Intraoperative monitoring of cortically recorded visual response for posterior visual pathway

Clinical article

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Object. Intraoperative monitoring of visual evoked potentials (VEPs) has been regarded as having limited significance for the preservation of visual function during neurosurgical procedures, mainly due to its poor spatial resolution and signal-to-noise ratio. The authors evaluated the usefulness of cortically recorded VEPs, instead of the usual scalp VEPs, as intraoperative monitoring focusing on the posterior visual pathway.

Methods. In 17 consecutive patients who underwent microsurgical procedures for lesions near the posterior visual pathway, cortical responses were recorded using 1-Hz flashing light-emitting diodes and subdural strip electrodes after induction of general anesthesia with sevoflurane or propofol. The detectability and waveform of the initial response, stability, and changes during microsurgical manipulations were analyzed in association with the position of electrodes and postoperative changes in visual function.

Results. Initial VEPs were detected in 82% of all patients. The VEPs were detected in 94% of patients without total hemianopia in whom electrodes were placed sufficiently near the occipital pole; in these cases the recordings were not significantly affected by anesthesia. The detectability rates of the negative peak before 100 msec (N1), positive peak before 100 msec (P100), and negative peak after 100 msec (N2) were 36, 50, and 100%, respectively. The mean latencies and amplitudes of N1, P100, and N2 were 90.0 ± 15.9 msec and 61.0 ± 64.0 µV, 103.9 ± 13.5 msec and 34.3 ± 38.6 µV, and 125.7 ± 12.2 msec and 44.9 ± 48.9 µV, respectively, showing great variability. In 11 patients, the initial waveforms of VEP remained stable during microsurgical procedures, and the visual status did not change postoperatively, while it disappeared in 2 patients who presented with postoperative hemianopia.

Conclusions. Direct recording from the visual cortices under general anesthesia achieved satisfactory detectability of the visual response to a light-emitting diode flashing light. Although the initial waveforms varied greatly among patients, they were stable during microsurgical procedures, and the changes were consistent with postoperative visual function. Intraoperative cortical VEP monitoring is a potentially useful procedure to monitor the functional integrity of the posterior visual pathway. (DOI: 10.3171/2009.6.JNS081272)

Key Words • visual evoked potential • cortical recording • posterior visual pathway • intraoperative monitoring

Intraoperative neurophysiological monitoring is now indispensable in many neurosurgical situations. Monitoring of VEPs during surgical manipulation along the visual pathway was commenced in the late 1970s almost concurrently with monitoring of somatosensory evoked potentials and auditory brainstem responses.1,2,5,13,15,23,26,30 While those earlier reports suggested the possible usefulness of VEP in detecting impending injury and preventing functional deterioration, some authors have pointed out the difficulty of obtaining stable recordings during surgery.5,23 and that intraoperative VEP monitoring is currently not as widely used as monitoring of 2 other sensory responses. According to Cedzich et al.,7 who challenged the usefulness of intraoperative monitoring of flash-evoked visual potentials, the essential limitation of intraoperative VEP monitoring lay in the instability of the potentials while technical interferences, such as the effect of volatile anesthesia and the difference in visual stimuli, that is, LED flash and strobe flash versus pattern reversal, also influenced reliability.

Most of the preceding studies on intraoperative VEP monitoring used scalp recording, which is beset by low signal intensity and poor spatial resolution. The detectability of an electroencephalogram recorded from scalp electrodes is susceptible to the depth and direction of signal generators. Segregate monitoring of unilateral visual cortices is almost impossible because the proximity of bilateral visual cortices causes mutual interference of the signals from bilateral generators. While modern techniques such as magnetoencephalography and dipole tracing by densely placed electrodes may compensate for these problems,10,14 it is presently difficult to apply those techniques to intraoperative monitoring.

