REVIEW ARTICLE

Issues in the Optimal Selection of a Cranial Nerve Monitoring System

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Abstract—Intraoperative nerve monitoring (IONM) is a safe technique that is of clear clinical value in the preservation of cranial nerves in skull base surgery and is rapidly becoming the standard of care. Available nerve monitoring systems vary widely in capabilities and costs. A well-informed surgeon may best decide on monitoring needs based on surgical case selection, experience, operating room space, availability of monitoring personnel, and cost. Key system characteristics that should be reviewed in the decision-making process include the monitoring technique (electromyography, pressure transducer, direct nerve monitoring, brainstem auditory evoked potential) and the stimulus technique (stimulating parameters, probe selection). In the past, IONM has been primarily employed in posterior fossa and temporal bone surgery, but the value of IONM is being recognized in more skull base and head and neck surgeries. Suggested IONM strategies for specific surgeries are presented. (*Skull Base Surgery*, 3(4):230–239, 1993)

Preserving neural structures in a complex operative field is a daunting surgical challenge. Identification of nerves is based on a clear knowledge of anatomy, and the visualization of the nerve in its expected location. Early visualization cannot always be accomplished due to distortion by tumor or infection. For this reason, surgeons have attempted to develop other means to accomplish neural identification and preservation.

For nearly 100 years, there has been interest in intraoperative neural monitoring (IONM).¹ Prior to 1979, investigators stimulating motor nerves depended on visual inspection of muscle activity as the standard technique to assess neural integrity.² In the case of acoustic neuroma resection, where the facial nerve is at considerable risk, a member of the operative team observed facial motion under the operative drapes and warned the surgeon of facial movement.

In 1979, Delgado and coinvestigators² introduced the use of electromyography (EMG) as a more sensitive tool for measuring neuromuscular function of the facial muscles. This technique eliminated reliance on physical movement or suprathreshold contraction as the detectable response. Instead, subtle electrical activity was detected before gross excitation occurred.

In 1982, Sugita and Kobayashi³ developed a system

employing real-time auditory feedback to alert the surgeon to facial nerve activity. The surgeon was thus warned immediately of facial nerve stimulation without diverting attention from the operative field. In 1984, Moller and Jannetta⁴ developed a combined EMG system with auditory feedback, where EMG activity was transduced into auditory signals to alert the surgeon of activity. Such auditory feedback may now be monitored aloud in the operating room by the surgeon or by dedicated monitoring personnel.

NERVE MONITORING TECHNIQUES: MOTOR NERVES

Electromyographic Nerve Monitoring

EMG monitoring involves measuring the end result of neural stimulation, the electrical activity of a targeted innervated muscle. In EMG the physiologic event recorded is the motor unit potential, which is defined as the normal electrical activity of all the muscle fibers excited by a single motor nerve fiber (Fig. 1). To record this event, a pair of needle electrodes are inserted into the muscle, and the potential difference between them amplified. The

Figure 1. Tracing of Nicolet Viking II IONM, illustrating activity of a single motor unit recorded from the orbicularis oris: channel VII₂.

electrical activity may be displayed as a trace on an oscilloscope. Figure 1 shows a trace obtained from a single motor unit firing at regular intervals. The constant amplitude and shape of the spikes indicate that a single motor unit is active.

As the wave of depolarization propagates over the muscle surface, the site of ionic current flux approaches one electrode. That electrode briefly becomes negative with the respect to the other electrode, and a deflection of the trace is observed. When the region of depolarization passes the first electrode, a large negative deflection ensues. As the wave passes the second electrode, a large deflection of similar amplitude and opposite polarity occurs. These events produce a characteristic biphasic wave form, which helps to distinguish muscle activity from artifacts.⁵

Following electrical stimulation of an efferent nerve, the traces appearing on an oscilloscope represent the summation of many motor unit potentials, which is called a compound muscle action potential (CMAP). Figure 2 shows synchronized activity of many different motor units, making up a CMAP.

Direct Nerve Monitoring

One modality for intraoperative monitoring has been developed that measures electrical activity of the facial nerve itself, not of its innervated muscle. The compound nerve action potential (CNAP) can be directly measured by placing electrodes on an exposed portion of the nerve. In addition, it is possible to stimulate a distal section of the nerve and record an antidromic potential in the proximal surgical field. One distinct advantage is that neuromuscular blockade may be used during anesthesia. However, this method is less sensitive than EMG, because the field potentials generated by depolarizing muscle are far larger than those propagating along axons. Proximal direct CNAP monitoring is cumbersome because it requires electrodes in the surgical field that obstruct visualization and exposure of the region precisely where the surgeon is working. Lastly, securing the electrodes can be tenuous due to the fragility of the nerves onto which the electrodes are attached.

