no	rt	OS	O1/Cz, Oz/Cz, O2/Cz
3	dec amp 20% inc latency 10 msec	temp lesion	no	move 1 mm sup	improved	no	rt	OD	O1/Cz, Oz/Cz, O2/Cz
4	inc latency 4 msec	perm lesion	no	none	persisted	no	rt	OD & OS	O1/Cz, Oz/Cz, O2/Cz
5	dec amp 30% inc latency 4 msec	temp lesion	no	move 1 mm sup	resolved	no	lt	OS & OD	O1/Cz, Oz/Cz, O2/Cz
6	inc latency 3 msec	perm lesion	no	none	resolved	no	rt	OD	O1/Cz, Oz/Cz, O2/Cz
7	inc variability	perm lesion	no	none	resolved	no	rt	OD	O1/Cz, Oz/Cz, O2/Cz
8	inc latency 3 msec	perm lesion	no	none	persisted	no	rt	OD	O1/Cz, Oz/Cz, O2/Cz
9	dec amp 10%	perm lesion	no	none	persisted	no	rt	OS	O1/Cz, Oz/Cz, O2/Cz
10	inc latency 5 msec	perm lesion	no	none	resolved	no	rt	OS	O1/Cz, Oz/Cz, O2/Cz
11	dec amp 40%	perm lesion	no	none	resolved	no	rt	OS	O1/Cz, Oz/Cz, O2/Cz

*Amp = amplitude; dec = decreased; inc = increased; perm = permanent; sup = superior; and temp = temporary.

Fig. 2. Representative VEPs recorded during macroelectrode-based pallidotomy (filtered data, 200 msec trace). A: Visual evoked potentials are unchanged throughout procedure. Such tracings are typical of 80% of patients. B: Visual evoked potentials showing increased latency bilaterally after a permanent lesion is made, which persisted throughout the procedure in Case 4. C: Visual evoked potentials showing decreased amplitude bilaterally with test lesioning. The probe was withdrawn 1 mm before permanent lesioning, and VEPs returned to baseline by the conclusion of procedure in Case 2. D: Intraoperative VEPs in a patient with a small postoperative quadrantanopsia showing transient amplitude reduction of 80% just after stimulation in Case 1. The electrode was withdrawn 1 mm prior to permanent lesioning.

Visual symptoms accompanied the VEP changes in only one patient (Case 1). This patient described a "honeycomb" effect in his visual field, and he sustained an injury to the optic tract. One patient without VEP changes experienced "flashing blue lights." The target in this latter patient was moved 1 mm superiorly, and no visual deficit was present postoperatively. The dissociation between visual symptoms and electrophysiological changes has also been noted by Lozano, et al.[22]

In all cases, the intraoperative VEP changes occurred across all three recording channels (O1/Cz, Oz/Cz, and O2/Cz). In five of 11 cases, the change was detected during contralateral monocular stimulation, in four of 11 cases, during ipsilateral stimulation, and in two of 11 cases, the change was confirmed for both ipsilateral and contralateral stimulation. Ten of the eleven patients with VEP changes had undergone right-sided pallidotomies. In seven of 11 cases, the VEP changes resolved prior to the conclusion of the procedure, although in four of 11 cases, the VEP changes persisted.

In four patients (Cases 1, 2, 3, and 5), VEP changes prompted a change in electrode position. In Cases 3 and 5, changes occurred during temporary lesioning. The electrode was withdrawn 1 mm in the dorsal

direction and the VEP changes resolved or improved. Additional testing prior to proceeding with permanent lesioning did not produce further VEP changes. In Case 2, VEP changes during performance of the test lesion likewise prompted a change in electrode position in the dorsal direction, but VEPs did not return to baseline. Additional testing prior to proceeding with permanent lesioning did not produce further VEP changes. None of these patients experienced visual morbidity.

In the single case (Case 1) with a postoperative visual deficit, visual symptoms were noted at the time of stimulation and a transient change in amplitude of 80% was noted (Fig. 2 lower right). The electrode was withdrawn 1 mm, and VEP changes and symptoms could no longer be evoked with stimulation. Permanent lesioning at the new target was completed. Formal visual field testing revealed a heteronymous superior quadrantanopia (Fig. 3). Postoperative MR imaging at 7 months showed the proximity of the lesion to the optic tract (Fig. 4).

Fig. 3. Postoperative visual field test results in Case 1, showing a small superior quadrantanopia. Preoperative visual fields were normal.

Visual Morbidity

The only confirmed visual deficit in this series was an asymptomatic superior quadrantanopia present on formal field testing and detectable on detailed clinical examination (Case 1). This was the first patient in this series to undergo pallidotomy using intraoperative VEPs.

Fig. 4. Postoperative T₂-weighted MR image obtained in Case 1 at 7 months showing proximity of the GPI lesion to the optic tract.