An electrocorticogram recorded with subdural electrodes reflects cortical activity with much higher spatial resolution and signal intensity. While some of the problems in scalp-recorded VEP monitoring may presumably

Abbreviations used in this paper: AVM = arteriovenous malformation; GBM = glioblastoma multiforme; LED = light-emitting diode; VEP = visual evoked potential.
be resolved using direct cortical recording, studies on cortical VEPs in humans are rare. These studies either used chronically implanted intracranial electrodes in epilepsy patients, or they were case reports of 1 or 2 patients. Surprisingly, there has been no systematic study on intraoperative monitoring of cortical VEPs. We found 2 cases of posterior craniotomy in which cortical VEPs were successfully monitored during microsurgical procedures, with intraoperative changes in VEPs associated with postoperative visual function. Placing the subdural strip electrodes on visual cortices and recording visual responses are not complex procedures in neurosurgical operations for lesions along the posterior visual pathway via a posterior craniotomy. Thus, in a series of 17 patients we evaluated whether cortical recording covers the problems in scalp-recorded VEP and thus improves the significance of intraoperative monitoring of VEP, focusing on the posterior visual pathway.

Methods

Patient Population

Intraoperative cortical VEPs were recorded in 17 consecutive patients who underwent posterior craniotomy for lesions or epileptic foci in the parietal, posterior temporal, and/or occipital lobes (Table 1). There were 10 males and 7 females with a median age of 41 years (range 10–72 years). Four patients had GBMs; 2 had meningiomas; and 1 each had metastatic tumor, malignant meningioma with radiation necrosis, focal cortical dysplasia, AVM, radiation necrosis, metastatic carcinosarcoma, ganglioglioma, and cryptococcal granuloma. Three patients underwent surgical treatment for nonlesional epileptic foci. Written informed consent for surgery, intraoperative monitoring, and general clinical research was obtained in all patients. The patients in Cases 2 and 12 were described in our previous technical report, which validated the efficacy of intraoperative VEPs.

Intraoperative Monitoring of Cortical VEPs

Following the induction of general anesthesia with sevoflurane or propofol and muscle relaxants, lightproof goggles with flashing LEDs for visual stimulation (Nihon Koden) were placed over both eyes. The combined light was 800 mCD per goggle. A flashing light was applied using the goggles through closed eyelids at a rate of 1 Hz. A needle electrode was placed subdermally at the nasion for reference.

After craniotomy, strip electrodes with 4 platinum contacts (3 mm in diameter placed at 10-mm intervals) were placed on the brain surface. Evoked potentials for 250 msec were recorded with 70-Hz low-pass, 1-Hz high-pass, and 50-Hz notch filters and were averaged for 10 recordings. The VEPs were constantly monitored every 1–5 minutes according to the stages of surgery.

Exact Location of Electrode Contacts

In 8 patients the craniotomy crossed the occipital midline covering the occipital pole. After dural opening, the calcarine fissure was identified visually or with the aid of a computer-guided navigation system. When visually confirming the fissure, care was taken that it ran parallel to the tentorium, thus passing not longitudinally but rather transversely to the brain surface, especially when viewed from the superior aspect of the cuneus. Using an operative microscope and gently retracting the occipital lobe laterally, the electrode strip was placed over the fissure and the superior and/or inferior bank of the fissure to explore where the most prominent potential could be recorded stably. Surface areas around the occipital pole were also explored. Once an appropriate location was determined, the electrodes were covered with a saline-soaked cotton sheet, and continuous monitoring was started. In 1 patient (Case 9), an electrode strip was placed on the dura parasagittally because of severe adhesion between the dura mater and brain surface following a previous surgery.

In 6 patients, the craniotomy did not cover the occipital midline. The strip electrode was subdurally inserted toward the occipital pole. The location with the most prominent and stable response was explored, shifting the position of the electrodes. In these patients, the minimum distance between the occipital pole and edge of the craniotomy was measured from postoperative CT and MR imaging. The actual locations of the electrodes were also confirmed from the operation records and videos.

Data Collection and Evaluation

Clinical data, including the visual status before and after surgery, histopathology of the lesion, pre- and post-operative imaging findings, as well as intraoperative VEP recordings and surgical observations were collected. The visual field was evaluated using the Goldmann perimeter by ophthalmologists.