Monitoring of Facial Movement via Pressure Transducers

Other methods of nerve monitoring involve detection of facial muscle contraction by pressure and movement transducing devices. The simplest device described in the literature involves the suturing of bells to the patient's face and listening for ringing.⁶ Other pressure transducer mechanisms have included an air-inflated bladder inserted under the patient's lip that senses changes in pressure with contraction of the orbicularis oris, and a clothespin-shaped pressure sensor that rests in the corner of the patient's mouth and senses oral commissure contraction. These types of devices are easy to use, require no special personnel and are inexpensive. However, all of these methods rely on suprathreshold excitation and are thus less sensitive than EMG. Also, excitation of the trigeminal nerve or movement of the patient's head during surgery cannot be differentiated from facial nerve muscle contraction and may lead to false-positive responses. In addition, these devices may become dislodged during surgery and thereby cause false-negative responses.

NERVE STIMULATION TECHNIQUES

Direct electrical stimulation may theoretically damage the very nerves that the surgeon wishes to preserve, since it is the poorly functioning nerve that requires the highest level of electrical stimulation to verify its integrity. The safety of intraoperative electrical nerve stimulation, however, has been borne out in animal studies as well as in clinical practice. Babin and coinvestigators⁷ stimulated the cat facial nerve with 1 hour of 1 mA (alternating) current at a rate of 3/sec. Fatigue of the EMG response was

Figure 2. Tracing of Nicolet Viking II IONM illustrating electrically elicited compound muscle action potential (CMAP) on both facial nerve channels: VII₁ and VII₂. The left half of the figure shows responses to a series of 0.1 mA facial nerve stimuli. The right half shows one of those responses on an expanded time scale. Note the characteristic latency and biphasic wave form of the response to facial nerve stimulation.

observed, but baseline sensitivity returned after 1 hour of rest. Hughes and coinvestigators⁸ demonstrated, using the mouse sciatic nerve, that pulsed current stimulation was safe and effective in eliciting EMG responses.

Constant Current Versus Constant Voltage Nerve Stimulation

Stimulation can be achieved using either a constant current or constant voltage system. Some commercially available machines are specifically designed to provide one or the other, and more versatile units offer both. There are theoretical advantages and disadvantages of both systems. In common practice both work well when their limitations are known.

The stimulation level, be it constant voltage or current, is chosen by the surgeon and is raised or lowered in a graduated fashion in order to determine a threshold level at a given site. Ohm's law states that voltage = current $\times$ resistance, so that a system that delivers an electrical stimulus with a chosen constant current level does so by automatically adjusting voltage to compensate for varying tissue resistance in order to keep that chosen current level constant. Conversely, a constant voltage system automatically varies the current, depending on the resistance of the tissue in question, so that the voltage remains constant.

The advantages and disadvantages of the two systems are based on their function when the potential for electrical shunting occurs. Blood, cerebrospinal fluid (CSF), and solid tissue will all shunt electricity away from the targeted nerve. The relatively low impedance fluids carry the bulk of the stimulation current. This fact is important when a constant current system is in use, because when fluid is accumulated in the field, much of the current will be

shunted away from the nerve. Therefore, one may have to raise the current stimulation level to obtain a threshold response. If that fluid is suctioned away while the stimulation is set artificially high, there is a possibility that the nerve will receive a jolt of current.

Constant voltage systems avoid this problem by taking advantage of the fact that when voltage is held constant, the current through a structure depends only on its own resistance. Although the total current delivered to the surgical field will vary according to the degree of shunting (total resistance), the current delivered to the nerve itself will depend mostly on the nerve's own resistance. The case for constant voltage stimulation has been well articulated by several authors.^{4,5,9}

There have been no controlled clinical studies comparing the safety of constant current and constant voltage systems. However, in 1985, Prass and Luders¹⁰ reported on a preliminary study comparing these systems using the rat sciatic nerve model. They tested constant current and constant voltage stimulation using optimal stimulating probes. These authors did not find that one system was safer than the other. Since there appears to be no demonstrable advantage to either system, the decision of which to use should be based on which system the monitoring personnel are most comfortable operating.

Stimulator Probes

Stimulator probes' physical and electrical characteristics vary. A disposable stimulator probe usually has an insulated handle with a metallic stimulator tip. It is advantageous for the probe tip to be malleable so that areas that are visually inaccessible can be swept for the presence of a targeted nerve. A blunt probe will be less dangerous

than a sharp probe when it is inserted into the depth of a surgical field.

