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Intraoperative Monitoring of Facial and Cochlear Nerves During Acoustic Neuroma Surgery

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COMMENTARY

While most of the information in this article is still useful and relevant, there have been several developments in cranial nerve monitoring during the 16 years since its initial publication. This brief addendum is not meant to be a comprehensive update, but rather a concise summary of some of the most relevant developments with references to more recent literature. For a more comprehensive treatment of many of these topics, see Yingling and Ashram [1]. More information specific to cochlear nerve monitoring may be found in Martin and Stecker [2].

In 1992, many of the systems used in intraoperative monitoring were cobbled together from laboratory equipment. Today, commercial systems specifically designed for intraoperative monitoring are available from several manufacturers, including Cadwell Laboratories, Axon Systems, and Nihon-Kohden. These systems typically include specialized low voltage and/or current stimulators suitable for direct cranial nerve stimulation, the ability to perform EMG and evoked potential recordings simultaneously, and can be configured to monitor many other types of surgery with appropriate software protocols.

A major limitation of EMG-based methods for facial nerve monitoring has been their inability to be used during electrocautery, which creates large electrical artifacts that obliterate EMG signals at times when cranial nerves may be at significant risk from thermal injury if cautery is applied in the vicinity of the nerve. Thus methods not based on electrical recordings are a useful adjunct to EMG, which remains the most sensitive indicator of facial nerve irritation. While methods based on direct detection of facial motion by attached sensors have been attempted [3], the best alternative to EMG may be a video-based system [4].

Another recent development is the identification of a specific EMG response to stimulation of the nervus intermedius [5]. This response has a characteristic low amplitude, prolonged latency, and restricted distribution compared to stimulation of the facial nerve itself. If this distinction is not recognized, the n. intermedius may be mistaken for the facial nerve; since these nerves are sometimes widely separated by the growth of the tumor this may lead to inadvertent section of the facial nerve.

Since the NIH Consensus Statement on Acoustic Neuroma [6] unequivocally recommended routine intraoperative monitoring of the facial nerve, there have been no formal clinical trials to assess the efficacy of facial nerve monitoring in improving outcome. However, numerous studies have shown than parameters derived from responses to intraoperative stimulation (ie, as threshold, amplitude, pre-post surgery, or proximal/distal ratios) are strong predictors of postoperative facial function [7–20]. While the consistency of these reports is encouraging, the optimum predictive variables have yet to be determined; this will require a larger population studied with a consistent set of parameters. In a different context (middle ear and mastoid surgery), Wilson and colleagues [21] demonstrated the cost-effectiveness of facial nerve monitoring.

Finally, one of the remaining issues in facial nerve monitoring is the necessity for surgeon-applied stimulation of the nerve itself, which is often difficult in larger tumors until substantial resection has taken place, sometimes without knowledge of the location of the nerve until it is too late. A method for continuous assessment of facial nerve function without the necessity for direct intracranial stimulation would help mitigate this problem. An obvious candidate

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is the blink reflex, which is elicited by stimulation of the supraorbital branch of the trigeminal nerve and, via a polysynaptic reflex arc, elicits responses in muscles innervated by the facial nerve. Unfortunately, although the blink reflex has shown promise as a prognostic indicator in the clinical setting [5], it has proven difficult to reliably elicit under general anesthesia [22].

The most promising solution to this problem may be elicitation of facial nerve motor evoked potentials by transcranial electrical stimulation of the contralateral face area of motor cortex [23]. Questions remain as to the specificity of this response to facial nerve activation (for example, trigeminal nerve activation could produce similar responses, and latency-based techniques for differentiation of V vs. VII as described in the main article may not be applicable to transcranial stimulation). Nevertheless, the method of transcranial stimulation has come into widespread use for monitoring corticospinal tracts during spinal surgery, and its application to facial nerve monitoring may prove to be the most significant advance in this field since the advent of EMG monitoring in the late 1970's.