Each patient’s VEP records were evaluated in terms of the following issues: detectability of initial VEP waveforms, that is, reproducible responses before microsurgical manipulations, latency and amplitude of major peaks in the initial VEP waveforms, stability during microsurgical manipulation, and significant changes in the latency and/or amplitude of waveforms during microsurgical manipulations. These issues were analyzed in association with the position of electrodes and postoperative changes in visual symptoms. To analyze the waveform, we defined the major positive deflection peaking at ~ 100 msec as P100. Large negative peaks before P100 were defined as N1, and N2 was the next major negative deflection after P100. Each trace was checked for the presence or absence of these main peaks. Consecutive traces were compared to confirm the reproducibility of the peaks. The amplitude of the peak was measured as the amplitude difference between the baseline and the peak.

Results

Initial Waveforms and Their Association With Recording Site and Preoperative Visual Status

Clear and reproducible waveforms were obtained before brain manipulation in 14 of 17 patients (Table 1); thus, the detectability of the initial VEP was 82%. Significant visual responses could not be obtained in 3 patients
TABLE 1: Clinical characteristics of 17 patients who underwent cortical VEP monitoring during posterior craniotomy*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Histopathology</th>
<th>Lesion Location</th>
<th>Preop Visual Status</th>
<th>Craniotomy</th>
<th>Anesthesia</th>
<th>Location of Strip Electrodes</th>
<th>VEP Peaks</th>
<th>Change in Waveform</th>
<th>Postop Visual Status</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>55, F</td>
<td>meningioma</td>
<td>falx, protruding into rt inf cuneus</td>
<td>total lesion removal</td>
<td>yes</td>
<td>P</td>
<td>sup &amp; inf bank of CS lat cortices (sup CS bank)</td>
<td>89</td>
<td>109.5 130</td>
<td>none 59.2</td>
</tr>
<tr>
<td>2‡</td>
<td>28, M</td>
<td>focal cortical dysplasia</td>
<td>lt precuneus</td>
<td>total precuneus resection, MST on inf surface of cuneus</td>
<td>yes</td>
<td>S</td>
<td>along CS (along CS)</td>
<td>—</td>
<td>— 136</td>
<td>— 112.2</td>
</tr>
<tr>
<td>3</td>
<td>20, M</td>
<td>NLE</td>
<td>rt PO cortices</td>
<td>extensive MST on PO cortices</td>
<td>yes</td>
<td>S</td>
<td>along CS</td>
<td>—</td>
<td>— — — — —</td>
<td>— — —</td>
</tr>
<tr>
<td>4</td>
<td>10, M</td>
<td>ganglioglioma</td>
<td>lt cuneus</td>
<td>total tumor removal</td>
<td>yes</td>
<td>S</td>
<td>sup &amp; inf CS bank lat cortices (sup CS bank)</td>
<td>81.6 93.4</td>
<td>103</td>
<td>17 35 23</td>
</tr>
<tr>
<td>5</td>
<td>54, M</td>
<td>GBM</td>
<td>rt cuneus, edema in lingual gyrus</td>
<td>occipital lobectomy</td>
<td>yes</td>
<td>S</td>
<td>inf CS bank (inf CS bank)</td>
<td>—</td>
<td>— 119</td>
<td>— 21.4</td>
</tr>
<tr>
<td>6</td>
<td>16, M</td>
<td>AVM</td>
<td>rt inf cuneus</td>
<td>total lesion removal</td>
<td>yes</td>
<td>P</td>
<td>sup &amp; inf CS bank (inf CS bank)</td>
<td>—</td>
<td>100.5 120.5</td>
<td>17.5 16.4</td>
</tr>
<tr>
<td>7</td>
<td>43, M</td>
<td>cryptococcal granuloma</td>
<td>rt hemi</td>
<td>occipital lobectomy</td>
<td>yes</td>
<td>S &amp; P</td>
<td>sup &amp; inf CS bank lat cortices</td>
<td>—</td>
<td>— — — — —</td>
<td>— — —</td>
</tr>
<tr>
<td>8</td>
<td>46, F</td>
<td>GBM</td>
<td>rt occipital</td>
<td>total lesion removal</td>
<td>yes</td>
<td>P</td>
<td>sup &amp; inf CS bank (inf CS bank)</td>
<td>105 121.5</td>
<td>138</td>
<td>47 14.6 29.3</td>
</tr>
<tr>
<td>9</td>
<td>58, F</td>
<td>recurrent malignant meningioma &amp; radiation necrosis</td>
<td>rt cuneus</td>
<td>total lesion removal</td>
<td>yes</td>
<td>P</td>
<td>parasagittal, epidural</td>
<td>106 120.5</td>
<td>139.5 22.1</td>
<td>6.4 11.3</td>
</tr>
</tbody>
</table>