Lesioning Parameters

There were no significant differences in the mean lesion coordinates for the group with VEP changes (x coordinate, 20.6 mm $\pm$ 0.9 SD; y coordinate, 2.8 mm $\pm$ 0.2 SD; z coordinate, -4.2 mm $\pm$ 0.7 SD) compared to the group without (x coordinate, 20.9 mm $\pm$ 0.9 SD; y coordinate, 2.4

mm $\pm$ 0.4 SD; z coordinate, -4.5 mm $\pm$ 0.8 SD). The mean impedance measured at the initial target also was not significantly different between the two groups (816 ohm $\pm$ 62 SD vs. 760 ohm $\pm$ 98 SD).

Clinical Outcomes

The detailed analysis of UPDRS scores in this group of patients is the subject of a forthcoming report. For the purposes of this report, outcome was ranked as excellent, good, or poor. An "excellent" outcome was defined as dramatic improvement in symptoms or functional gains, as reported by the patient and assessed by the neurologist; a "good" outcome was defined as modest improvement in symptoms; and a "poor" outcome as no improvement. No patient's condition was worse after pallidotomy. Overall for this group, 68% had an excellent outcome, 24% had a good outcome, and 8% had a poor outcome. To determine whether the target adjustments based on VEP changes had a detrimental effect on outcome, we assessed the outcomes of that subgroup of patients in whom target adjustments were made solely based on reported VEP changes. In those four patients, there was one excellent outcome, two good outcomes, and one poor outcome. This difference did not reach statistical significance (chi-square test = 4.8, $p = 0.09$).

DISCUSSION

Flash VEPs

Flash VEPs have been used to avoid injury to the anterior optic pathways during parasellar surgery,[10,30] resection of chiasmal gliomas,[1] intraorbital surgery,[31] and endoscopic sinus surgery.[16] Although pattern-reversal evoked potentials are generally considered more sensitive than flash evoked responses,[24,28,29] we have found, as have others, that with current technology, the use of pattern reversal stimulation is impractical during surgical procedures. Furthermore the central 2° of fovea is estimated to generate 65% of the pattern-reversal response;[5] flash stimuli, in contrast, tend to generate response from the peripheral retina as well. The purported insensitivity of flash VEPs, particularly in retrochiasmatic lesions, has been based on diagnostic studies in which patient recordings must differ from normative population data by 2 SDs to be considered abnormal. However, for intraoperative monitoring, comparisons are made on a minute-by-minute basis to the patient's own stable baseline data, and thus smaller changes due to acute injury may be more readily detected.

Retrochiasmatic Lesions

Visual evoked potentials have been used in the diagnosis of retrochiasmatic lesions using hemifield pattern stimulation,[6,19,24,27] rather than full-field stimulation, to isolate the responses of each optic tract. Like pattern-reversal, the use of hemifield stimulation appears to be impractical during many neurosurgical procedures. Cedzich, et al.,[8] found two cases of occipital tumors in which postoperative visual deficits occurred with no intraoperative VEP change. However, such "false-negative" results have not been reported, to our knowledge, in lesions of the optic tract.

Optic Tract Anatomy

Although the retinotopic organization of the optic nerves has been well demonstrated, the organization of the optic tract is less well understood and is probably determined by retinotopic fiber order and morphological fiber class.[26] Nevertheless, the general pattern is still thought to be one in which fibers

from the fovea course dorsally in the tract, fibers from the peripheral retina course through more ventral locations, fibers from the inferior retina are distributed medially, and those from the superior retina laterally.[7] Thus, as the optic tract is approached from the more lateral and superior GPI, injury to the lateral optic tract would produce a contralateral superior quadrantanopsia, as we saw in our Case 1. Baron and associates[5] reported one patient with a similar deficit. A more direct superior injury to the optic tract would produce macular defects, as described by Iacono, et al.[17] An inferior quadrantanopsia, as described by Laitinen and colleagues,[21] seems to be the most unlikely occurrence based on anatomical considerations. Because the input from each eye to the optic tract is not in exact retinotopic registration, visual field deficits are expected to be heteronymous, as in our patient.

Pallidotomy and Visual Morbidity

In the initial series of 42 pallidotomies performed by Laitinen and coworkers[21] using a macroelectrode technique, a 14% incidence of homonymous hemianopsia was reported. With further experience, Laitinen[20] encountered no additional visual deficits in his next 100 reported patients. Dogali, et al.,[11] reported no visual morbidity in 18 patients undergoing pallidotomies with a microelectrode technique, whereas Baron and colleagues[4] noted a persistent superior quadrantanopsia in one (6.7%) of 15 patients when they used similar techniques. Lozano, et al.,[22] used a combination of microstimulation and recording of strobe-evoked optic tract potentials to completely avoid optic tract injury in 27 patients. In Iacono and coworkers'[17] experience, using a combination of microelectrode and macroelectrode localization, three of 126 patients suffered partial pericentral (macular) hemianopsia. Although the best method for localization remains controversial, the evidence suggests that visual complications may be more frequent when macroelectrode techniques are used. This pilot study was undertaken with the goal of minimizing visual morbidity during macroelectrode pallidotomy by monitoring intraoperative VEPs.