The first use of cranial nerve monitoring during posterior fossa surgery was almost a century ago. On July 14, 1898, Dr. Fedor Krause performed a cochlear nerve section for tinnitus and noted that "... unipolar faradic irritation of the (facial) nerve-trunk with the weakest possible current of the induction apparatus resulted in contractions of the right facial region, especially of the orbicularis oculi, as well as of the branches supplying the nose and mouth..." [24]. The patient awoke with a slight facial paresis, which mostly resolved within a day. Krause also noted contractions of the shoulder, which he attributed to stimulation of the spinal accessory nerve, which "... had undoubtedly been reached by the current, because it was, together with the acusticus, bathed in liquor that had trickled down... ." He thus anticipated not only the use of electrical stimulation to locate cranial nerves but also the enduring problem of artifactual responses from current spread.

Frazier [25] described a similar technique used in 1912 during an operation for relief of vertigo, pointing out the importance of facial nerve preservation and the fact that it could be identified by "galvanic current." Similar methods were later described by Olivecrona [26,27], Hullay and Tomits [28], Rand and Kurze [29], Pool [30], and Albin and colleagues [31]. Givre and Olivecrona [26] and Hullay and Tomits [28] even recommended removal of acoustic neuromas under local anesthesia to facilitate assessment of facial function. This early technique, in which the face was observed for visible contractions after electrical stimulation, remained the state of the art for facial nerve identification until the late 1970s, when the use of facial electromyography (EMG) was introduced by Delgado et al in 1979 [32].

There are, to our knowledge, no reports of VIIIth cranial nerve monitoring until the late 20th century, undoubtedly because the development of techniques for signal averaging and the discovery of the human auditory brain stem response (ABR) by Jewett and Williston in 1971 [33] were necessary preconditions for attempting to monitor cochlear nerve function. Also, during the early days of acoustic neuroma surgery, the generally large size of the tumors when diagnosed and the relatively crude state of surgical techniques made mortality the main issue, rather than cranial nerve preservation. As advances in diagnosis and microsurgical techniques have made such surgery safer, increasing emphasis has been placed on preservation of cranial nerve function, with a resultant growth in development of techniques for monitoring these nerves during surgery.

Now VIIth cranial nerve monitoring during acoustic neuroma surgery has become routine, and anatomic preservation of the facial nerve is regularly achieved in all but a few of the largest tumors. Facial motility is still often compromised in the immediate postoperative period, but the prognosis for eventual recovery of function is good if the nerve is intact and can be electrically stimulated after tumor removal. Preservation of hearing has been more difficult to achieve, owing to the more intimate relationship of the tumors with the cochleovestibular nerve, but can now often be achieved in smaller tumors with the aid of VIIIth cranial nerve monitoring techniques. This article, based on our experience in over 500 posterior fossa procedures as well as a review of the literature, describes the methods currently available for cranial nerve monitoring, emphasizing facial and cochlear nerve monitoring during acoustic neuroma surgery.

Technical issues

Personnel

Successful performance of intraoperative monitoring is not simply a matter of bringing another piece of equipment into the operating room. Applying neurophysiologic techniques in the time-pressured and electrically hostile environment of the operating room requires specialized skills that may make the difference between successful monitoring and no monitoring or, even worse, inadequate monitoring that provides inaccurate feedback to the surgeon. As a result, a new specialty field of intraoperative neurophysiologic monitoring is evolving, and a professional organization, the American Society of Neurophysiological Monitoring (ASNM), has been founded. Specialists in intraoperative monitoring have come from diverse backgrounds, including neurology, neurophysiology, audiology, and anesthesiology; regardless of background or professional degree, however, such personnel share a common fund of knowledge including the relevant neuroanatomy and neurophysiology, principles of biomedical instrumentation, knowledge of the variety of intraoperative monitoring techniques and their uses and limitations, and practical experience in performing these techniques and interpreting their results. Given the potentially catastrophic consequences of inappropriate application of monitoring techniques, we believe that the participation of professional monitoring personnel is highly desirable, despite the additional costs incurred. Third-party reimbursement should be facilitated by the recent addition of a CPT code (95920) specific to intraoperative neurophysiologic monitoring.

Anesthetic considerations

Unlike cortical evoked potentials, which are notoriously sensitive to many anesthetic agents, the ABR and EMG responses that are monitored during acoustic neuroma surgery are essentially unaffected by any commonly used anesthetic regimens. The one exception to this is a contraindication to the use of any muscle relaxants because blockade of the neuromuscular junction is incompatible with meaningful monitoring of EMG activity. A recent report [34] has suggested that partial blockade can be used to prevent patient movement while still retaining the ability to elicit EMG responses with facial nerve stimulation. Our experience has verified this observation but indicates that although electrically evoked EMG is relatively preserved, both spontaneous EMG and *mechanically elicited activity* appear to be obliterated by these agents. This compromises two of the more important indicators of facial nerve injury.