(continued)
TABLE 1: Clinical characteristics of 17 patients who underwent cortical VEP monitoring during posterior craniotomy* (continued)

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Histopathology</th>
<th>Lesion Location</th>
<th>Preop Visual Status</th>
<th>Craniotomy Crossing Midline?†</th>
<th>Anesthesia</th>
<th>Op</th>
<th>Location of Strip Electrodes (continuous)</th>
<th>VEP Peaks</th>
<th>Change in Waveform</th>
<th>Postop Visual Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>33, F</td>
<td>meningioma</td>
<td>rt occipital</td>
<td>none</td>
<td>yes</td>
<td>S</td>
<td>lat cortex</td>
<td>— — 133 — — 25 none</td>
<td>none</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>79, F</td>
<td>metastatic brain tumor</td>
<td>rt occipital</td>
<td>rt sup partial</td>
<td>no (1.3)</td>
<td>P</td>
<td>along CS</td>
<td>— — 123.5 — — 24.1 none</td>
<td>rt sup partial scotoma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12‡</td>
<td>45, F</td>
<td>GBM</td>
<td>rt postero-temp</td>
<td>none</td>
<td>no (4.0)</td>
<td>S</td>
<td>lat cortex</td>
<td>— — 117.5 — — 16.7 disappeared</td>
<td>lt hemi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>29, M</td>
<td>NLE</td>
<td>lt mediobasal &amp; lat temp cortices</td>
<td>none</td>
<td>no (3.3)</td>
<td>S</td>
<td>lat cortex</td>
<td>68.5 94.5 128 173 115.9 186.6 none none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>59, M</td>
<td>metastatic esophageal carcinosarcoma</td>
<td>rt postero-temp</td>
<td>none</td>
<td>no (6.5)</td>
<td>S</td>
<td>lat cortex</td>
<td>— — — — — none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>72, M</td>
<td>GBM</td>
<td>lt postero-temp</td>
<td>none</td>
<td>no (5.5)</td>
<td>S</td>
<td>lat cortex</td>
<td>— — 119 — — 22.5 none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>18, M</td>
<td>radiation necrosis</td>
<td>lt occipital</td>
<td>3 cm lat to midline</td>
<td>no (1.5)</td>
<td>S</td>
<td>lat cortex</td>
<td>— — 145 — — 61.6 none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>41, F</td>
<td>NLE (post–standard temp lobectomy)</td>
<td>rt postero-temp</td>
<td>rt 3/8 anopsia</td>
<td>no (3.5)</td>
<td>S</td>
<td>lat cortex</td>
<td>87.5 107.5 44 19 none rt 3/8 anopsia</td>
<td>none</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Initial waveforms were recorded in all patients except for those in Cases 3 (due to noise), 7 (due to hemianopia), and 14 (no significant waveforms could be recorded). Abbreviations: CS = calcarine sulcus; hemi = hemianopia; inf = inferior; MST = multiple subpial transection; NLE = nonlesional epilepsy; P = propofol; PO = parietooccipital; quadrant = quadrantanopia; S = sevoflurane; sup = superior; temp = temporal.
† The numbers in parentheses indicate the minimum distance between the occipital pole and craniotomy edge in centimeters.
‡ The patients were previously reported in the article by Kamada et al.
Intraoperative recording of cortical VEPs