Visual Evoked Potential Changes During Pallidotomy

In this series, VEPs were recorded reliably and reproducibly in awake patients undergoing pallidotomy, probably at least in part due to the lack of anesthetic- and metabolic-induced variability. In 11 of 59 procedures, VEP changes were noted, although only four of these changes led to target adjustments. The changes in all cases occurred within approximately 1 minute of surgical manipulation, corresponding to the time frame necessary to obtain a time-averaged epoch. Because the changes associated with stimulation and "test" lesioning are temporary, this time frame was sufficient to allow for adjustment of the target prior to further lesioning.

Intuitively, one might expect unilateral optic tract injury to affect the ipsilateral scalp recording preferentially. In our patients, changes appeared to be present to a similar degree in all three recording channels, making left-to-right comparisons less helpful. Symmetrically delayed occipital VEP responses after whole-field stimulation in unilateral retrochiasmatic lesions have also been described by others.[27] As compared to somatosensory evoked potentials, the generation of VEPs is a more complex phenomenon. A variety of pathways for visual information may be involved, including the retinogeniculostriate pathway, retinotectal pathway, and retinocerebellar pathways.[27] The "generators" of each portion of the response are distributed throughout various structures,[27] but at least in part are accounted for by the mesial surface of the occipital lobe.[9] This latter fact accounts for the sometimes observed paradoxical lateralization[9,19] of the VEP response after hemifield stimulation and suggests that the optic tract contributes to the generation of both the ipsilateral and contralateral surface responses (despite the fact that the tract projects only to the ipsilateral occipital lobe).

In this series, we encountered one false-negative VEP recording: that is, one in which VEPs were unchanged in an optic tract injury. In Case 1, the initial 80% VEP amplitude reduction resolved and was not reproduced after electrode repositioning, yet the patient developed a visual field deficit. The proximity of the pallidal lesion to the optic tract on postoperative imaging (Fig. 4) suggests that a more significant visual field deficit would likely have resulted had target adjustments not been made. Thus VEPs were still helpful in this case.

In Cases 3 and 5, optic injury appears to have been averted with the aid of VEP monitoring, although false-positive VEP changes cannot be excluded. To determine if these cases represent false-positives, one would need to proceed with permanent lesioning despite the VEP changes. In Case 2, the VEP changes induced by temporary lesioning persisted through the end of the case. We opted to proceed with permanent lesioning after repositioning the electrode despite these persistent changes for two reasons. First, the 30% reduction in amplitude with preserved latency was a relatively minor change compared with Cases 1, 3, and 5. Furthermore, at the new target, we were unable to produce further changes in the VEP recordings with stimulation or test lesioning. Although Case 2 represents a false-positive, the initial adjustment in target coordinate may still have been appropriate to avoid optic tract injury.

In seven cases, VEP changes occurred after permanent lesioning that were not detected after stimulation or test lesioning. Most of these changes were transient, and none of these patients had visual deficits. Of importance, we did not consider these cases to be false-positives because the changes did not result in erroneous alteration of the lesion target. Permanent radiofrequency lesions may produce a transient neuropraxic dysfunction of the optic tract, and concomitant VEP changes, at a greater distance from the probe compared with the test lesions and stimulation protocol. In the absence of VEP changes during stimulation or test lesioning, VEP changes following permanent lesioning do appear to predict optic tract injury.

Based on this small number of patients, changes in VEP amplitude of greater than 10% or latency shifts longer than 3 msec occurring during stimulation or test lesioning under the conditions described indicate a need for target adjustment. Raising the threshold for amplitude changes to between 30% and 40% might increase the specificity of the test, at the risk of decreasing sensitivity. Although this would have been a more powerful study had we obtained preoperative and postoperative visual field testing in all patients, we could not justify the expense of routine testing. Furthermore, our endpoint of "clinically significant" visual field deficits may be more appropriate. Finally, the lack of visual morbidity in this series cannot be entirely attributed to the use of VEPs and may be a result of improved neuroimaging and target localization or a result of the small volume of tissue lesioned relative to other series.

CONCLUSIONS

Visual evoked potentials can be recorded easily, safely, and reliably during procedures performed in the awake patient. This is aided by the lack of variability induced by anesthetics and other metabolic changes. The 1.7% visual morbidity rate reported here using macroelectrodes and VEPs compares favorably with other series in which microelectrodes were used. Although the low incidence of visual morbidity cannot be completely ascribed to the use of VEPs, this preliminary report suggests that the technique may be useful to reduce the incidence of clinically significant visual morbidity during pallidotomy, especially during formal lesioning of the ventral pallidum close to the optic tract. More detailed study will be required to define the role of VEPs during macroelectrode-based pallidotomy.

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