We therefore recommend that *no paralytic agents* be used during acoustic neuroma surgery. This, of course, creates its own problems for anesthetic management because patient movement could have disastrous consequences and must be prevented by maintaining an adequate level of anesthesia. Fortunately, the ABR and EMG are not affected by routine concentrations of common anesthetics, such as nitrous oxide, opiates, or halogenated agents, so no other constraints on anesthetic technique are necessary. Short-acting agents such as succinylcholine may be given to facilitate intubation, but it must be verified that such agents have cleared before any manipulations that might affect the facial nerve are undertaken. For a suboccipital approach, this would be the time of opening the dura and retraction of the cerebellum; in a translabyrinthine approach, the facial nerve is first at risk during skeletonization of the horizontal portion in the temporal bone. Fortunately these events typically occur far enough into the procedure that any relaxants given at intubation will have cleared in time.

Instrumentation

Electromyography instrumentation

The essential requirements for facial EMG monitoring are a stimulator that can be precisely controlled at low levels, one or more low noise amplifiers capable of amplifying microvolt level signals, an oscilloscope, and an audio monitor with a squelch circuit to mute the output during electrocautery. The NIM-2 (Nerve Integrity Monitor), manufactured by Xomed-Treace (Jacksonville, Florida), is a commercial device offering two channels (only one of which is displayed at a time) and appropriate stimulation and squelch circuits. It is relatively easy, however, to put together a system from off-the-shelf components that can provide more channels at a substantially lower cost. At the University of California, San Francisco (UCSF), we use a four-channel system with Grass amplifiers and stimulator (Quincy, Massachusetts) and a Tektronix oscilloscope (Beaverton, Oregon), with a custom audio monitor. Another possibility, although generally more expensive, is to use a commercial multichannel EMG machine, provided that low enough levels of stimulation are available. Although several multichannel machines are available, most are designed for percutaneous stimulation at higher levels (ie, 1 to 300 V or 1 to 50 mA), whereas the levels needed for safe intracranial stimulation are less than 1 V or 1 mA. A qualified biomedical engineer can usually modify such systems to lower the stimulation range, although care must be taken not to compromise patient safety features. The availability of more channels allows simultaneous monitoring of multiple divisions of the facial nerve independently as well as other cranial motor nerves such as V and XI, which are often involved in acoustic tumor surgery (see later).

Auditory brain stem response

The primary requirements for ABR monitoring are an averaging computer with appropriate high gain, low noise electroencephalogram (EEG) amplifiers, and an acoustic stimulus generator capable of delivering clicks of calibrated intensity, with control of polarity (condensation, rarefaction, or alternating) and repetition rate. Most commercial evoked potential systems meet these essential specifications and can be adapted to use in the operating room. Typical clinical systems include modules that accomplish two- to four-channel, high-gain (100 to 500 K) differential amplification with multipole, band-pass filtering capabilities; acoustic stimulus generation with a stimulus intensity range from threshold to at least 70 to 80 dB normal hearing level (NHL); response averaging with real time display of the evolving averages as well as the raw trace; and permanent record keeping on a disk medium with hard copy printout. Several additional features, however, are desirable for optimum monitoring performance. Key design features of the ideal monitoring system are versatility, portability (and size), and degree of automation.

General technical considerations

Ideally, systems for use during acoustic neuroma surgery would be capable of simultaneous EMG and ABR monitoring. This would require independent control of the time base, stimulation, and averaging parameters for the EMG and ABR channels, features that are not generally available in clinical EMG/evoked potential (EP) machines, which are designed to perform a single test at a time. The only exception that we are aware of at this writing is the Nicolet Viking II (Nicolet Instrument Corporation, Madison, Wisconsin), which has a recently released software package for intraoperative monitoring that allows for such simultaneous protocols. Simultaneous collection of ABRs from left and right ears is also desirable to control for nonspecific effects, such as anesthesia, acoustic artifact, and patient temperature. Again, this feature is not typically available in commercial systems; see under "Monitoring the VIIIth Cranial Nerve" later for details on how such a protocol has been implemented on a custom system.