One had nonlesional epilepsy without presurgical visual symptoms. We recorded potential waves from several locations, including the occipital parietal and lateral cortices, but waveforms were not reproducible because of large noise. Another had preoperative hemianopia due to a diffuse granulomatous lesion in the left occipital lobe. We could not obtain significant VEP waveforms from the left occipital cortices, including the pericalcarine areas. The remaining patient had a metastatic tumor in the posterior temporal area but no preoperative visual symptoms. We inserted the electrode strip subdurally from the posterior edge of the craniotomy, but no significant waveforms were recorded. The minimum distance between the craniotomy edge and the occipital pole was 6.5 cm, the largest among the 7 patients whose craniotomy did not cross the midline (Table 1). Therefore, the actual detectability was 94% in patients without total hemianopia and when electrodes were placed sufficiently near the occipital pole.

The initial waveforms, especially those produced earlier than 100 msec, varied greatly among patients. The negative peak with latency of 100–150 msec (N2) was obtained in all 14 patients, while the negative peak before 100 msec (N1) and positive peak ~100 msec (P100) were clearly identifiable in 5 and 7 patients, respectively (Table 1). Thus, the detectability rates of N1, P100, and N2 were 36, 50, and 100%, respectively. The mean latencies and amplitudes were 90.0 ± 15.9 µV for N1, 103.9 ± 13.5 msec and 34.3 ± 38.6 µV for P100, and 125.7 ± 12.2 msec and 44.9 ± 48.9 µV for N2. The detectability and the waveform of the initial response were not significantly affected by different anesthetic agents (Table 2).

The initial response was obtained in 7 patients without preoperative visual symptoms (Cases 1, 2, 4, 10, 12, 13, and 15): 4 from the pericalcarine area and 3 from the lateral occipital cortices. The response was most prominent from the shallowest contact in the former and from the deepest, that is, the most medial, contact in the latter (Fig. 1). In 5 patients (Cases 5, 6, 8, 9, and 16) with preoperative quadrantanopia, the initial waveform was obtained from the corresponding area to the residual visual field. The significant waveform was obtained from the inferior bank of the calcarine fissure but not from the superior bank in the patient with inferior quadrantanopia (Fig. 2). Even in a patient with a smaller remaining visual field (Case 17), significant waveforms were obtained from the properly placed electrode (Fig. 3).

**Stability and Changes During Microsurgical Manipulations**

While the initial waveforms of visual response were considerably variable among patients, they were stable and consistent during microsurgical manipulations once reproducible waveforms were initially obtained and unless the manipulations directly involved the visual pathway (Fig. 4). Stability was not significantly affected by different anesthetic agents (Table 1). In 1 patient (Case 6), the waveforms changed because the electrode shifted during microsurgical manipulation, but they recovered after correcting the electrode position (Fig. 5). Thus, in 11 patients, the initial waveforms of VEPs remained stable during microsurgical procedures, and the preoperative visual status did not change postoperatively.

In 3 patients the changes of VEP waveform were directly associated with surgical manipulation. In 2 patients (Cases 5 and 12) the amplitude of N2 decreased as the resection of GBM proceeded deeply. It finally disappeared when the resection reached the lateral ventricle (Fig. 6). Both patients developed total hemianopia postoperatively.

**TABLE 2: Detectability, latency, and amplitude of initial visual responses**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>N1</th>
<th>P100</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. of patients anesthesia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>propofol</td>
<td>2/1 (40.0)</td>
<td>2/5 (40.0)</td>
<td>4/5 (80.0)</td>
</tr>
<tr>
<td>sevoflurane</td>
<td>3/11 (27.2)</td>
<td>5/11 (45.4)</td>
<td>9/11 (82.0)</td>
</tr>
<tr>
<td>recording site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>parietal cortex</td>
<td>3/9 (33.3)</td>
<td>4/9 (44.4)</td>
<td>7/9 (77.8)</td>
</tr>
<tr>
<td>lat cortex</td>
<td>2/8 (25.0)</td>
<td>3/8 (37.5)</td>
<td>7/8 (87.5)</td>
</tr>
<tr>
<td>preop</td>
<td>2/9 (22.2)</td>
<td>3/9 (33.3)</td>
<td>7/9 (77.8)</td>
</tr>
<tr>
<td>visual deficit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quadrant†</td>
<td>4/6 (66.7)</td>
<td>4/6 (66.7)</td>
<td>6/6 (100.0)</td>
</tr>
<tr>
<td>hemi</td>
<td>0/1 (0.0)</td>
<td>0/1 (0.0)</td>
<td>0/1 (0.0)</td>
</tr>
</tbody>
</table>