As noted earlier, the constant current stimulation mode is subject to current shunting by blood or CSF. In order to minimize this occurrence, flush tip probes have been developed. A flush tip probe is lined by an insulator throughout its length, so that the insulation is flush with the end of the stimulator. This decreases the surface area of the probe tip and decreases the risk of probe contact with blood or CSF. In 1985, Kartush and coinvestigators¹¹ compared noninsulated with insulated, flush-tip probes under simulated conditions of CSF shunting in the facial nerve of the guinea pig. They found that when using either monopolar or bipolar stimulation, insulated electrodes were significantly ($p < 0.05$) less affected by shunting than uninsulated electrodes.

Permanent surgical tools may also be used as electrical stimulators. Two different systems are available for this. The first employs a clip that can be attached to any metallic (conducting) instrument. The main disadvantages are that the instruments are not insulated and the clip connecting the stimulation source to the instruments may become dislodged. A second system involves the use of instruments specifically engineered for nerve stimulation as well as surgical dissection. These stimulators are available as round knives or probes that have a well-insulated handle, although not flush with the instrument tip, since a sharpened dissecting surface must be available for use. These instruments have a permanent safe adaptor for connection to a current source.

Monopolar Versus Bipolar Stimulation

Electrical stimulation may be delivered to a nerve via one of two modes: monopolar or bipolar. In a monopolar system, current is passed in all directions from a single electrode to surrounding tissue. The ground is placed far afield. Monopolar stimulation is helpful in mapping the course of a nerve. For example, when the course of the facial nerve is obscured or distorted by tumor, monopolar stimulation allows the surgeon to map the nerve by placing the stimulator in contact with tissue and raising the stimulus level until a response is obtained, even if the nerve is not physically touched. A threshold response depends on the distance from the stimulating probe to the nerve in question and the resistance of the tissue through which the stimulus must travel, as well as the electrical health of the targeted nerve. If the nerve is nearby, even a low stimulation threshold is sufficient to elicit a response, whereas if the nerve is distant, a high stimulation level is required (Fig. 2). This allows the surgeon to search for the nerve without moving the electrode, but rather by placing it in the area in question and raising the stimulus until a response is elicited. Silverstein and coinvestigators¹² have suggested that the relationship between the current threshold and the distance through bone is linear. The exact

relationship between current threshold and other tissues has not been adequately investigated.

In a bipolar system, two electrodes are adjacent to each other, with current passing between them. This method of stimulation minimizes the spread of current to nearby structures, and is thus more precise. It is also more limiting. Little or no response may be observed if the stimulator is not properly oriented with respect to the nerve, and quite close to it. This is true because current flow is localized to the area between the electrodes. Since a bipolar stimulator must be placed in a proper orientation, it is best to use when the course of the nerve has been demonstrated, as in precise differentiation of an attenuated facial nerve from similar-appearing thickened arachnoid. Bipolar stimulators are bulkier than monopolar stimulators since two electrodes are introduced into the operative field rather than one.

Duration, Frequency, and Intensity of Electrical Nerve Stimulation

The monitoring team must choose the parameters that will evoke the greatest neuromuscular response with the least amount of electrical stimulation. Most commercially available systems deliver a square-wave, pulsed current stimulus, the parameters of which are easily manipulated. The optimal frequency of stimulation allows the nerve monitoring personnel the time to assimilate the incoming information at a comfortable speed (3 to 5 pulses/sec). Duration of current pulses should be in the range of 50 to 100 μ sec. It is important that the current be delivered as a pulsed stimulus because the danger of nerve injury exists when continuous electrical stimulation is used.⁸

When using a constant current system, the stimulus intensity is controlled by manually changing the current level. On a bare intracranial facial nerve, 0.1 or 0.2 mA is usually sufficient to obtain a robust response. When the course of the nerve is obscure, the surgeon may place the electrode in the surgical field and the monitoring personnel may increase the current until a response is observed. If no response is elicited, the electrode may be placed elsewhere and stimulation delivered again. With a constant voltage system, mapping the course of the nerve is performed in much the same way as with constant current. For IONM, voltages required are far less than for conventional surface electrophysiology, so the surgeon must ensure that the equipment is capable of precise voltage control in the 0.1 to 1 V range.