Degree of automation and size are also important design issues. In general, the more compact and portable the system, the more likely it will be accommodated without major complaints from surgical personnel, especially if it is transported between various operating rooms. Automated data collection protocols, with simultaneous display of baseline traces and recent trends as well as the current trace, facilitate continuous monitoring and assessment of intraoperative changes, although the capability for manual override of automated protocols is desirable.

Surgical monitoring is done in an electrically hostile environment. Every effort must be marshalled to eliminate or reduce 50 or 60 Hz power line interference as well as the frequently broadband noise originating in other operating room equipment (eg, electrocautery, lasers, ultrasonic aspirators, microscopes, anesthesia machines, electrified beds, light dimmers, patient warmers, compression stockings). The 60 Hz notch filters found on most equipment are of limited utility because they remove only 60 Hz sinusoidal activity; more common is noise that recurs at the line frequency but consists of complex spikes with a high fundamental frequency that is not affected by notch filters. Therefore every effort should be made to identify such sources and eliminate their interference if possible. Frequently this can be done by grounding these items, plugging them into a different AC outlet, rerouting cables away from monitoring equipment, or even disconnecting them during crucial periods for monitoring. Unfortunately it is not always possible to eliminate or even identify some sources of interference (at UCSF, one particularly noisy operating room turned out to be upstairs over a magnetic resonance imaging scanner, which generated large pulsatile magnetic fields that were of sufficient strength to cause problems a floor away). Techniques for distinguishing residual artifact from physiologic activity are discussed later under "Monitoring the VIIth and Other Cranial Motor Nerves."

Another important technique is to ensure that the patient is adequately grounded to the recording apparatus and that no alternate ground paths exist. The patient ground should be placed close to the recording electrodes and care taken to obtain a low impedance ground by removing surface oils with alcohol, then rubbing conductive paste into the skin before applying a ground pad. All equipment should be grounded to the same spot with heavy-duty cables to avoid ground loops. A detailed analysis of these issues is beyond the scope of this article, but an excellent tutorial is provided by Møller [35].

Type and placement of recording electrodes

Either surface or needle electrodes can be used. Surface electrodes are less specific, more prone to artifact, and more timeconsuming to apply, so their use has largely been supplanted by needle electrodes, which can be quickly inserted and taped into place. The most commonly used are platinum needle electrodes designed for EEG recording (Grass E2), which have a larger uninsulated surface than electrodes designed for single-fiber EMG recording and thus are more likely to detect EMG activity arising anywhere in the desired muscle. Prass and Liiders [36] recommend the use of intramuscular hook wire electrodes, which are inserted with the aid of a hypodermic needle; in our experience, these are more traumatic and offer no major practical advantage, so we routinely employ the simpler needle electrodes.

The first uses of facial EMG primarily employed a single recording channel, typically with a bipolar configuration with one electrode in orbicularis oculi and another in orbicularis oris [37]. This montage provides coverage of muscles innervated from both superior and inferior branches of the facial nerve. It has several disadvantages, however, which have led to increasing use of multiple channels. First, the wider the spacing between two electrodes, the greater is the sensitivity to artifact pickup, which in the electrically hostile environment of the operating room can lead to difficult or erroneous interpretations. Second, mechanical trauma to the VIIth cranial nerve frequently causes sustained EMG activity that can make the identification of responses to electrical stimulation difficult. With two or more independent channels, there is a greater likelihood that at least one will be quiet enough to allow stimulation to be used even during high ongoing EMG activity.

For these reasons, we advocate the use of at least two channels of facial EMG as well as recordings from muscles innervated by other cranial nerves. For ABR recording in hearing conservation, one electrode is placed in the ear canal and another on the forehead or vertex; the placement of this electrode is not critical as long as it is near the midline. (See under "Monitoring the VIIIth Cranial Nerve" for further details on ABR recording procedures.) The positioning of the recording electrodes for a suboccipital approach with an effort to preserve hearing are shown in Fig. 1. For translabyrinthine approaches, the same configuration is used, with the exception of the earphone and electrodes for ABR recording.