* Latency and amplitude values are presented as the means ± SDs.
† Quadrantanopia including 3/8 visual field defect.
In the other patient (Case 4), the change in VEPs directly affected the course of surgery. The amplitude of P100 decreased as the resection of the inferolateral portion of ganglioglioma in the cuneus proceeded deeply (Fig. 7). The surgeon stopped the dissection in this direction, and the VEP recovered during dissection in the superior aspect after some time of interruption of manipulation. It remained stable thereafter until total resection of the tumor. The patient’s visual field was full and normal postoperatively.

Monitoring of visual response aided the surgeon in the decision-making process regarding the vascular manipulation in 2 patients. In 1 patient (Case 6) with an occipital AVM, we temporarily clipped some arteries and checked the change of VEP to decide whether these feeding vessels could be sacrificed, passing through arteries to the visual cortex. After confirming that there was no change in the VEPs, we permanently clipped and severed them. In another patient (Case 9) with recurrent malignant meningioma invading extensively into the superior sagittal sinus, we temporarily clamped the sinus at the proximal and distal portions of the tumor invasion for 5 minutes. After confirming that there were no changes in VEPs, we resected the sinus with tumor. In the latter case, however, we were not sure that the VEP findings really helped the surgeon’s decision since the preoperative angiogram had already revealed almost complete occlusion of the sinus, and 5 minutes may not have been long enough to evaluate functional deficit due to venous congestion.

**Discussion**

The results of the present study suggest the feasibility and significance of intraoperative monitoring of cortically recorded visual response of the posterior visual pathway. Although the initial waveforms varied greatly among patients, detectability was acceptably high, and they were stable and consistent once obtained successfully. Furthermore, the waveforms demonstrated the changes associated with injurious manipulations to the visual pathway, which was consistent with postoperative visual dysfunction. Subjective visual function can also be monitored in patients who undergo awake craniotomy, but the procedure is susceptible to the effect of positioning, age, and neurological deficits other than visual function, making its application to all types of patients difficult. Thus, we believe that it remains necessary and significant to estab-
Intraoperative recording of cortical VEPs

Previous studies on intraoperative VEP monitoring used scalp recording. While preservation of the anterior visual pathway during anterior craniotomy, transsphenoidal surgery, or craniofacial surgery was the main purpose of VEP monitoring in most of these studies, it was inevitable to use scalp recording without posterior craniotomy. We rather focused on the posterior visual pathway to evaluate the feasibility and significance of intraoperative monitoring since direct cortical recording from the visual cortices is straightforward during posterior craniotomy. The major flaws of recording evoked responses from the scalp are weakened signal intensity and low spatial resolution. Responses diminished by the CSF, dura, and skull are themselves susceptible to noise from movement and electrocautery. Increasing the number of responses (thereby obtaining a more accurate VEP) to improve the signal-to-noise ratio results in a longer acquisition time, making the response further susceptible to noise unless ongoing surgical manipulations are interrupted. For example, acquiring 1 record takes > 2 minutes when the stimulation rate is at 1.5 Hz and the average number is 200. Wiedemayer et al. reported that stable recording was possible by increasing the stimulation rate to 8.5 Hz; however, in their study, the surgery was not cranial and the artifacts would be much less than in cranial surgery. Low spatial resolution makes it difficult to obtain significant responses when patients have preoperative visual field defects, and to detect intraoperative changes in VEPs associated with injury to the unilateral visual pathway or vertically restricted injury to areas superior or inferior to the calcarine sulcus. On the other hand, cortical recording produced an ~10 times higher signal intensity, resulting in high detectability and stable recording during surgical manipulation.