REVIEW OF RECENT LITERATURE: FACIAL NERVE MONITORING

A standardized facial function scale allows comparisons of outcome between studies. The most widely used

scale is the House-Brackmann Facial Nerve Grading System¹³ (Fig. 3), which measures facial function from level I (perfect function) to level VI (total paralysis). The House scale may also be simplified to a three-point system of satisfactory, moderate, and poor function.

Although many authors have written about IONM since its inception, few have included controls or statistical analysis (Table 1). In 1988, Harner and coinvestigators¹⁴ conducted one of the largest controlled studies. A series of 91 consecutive acoustic neuroma cases performed with IONM were compared to 91 matched, historical controls performed without monitoring. All procedures used a suboccipital approach to the cerebellopontine angle (CPA). Trends reported included an increase in anatomically preserved facial nerves from 84% in the unmonitored group to 92% in the monitored, with the largest difference in the group with the largest tumors (41% unmonitored, 71% monitored). There was also a distinct increase in the number of monitored patients with postoperative House grade I facial function and a decrease in those with postoperative House grade VI.

In 1989, Niparko and coinvestigators¹⁵ compared 29 monitored translabyrinthine acoustic neuroma surgeries with 75 unmonitored surgeries using the same approach.

Grade	Description	Characteristics
I	Normal	Normal facial function in all areas
II	Mild dysfunction	Gross: slight weakness noticeable on close inspection; may have very slight synkinesis At rest: normal symmetry and tone Motion Forehead: moderate to good function Eye: complete closure with minimum effort Mouth: slight asymmetry
III	Moderate dysfunction	Gross: obvious but not disfiguring difference between two sides; noticeable but not severe synkinesis, contracture, and/or hemifacial spasm At rest: normal symmetry and tone Motion Forehead: slight to moderate movement Eye: complete closure with effort Mouth: slightly weak with maximum effort
IV	Moderately severe dysfunction	Gross: obvious weakness and/or disfiguring asymmetry At rest: normal symmetry and tone Motion Forehead: none Eye: incomplete closure Mouth: asymmetric with maximum effort
V	Severe dysfunction	Gross: only barely perceptible motion At rest: asymmetry Motion Forehead: none Eye: incomplete closure Mouth: slight movement
VI	Total paralysis	No movement

Figure 3. House-Brackmann facial nerve grading system. A standardized method for assessing facial function. Satisfactory function corresponds to House Grades I and II, moderate function corresponds to House grades III and IV, and poor function corresponds to House grades V and VI. (Reprinted with permission from House and Brackmann.¹³)

In this study, the historical controls were not matched, but results were rigorously analyzed. They found that the incidence of satisfactory facial function (House scale I and II) was significantly higher in monitored than in unmonitored patients at 1 year follow-up ($p = 0.05$). Testing of sub-groups indicated that the significant difference remained valid only in the group with tumors larger than 2.0 cm. Improvements in facial function 1 week postoperatively were measurable but not significant.

In 1989, Leonetti and coinvestigators¹⁶ studied a series of 20 infratemporal approaches to the skull base where monitoring was performed. Thirty-one patients undergoing similar procedures served as unmonitored controls. Postoperative results were reported only for patients with normal (House grade I) preoperative facial function, and who had facial nerve rerouting during surgery. They observed 70% of unmonitored patients with satisfactory facial function immediately postoperatively and 48% at discharge. In the monitored group, 93% showed satisfactory function immediately postoperatively and 80% at discharge. No monitored patients were observed to have poor function at any time, but 48% of unmonitored patients were discharged with poor function. No tests of significance were reported.

In 1990 Hammerschlag and Cohen¹⁷ compared a series of 111 monitored surgeries of the CPA to 207 unmonitored, historical controls. Of the 318 procedures, 314 were for acoustic neuroma. They found a significant decrease in the number of patients with complete facial paralysis in the monitored group ($p = 0.001$). Most postoperative paralysis was associated with large tumors; however, analysis of subgroups based on tumor size failed to show significance, perhaps because of the small size of some of the subsets. Intact facial function was not significantly different between groups, but incidence of moderate function was increased in the monitored group ($p = 0.05$). This is perhaps due to patients who would otherwise have been paralyzed, but who improved to moderate postoperative function with monitoring.

In 1991, Dickins and Graham¹⁸ conducted a comparison of two groups undergoing CPA tumor surgery using two types of monitoring modalities and a third unmonitored control group. The 38 unmonitored patients were operated on earliest in the series, then 29 monitored by a muscle contraction sensor-transducer system, and, finally, 41 monitored by EMG. An increase in postoperative facial function was observed in each monitored group. Satisfactory results (House grades I and II) were achieved in 39% of the unmonitored group, 55% of the sensor-transducer group, and 87% of the EMG group. Poor results (House grades V and VI) were observed in 37% of the unmonitored group, 21% of the sensor-transducer group, and 4% of the EMG group. No tests of significance were reported.