Monitoring VIIth and other cranial motor nerves

Three main techniques for monitoring cranial motor nerve activity can be distinguished: (1) monitoring ongoing EMG activity for increased activity or changes in activity patterns related to irritation of the nerves by intraoperative events, such as retraction, tumor dissection, use of electrocautery, lasers, and ultrasonic aspiration; (2) identifying and mapping the course of the nerves with activity evoked by intracranial electrical stimulation; and (3) determining nerve functional integrity using evoked EMG methods.

Activity evoked by electrical stimulation

Until the late 1970s, the typical method for facial nerve identification involved someone (usually the anesthesiologist) observing the patient's face for evidence of movement related to intraoperative events or electrical stimulation. Unfortunately in many cases a complete facial palsy resulted even though the face was observed to move with stimulation. It is likely that the high level of stimulation necessary to produce gross movement from a nerve both chronically stretched by the tumor and acutely traumatized during surgery was itself damaging to the nerve and thus contributed to this apparently contradictory outcome. As a result, considerable effort has gone into developing more sensitive measures of facial activity that can be elicited with lower and safer levels of stimulation.

Modalities for monitoring

Several early efforts focused on the use of more sensitive detectors of facial motion, using photoelectric devices, strain gauges, or accelerometers mounted on the face [38,39]. A commercial device is available that uses this technique [40,41]. A low-tech version of this method has been described in a whimsically titled paper "Bells against palsy," [42] which uses small "jingle bells" sutured at the points of maximum excursion of the facial musculature. A technique has also been described