**Fig. 3.** Case 17. Representative waveforms of visual response recorded from the occipital cortices in a patient with larger visual field defect. The waveform was identifiable only from the most medial contact (A). She had left hemianopia sparing the lower one-eighth of her vision. There was no significant difference between the preoperative (B) and postoperative (C) visual fields.

**Fig. 4.** Case 13. Series of visual responses before and during microsurgical manipulation recorded in a patient with temporal lobe epilepsy. The strip electrode was subdurally inserted toward the occipital pole. The manipulation was a multiple subpial transection that did not directly involve the visual pathway. Waveforms were stable throughout the procedure.
took only 10 seconds to obtain 1 recording, and results could be easily rechecked when an inconsistent recording occurred. In patients with preoperative quadrantanopia, VEPs were obtained only from the visual cortex superior or inferior to the calcarine sulcus corresponding to the visual field deficit. It was particularly useful in these cases to monitor VEPs from the residual visual field that should be preserved during surgery by placing electrodes on the superior or inferior bank of the calcarine sulcus.

Strikingly, the detectability and stability of VEP were not significantly different between the 2 anesthetic agents used. Scalp VEPs were highly susceptible to volatile anesthesia. Nitrous oxide, isoflurane, and halothane all prolonged latencies and suppressed the amplitude of VEP waveforms. Propofol exerted a similar but much less effect—8% prolongation of latency and 60% reduction in amplitude. In a study that compared the effects of sevoflurane and propofol on evoked potentials, both agents depressed VEPs in a dose-dependent manner while somatosensory potentials and auditory brain responses showed less marked influence with propofol. The exact reasons for the difference between our findings and those of previous studies are unknown, but our findings suggested that both sevoflurane and propofol do not endanger the feasibility and significance of intraoperative VEP monitoring when direct cortical recording is adopted. One point should be noted, however; the 1 patient (Case 3) in whom initial VEPs could not be obtained due to noise was anesthetized with sevoflurane. That patient had nonlesional epilepsy, and frequent high-amplitude spikes were recognized on the electrocorticograms acquired pre- and intraoperatively; therefore, sevoflurane-induced severe epileptiform discharges may be a cause of noise in cortical VEPs and the inability to acquire significant VEP waveforms.

Waveforms of visual response and their origins have been studied in awake humans using magnetoencephalography, dense array electroencephalography, and chronically implanted intracranial electrodes for epilepsy surgery. The dipole modeling method with multichannel recording of VEP to checkerboard stimuli revealed that the early negative peak at ~ 90 msec was generated in the primary visual area while early and late positive peaks ~ 100 msec and ~ 140 msec were generated in the dorsal extrastriate cortex of the middle occipital gyrus and the ventral extrastriate cortex of the fusiform gyrus, respectively. Late negative peaks (~ 150 msec) were localized to the same source as the positive peak (~ 100 msec) and a deep source in the parietal lobe.

According to Farrell et al., subdurally recorded VEPs in 15 awake patients showed very complex, multi-

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**Fig. 5.** Case 6. Series of visual responses before and during microsurgical manipulation recorded in a patient with an AVM in the inferior cuneus who presented with inferior quadrantanopia. The strip electrode was placed on the inferior bank of the calcarine fissure. Waveforms changed because of electrode shift but recovered after correction of the electrode position and remained stable thereafter.