In 1991, Kwartler and coinvestigators¹⁹ reported a retrospective series, consisting of 89 patients who had undergone translabyrinthine resection of acoustic neu-

Table 1. Literature Review: Facial Nerve (FN) Monitoring

<i>All Studies Compared Against Historical Controls</i>	<i>No.</i>	<i>Surgery</i>	<i>House I or II FN Function</i>
Harner et al, 1988	91	Suboccipital AN*	55% at 1 year
Niparko et al, 1989	29	Translabrynthine AN	86% at 1 year
Leonetti et al, 1989	20	Infratemporal fossa.	80% at discharge
Hammerschlag and Cohen, 1990	111	Eclectic CPA surgeries	82% at 6 months
Dickins and Graham, 1991	41	Eclectic CPA surgeries	87% at 6 months
Kwartler et al, 1991	89	Translabrynthine AN	82% at 1 year

*AN: acoustic neuroma.

roma with monitoring and 155 patients who had undergone the same procedure without monitoring. Facial function was assessed immediately postoperatively, at discharge, and at 1 year. Satisfactory results were achieved in 66% of unmonitored patients immediately postoperatively and in 49% at discharge. Satisfactory results were observed in 81% of monitored patients postoperatively and in 65% at discharge. These differences were significant ($p \leq 0.05$). Testing of subgroups showed a significant difference between monitored and unmonitored patients if their tumors were larger than 2.5 cm ($p \leq 0.02$). Differences between the groups at 1 year follow-up were not significant.

Within these controlled studies, statistically significant results were obtained exclusively among patients with large tumors. Patients with smaller tumors revealed a trend towards better function with monitoring, but statistically significant differences were not attained. Some investigators either did not perform or did not report tests of significance, but in all the reviewed series, facial function measurably improved or remained the same between monitored and unmonitored groups.

It should be noted that since all control procedures were historical, the chronologic sequence suggests that a learning curve in surgical technique may also have contributed to better outcome in later (monitored) patients. Also, advances in instrumentation and magnification over time have improved the safety of acoustic neuroma surgery and thus the postoperative outcome.

EMG monitoring improves identification and preservation of targeted nerves and provides prognostic information in two ways. First, it appears that those patients with the best surgical results have low stimulation thresholds at the end of surgery and, second, that EMG evidence of nerve damage, in the form of neurotonic discharges, was absent during surgery.²⁰ IONM has become indispensable to surgeons who recognize its value.

NERVE MONITORING TECHNIQUES: SENSORY NERVE

Cochlear Nerve (Auditory Pathway)

In addition to preservation of the facial nerve, maintenance of cochlear nerve function has become a priority

in acoustic neuroma surgery in recent years. Many patients who have residual hearing despite the presence of an acoustic tumor may benefit from techniques to monitor the cochlear nerve. These patients represent a minority of total acoustic neuroma cases. Nevertheless, measurable postoperative hearing in as many as 50% of patients with measurable preoperative hearing has been reported.^{21,22} However, most of these cases represent patients with only poor or barely serviceable hearing. Preservation of useful hearing is less successful but has been reported with small tumors. It is thought that brainstem auditory evoked response (BAER) has been of use in achieving this end.

It is important to note that other cochlear nerve monitoring strategies have been employed, including electrocochleography and direct intracranial measurement of cochlear nerve compound action potential, but, at present, the bulk of the literature is comprised of investigations using BAERs.

Brainstem Auditory Evoked Response

The most commonly used method of monitoring the cochlear nerve is BAER. Stimuli are introduced to the ear in the form of clicks or tones, and far-field potentials are recorded from electrodes placed on the earlobes and the vertex of the head (similar to EEG monitoring). Computer-averaging techniques are required to separate the auditory potentials from background EEG activity. The waveforms elicited by this technique represent potentials occurring in specific structures along the auditory pathway. There are normally five waves, the first of which (wave I) is associated with the distal cochlear nerve. Waves III and V are associated with the superior olive and the inferior colliculus of the midbrain, respectively. Increased latency of wave V and increased interpeak latency between wave I and wave V indicate decreased conduction velocity in the auditory pathway. The shape and latencies of the BAER waveform at the end of surgery offer prognostic information about the possibility of maintaining hearing postoperatively. If wave V is present, there is even a chance for useful hearing postoperatively.