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**Fig. 6.** Case 5. Series of visual responses before and during microsurgical manipulation recorded in a patient with a GBM in the right cuneus who had postoperative total hemianopia. The amplitude of N2 decreased as the resection went deeper and disappeared when the resection reached the lateral ventricle.
potential waveforms in the striate and visual association cortex that did not resemble scalp VEPs. Flash stimulation activated a larger volume of visual cortex than pattern reversal. Earlier responses tended to cluster in the pericalcarine cortex and occipital macular areas, and P100 and N145 were detected in a much wider area, including the visual association cortex. Similarly, 2 other groups studied VEPs to checkerboard stimuli recorded from subdural electrodes in awake patients. Both found that the initial component was localized to the primary visual cortex in the lips of calcarine fissures and was considered to be an expression of the afferent volley. Subsequent positive potentials ~ 100 msec originated from the occipital pole and lingual gyrus, close to the calcarine fissure, and were further followed by potentials at the lateral occipital lobe.

These findings in awake patients suggest that the electrodes should be placed sufficiently close to the calcarine fissure to detect consistent VEP waveforms; therefore, ideally the electrodes should be placed on the interhemispheric surface of the occipital lobe. Our experience in patients under general anesthesia demonstrated that at least N2 could be detected with a high detectability rate when strip electrodes were slid subdurally to reach the midline even if craniotomy did not cross the midline. While it is speculated that the later components of VEP waveforms are more susceptible to anesthetic agents due to polysynaptic conduction, the detectability of N2 was much higher than the detectability of earlier N1 and P100 in our study. We think that the most probable cause of this apparently conflicting result was inappropriate placement of the electrodes. It may be essential for electrodes to be placed accurately along the calcarine fissure to detect earlier components.

Even though the detectability of earlier components was quite low and there was large interindividual variability in waveforms, we do not think that these factors essentially depreciated the significance of VEP monitoring since even N2 remained stable or showed changes consistent with postoperative visual dysfunction. One concern to be noted is the possibility that the later components of VEP may reflect the activity of the contralateral cortex or activity of the ipsilateral association cortex conducted from the contralateral visual cortex via the corpus callosum because the contralateral visual cortex is also activated with the entire visual field stimulation by flashing light; however, this possibility is unlikely since N2 disappeared completely after surgical disconnection of the unilateral optic radiation in our 2 patients with GBM and postoperative hemianopia.

Our study focused on the posterior visual pathway, and a separate discussion would be necessary for application of the anterior visual pathway to intraoperative VEP monitoring. Goggles are more susceptible to movement by surgical manipulation, and placement of electrodes on visual cortices is usually inappropriate in anterior craniotomy. In flashing light stimulation of the entire visual field of 1 eye, volume conduction of symmetrical electrical activities from bilateral visual cortices may interfere mutually when it is recorded at the scalp. Thus, cortical recording is expected to achieve more stable recording with higher spatial resolution for monitoring the anterior visual pathway. After the significance of cortical VEP is confirmed in further studies, its application may be accomplished by less invasive procedures, such as placement of subdural or depth electrodes via a bur hole or small trepanation.

In 1 patient (Case 4) we actually changed the surgical manipulation based on the change in VEPs considering the risk of the postoperative deficit, although it remains unknown whether continuation of dissection of the inferolateral aspect of tumor would have resulted in a permanent visual deficit in this case. The significance of intraoperative neurophysiological monitoring is 3-fold as follows: 1) identification and localization of the targeted neural structure; 2) evaluation of functional integrity of the structure in association with decision-making as to the extent of resection and dissection of the lesion; and 3) evaluation of the effect of vascular interference in the manipulation site or in distant brain regions. Our findings are not sufficient to answer all these issues. The number of patients was too small, particularly those who had intraoperative changes in VEPs and postoperative visual dysfunction, to evaluate the exact association of characteristics of the changes and the accurate postoperative visual function including both acuity and field. Particularly, to establish the true usefulness of intraoperative VEP, we need to demonstrate that a change in VEP signal precedes and predicts the potential for damage while such damage is reversible. These issues must be clarified in further studies.
Conclusions

Direct recording from the visual cortices under general anesthesia achieved satisfactory detectability of the visual response to LED flashing lights. Stability was not significantly affected by different anesthetic agents. Although the initial waveforms varied greatly among patients, they were stable during microsurgical procedures and the changes were consistent with postoperative visual function. Intraoperative cortical VEP recording is a potentially useful procedure to monitor the functional integrity of the posterior visual pathway.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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