The primary disadvantage of the BAER is that 500 to 1000 stimulus or response events must be averaged in order to obtain a meaningful wave form. This can take a

minute or more, depending on the rate of stimulus delivery. Any changes in the BAER waveform due to surgical maneuvers will not be apparent until well after injury has taken place, so that this is not a real time system.²³

Another use for intraoperative BAER involves monitoring of general brainstem function. In patients who are already deaf ipsilaterally, the contralateral BAER may still be monitored. Monitoring of the contralateral BAER may be especially useful in patients with very large tumors and substantial brainstem compression. The loss or delay of late BAER waves signifies compromise of global brainstem function and may reflect ischemia or excessive retraction.

Review of Literature: Hearing Preservation

There remains debate over a standardized method of reporting functional hearing in the literature.²⁴ This problem makes the literature on hearing preservation difficult to interpret, because results are often not comparable between investigators. The most common system defines serviceable hearing as a speech reception threshold (SRT) of less than 50 db and a speech discrimination score of better than 50% (the 50/50 rule).

The first report of intraoperative BAER recording during acoustic neuroma surgery was in 1978.²⁵ Since then, the literature concerning hearing preservation and BAER monitoring has been abundant (Table 2).

In 1985, Abramson and coinvestigators²⁶ reported a series of hearing preservation procedures on 16 tumors of the CPA in which BAER was performed. Some postoperative hearing was retained by four patients, but only two retained serviceable hearing by the 50/50 criteria (10%).

In 1986, Cohen and coinvestigators²¹ performed 29 surgeries for acoustic neuroma with attempted hearing preservation. It is not clear how many of these procedures were performed with intraoperative BAER monitoring. They reported preserved hearing in 12 of 29 patients (41%), all of whom displayed serviceable or good function.

In 1990, Kemink and coinvestigators²² reported a series of 20 patients with acoustic neuroma for whom hearing preservation surgery was attempted. Intraoperative BAER monitoring was performed in 17 of 20 proce-

dures. Excellent results, defined as less than a 20 dB increase in SRT and less than a 15% decrease in speech discrimination, were reported in 10 of 20 patients (50%). All 10 cases also fell within the 50/50 guideline for serviceable hearing. However, it is not clear whether all of the patients with excellent results fell in the monitored group.

In 1992, Fischer and coinvestigators²⁷ reported a retrospective study of 99 patients who underwent attempted hearing preservation acoustic neuroma surgery; 57 of 99 (58%) had intraoperative BAER monitoring performed. Some hearing preservation was observed in 29 of 99 (29.3%) patients, but serviceable hearing was preserved in only 12 of 99 (12%). Twenty-two of 57 (39%) monitored patients had some preserved hearing and 7 of 42 (17%) unmonitored patients had similar results. This difference was significant ($p = 0.05$); however, it is not clear if the significance holds when tested with patients with serviceable hearing.

Ebersold and coinvestigators²⁸ reported a series of 221 patients with some preoperative hearing who underwent surgery for acoustic neuroma. Intraoperative BAER monitoring was performed in 90; however, a comparison of results between monitored and unmonitored groups was not reported. Some hearing was preserved in 52 of 221 patients (24%), although serviceable hearing was preserved in only 24 of 221 (11%). Their criteria for serviceable hearing was somewhat more lenient than most, with a pure-tone average of lower than 60 dB and a speech discrimination of better than 40%.

Some of the recent literature has called into question the usefulness of BAER monitoring in hearing preservation during acoustic neuroma surgery. It is not clear from these studies whether the BAER is associated with successful hearing preservation or if a learning curve or easier dissection of smaller tumors has contributed to better outcomes. Kveton²³ compared a series of 16 patients who underwent acoustic neuroma surgery, nine with BAER monitoring and seven without. Of note, he found that more patients in the unmonitored group had serviceable hearing (57%) than in the monitored group (44%). Other investigators also report doubt that intraoperative BAER monitoring substantially aids in hearing preservation.²⁹

Despite the questions about BAER and hearing preservation, BAER data may be used as a prognostic indicator for postoperative hearing. In 1989, Watanabe and coinvestigators³⁰ reported that loss of wave V is usually associated with loss of useful hearing and that preservation of waves I and V usually indicates the possibility of retained useful hearing. These findings have been corroborated by Ebersold et al,²⁸ Kemink et al,²² and Fischer et al.²⁷

Table 2. Literature Review: Hearing Conservation*

	No.	Overall Hearing (%)	Serviceable Hearing (%)
Levine et al, 1978			
Abramson et al, 1985	20	20	10
Cohen et al, 1986	29	—	41
Kemink et al, 1990	20	65	50
Fischer et al, 1992	99	29	12
Ebersold et al, 1992	221	24	11

*Not all patients had BAER monitoring.

MULTICHANNEL INTRAOPERATIVE NEURAL MONITORING

Multichannel IONM allows simultaneous assessment of combinations of motor and sensory cranial nerves.

These combinations are based on the specific surgery being performed and the particular nerves at risk. Table 3 delineates accessible and appropriate targeted muscles to monitor specific motor cranial nerves.

In addition, in a multichannel system, the use of a control channel serves as a system check. The nerve most frequently monitored as a control is the spinal accessory nerve (XI). By monitoring the XI nerve in conjunction with the VII nerve, for example, the monitoring personnel can easily distinguish true VII nerve activity from systemic artifact, such as diffuse muscle contraction associated with light anesthesia that would register on both the VII and XI nerve channels. The particular advantages of the XI nerve electrodes are that they usually are out of the operative field and that the trapezius has a robust EMG response.

Many surgeons, however, attain excellent results with the use of a single-channel system targeted at the nerve of greatest concern.

PERSONNEL

IONM can be performed by surgeons, anesthesiologists, technicians, or neurophysiologists. There are specific advantages and disadvantages to each system.

If a surgeon performs IONM, a single-channel nerve monitoring system with auditory feedback is necessary. Since the surgeon is occupied with this surgical task, he cannot be distracted by a complicated (multichannel) system or even by watching the oscilloscope of a single-channel unit. It is the auditory alarm that alerts the surgeon to impending neural compromise. However, it is not possible to differentiate true neural responses from artifact with auditory feedback, since the auditory alarm cannot make that distinction. If the alarm sounds frequently due to artifact, the temptation to quiet the alarm by lowering the sensitivity of the system should be resisted, because, along with eliminating extraneous artifact, lowering the sensitivity also eliminates valuable and subtle IONM information. This makes IONM a less valuable and reliable tool. The advantages of a surgeon performing his own IONM includes the fact that no extra personnel are employed. It is therefore less expensive, and more space in the operating room is available.

Anesthesiologists may also perform IONM, but again, the anesthesiologist's attention is required by his

routine tasks and cannot be diverted by a complicated protocol. An oscilloscope may be available to assess EMG waveforms but an anesthesiologist may not possess sophisticated knowledge in this area. Again, no extra personnel are employed and costs are kept low.

When a technician performs IONM, the problems of distraction and divided attention are absent. The technician's full attention is occupied with IONM, so that a more complex, multichannel system may be employed. A technician has limited knowledge of waveforms and EMG interpretation, so that the full benefit of interpretation of the EMG data is not gained. In addition, extra personnel add to the operating room crowd.

When a neurophysiologist performs IONM, the system can be used optimally. A sophisticated multichannel system may be used, providing optimal flexibility in the IONM protocol. A neurophysiologist is an expert in interpretation of EMG data, and therefore false-positive and false-negative responses will be identified accurately and not reported, so that the surgeon is only alerted to relevant information. Both surgeon and patient may be most comfortable with the knowledge that an expert is performing the technique. Collaborating with the neurophysiologist increases expenses, since an additional physician is consulted and a complex and expensive system may now be used.

SURGERIES WHEN INTRAOPERATIVE NEURAL MONITORING IS INDICATED

Many surgeries may gain an additional margin of safety through the use of IONM. Since its inception, IONM has been used almost exclusively in the surgical treatment of posterior fossa tumors, primarily resection of acoustic neuromas. As the value of IONM becomes more apparent, indications for its use will widen.

The monitoring needs for a specific surgery depends on the nerves at risk (Table 3). Acoustic neuroma surgery involves identification of the facial nerve (VII) in the internal auditory canal and microdissection of the VII nerve off of the tumor capsule of the cerebellopontine portion of the tumor. The most frequently monitored nerve is the facial nerve. In order to minimize the risk of an inaccurate response, two channels of VII should be monitored, the orbicularis oculi and oris. Large tumors, however, frequently abut the trigeminal nerve superiorly and the jugular foramen nerves inferiorly. The trigeminal nerve (V) is monitored via the temporalis or the masseter muscles. The XI nerve is monitored via the trapezius muscle and is the simplest of the jugular foramen nerves to monitor. Monitoring of nerve V can differentiate facial movement by nerve V innervated muscles (masseter and temporalis) from movement due to muscles of facial expression. If the patient has preoperative hearing and a preoperative reproducible BAER, the BAER can be monitored intraoperatively for hearing preservation. For large

Table 3. Monitored Nerve and Associated Muscle

<i>Targeted Nerve</i>	<i>Targeted Muscle</i>
Trigeminal (V)	Masseter or temporalis
Facial (VII)	Orbicularis oculi or oris
Glossopharyngeal (IX)	Soft palate
Vagus (X)	Soft palate, vocal folds
Spinal accessory (XI)	Trapezius
Hypoglossal (XII)	Intrinsic tongue

acoustic neuromas, then, five channels could be used for optimal monitoring: two for nerve VII, one for nerve V, one for nerve XI, and one for the BAER. The nerve of greatest concern is nerve VII, and many surgeons will monitor this nerve alone with a single-channel system (Table 4).

Other posterior fossa surgeries also benefit from the use of IONM (Table 4). Vestibular nerve section or vascular decompression of nerve VII for hemifacial spasm would both use two channel nerve VII monitoring, nerve XI monitoring as a control, and BAER to monitor hearing: a total of four-channel simultaneous IONM. Lower posterior fossa tumors, such as meningiomas or glomus jugulare tumors, that involve the region of the jugular foramen may require monitoring of the glossopharyngeal (IX), vagus (X), and spinal accessory (XI) nerves as well as the hypoglossal nerve (XII). Nerves IX and X can be monitored by placing electrodes in the soft palate, and nerve X can be monitored separately by placing needle electrodes in the false vocal cords on direct laryngoscopy. Nerve XII can be monitored by placing electrodes in the tongue.

Temporal bone surgery always involves circumventing or rerouting the facial nerve (Table 5). Temporal bone surgery would be optimally monitored with a two-channel nerve VII and nerve XI monitoring system. Again nerve XI would be used as a system check. Not all temporal bone surgery requires IONM, but specifically middle ear exploration for conductive hearing loss in the patient with a congenital middle ear malformation, surgery for external auditory canal atresia, and revision tympanomastoid surgery are those for which the facial nerve is at higher than usual risk.

IONM has not been extensively in extracranial head and neck surgeries, but this may change as monitoring units become more ubiquitous (Table 6). IONM would be especially useful in revision surgery where the clarity of anatomy may be lost. Monitoring of the facial nerve in parotid surgery, or the recurrent laryngeal branch of the vagus nerve in thyroid surgery, may be of significant benefit. In the case of revision carotid endarterectomy, IONM would aid in locating nerve X. In revision neck dissection, identification of nerves VII, IX, X, XI, or XII would also be made easier through the use of IONM.

Table 4. Intracranial Surgeries

<i>Surgeries</i>	<i>Nerves Monitored</i>
Acoustic neuroma resection	
Suboccipital	V, VII (eye and mouth),
Translabyrinthine	XI, BAER
Other cerebellopontine angle surgeries	
Vestibular nerve section	VII (eye and mouth), XI,
Vascular decompression for hemifacial spasm	BAER
Jugular foramen surgeries	
Meningioma	IX, X, XI, XII
Glomus tumor resection	

Table 5. Temporal Bone Surgeries

<i>Surgeries</i>	<i>Nerves Monitored</i>
Congenital middle ear malformation	VII (eye and mouth), XI
External auditory canal atresia	VII (eye and mouth), XI
Revision tympanomastoid surgery	VII (eye and mouth), XI

Table 6. Extracranial Surgeries

<i>Surgeries</i>	<i>Nerves Monitored</i>
Parotid	VII (eye and mouth)
Thyroid	X (recurrent laryngeal nerve)
Carotid endarterectomy	X
Neck dissection	VII, IX, X, XI, XII

REVIEW OF INTRAOPERATIVE NEURAL MONITORING SYSTEMS

IONM can be performed with commercially available or custom systems. Several key parameters are of particular importance in deciding on which system is most appropriate for a given surgery. These include the number of monitoring channels, monitoring technique, variables in stimulation parameters, and BAER capabilities. Also of importance are the IONM requirements for a specific surgery, space in the operating room, the need for personnel to operate the system, and cost.

CONCLUSIONS

The surgeon should be well informed to select an IONM system. A team of surgeon and neurophysiologist may collaborate on decisions concerning which system to purchase, if a team-monitoring approach is planned. IONM is a safe technique and is of clear clinical value in the preservation of cranial nerves in otolaryngology/head and neck surgery and is rapidly becoming the standard of care.

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