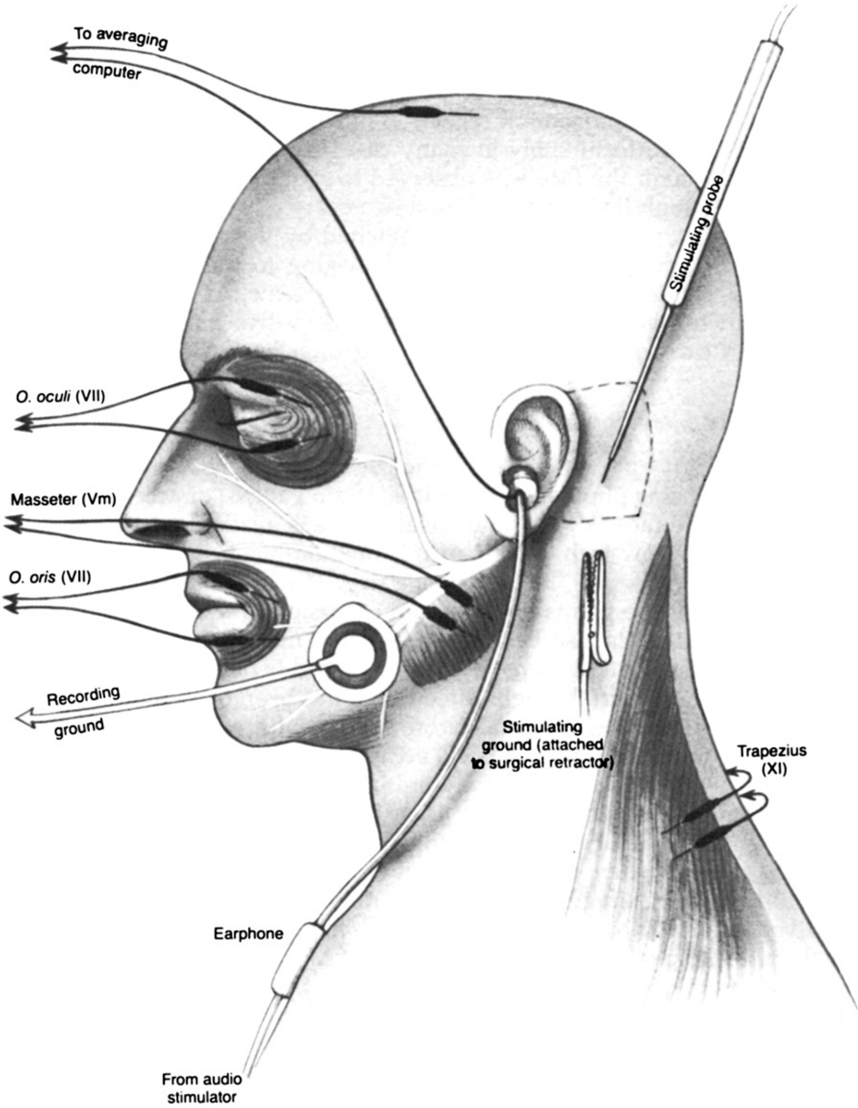

Fig. 1. Diagrammatic representation of electrode placement for monitoring acoustic neuroma surgery with attempted hearing conservation. Pairs of needle electrodes are placed in the following muscles: masseter (Vm); orbicularis oculi and o. oris (VII); and trapezius (XI). Click stimuli from a small transducer are fed into the ipsilateral ear through a foil-covered sponge insert that also serves as a recording electrode, referred to a needle electrode on the vertex. A ground electrode is placed on the cheek. A flexible-tip probe is used to stimulate cranial motor nerves. (*From* Jackler RK, Pitts LH. Acoustic neuroma. Neurosurg Clin North Am 1990;1:199–223; with permission.)

that measures pressure variations in air-inflated rubber sensors that are placed beneath the upper lip [43].

Although a step in the right direction, it has been our experience that techniques for monitoring actual facial movement are less sensitive than those based on recording facial EMG activity, which has become the most widely used technique following the initial report in 1979 by Delgado and colleagues [32]. It should be noted, however, that a major limitation of the EMG method is the difficulty in monitoring during the use of electrocautery, which is a time when the facial nerve is potentially at high risk. The amplitude of the artifact from bipolar cautery can be reduced by using a solid-state unit that operates at a single high frequency (ie, Davol System 5000, Bard Biomedical Division, Billerica, Massachusetts), rather than a spark-gap unit such as the Codman-Malis (Codman and Shurtleff, Inc., Randolph, Massachusetts), which generates a broad-band noise that is difficult to filter out. The use of techniques based on detection of motion, which are not subject to electrical interference, may provide an important adjunct to EMG monitoring despite their relatively lower sensitivity.

A novel method was described by Prichep and colleagues [44,45] that was based on the crossed auricular reflex, elicited by stimulation of the contralateral ear and recorded from the ipsilateral mastoid-forehead (Fpz). This reflex, which mediates movement of the pinnae in lower animals in response to sounds, is present in vestigial form in humans. It is mediated through a crossed (and uncrossed) pathway with the motor outflow through the facial nerve and appears as a positive-negative-positive complex at a latency of 12 to 16 msec, following the contralateral ABR. This brain stem facial evoked response (BFER) is so small in amplitude that it can be detected only with the use of digital filtering before signal averaging (see "Extension of Techniques to Other Cranial Motor Nerves, Other Posterior Fossa Procedures," later). Prichep and colleagues [44,45] give several examples of changes in the BFER that were associated with surgical manipulation of the VIIth cranial nerve, with recovery of the response when the surgeon reversed the manipulation. Although this novel technique deserves more study, the lack of ready availability of systems incorporating online digital filtering has limited its application, in contrast to EMG-based methods, which can be accomplished with much simpler instrumentation.

Finally, a method that uses recording of compound nerve action potentials (CNAP) from the facial nerve at the stylomastoid foramen after intracranial stimulation has been described by Schmid and colleagues [46]. Similarly, Richmond and Mahla [47] used antidromic recording, stimulating the facial nerve distal to the stylomastoid foramen and recording within the surgical field. These methods have the advantage that they can be used even when the patient is paralyzed, which prevents coughing and allows the use of lower levels of narcotics or other anesthetic agents. Another potential advantage is that the entire nerve can be monitored with a single electrode placed proximal to the divergence of the various branches in the face. On the other hand, the CNAP cannot be easily made audible for direct feedback to the surgeon, and it is not clear whether it is sensitive to facial nerve activity because of injury or manipulation of the nerve. Further investigation of these techniques is warranted.

For the remainder of this section, we focus on techniques using EMG recordings, which are the most commonly used method and the one that we have primarily employed in our own experience.

Types of stimulating electrodes

Both monopolar and bipolar stimulating electrodes have been employed. Theoretically a bipolar electrode should show more specificity and precision of localization because there would be less likelihood of spread of current to adjacent structures than with a distant reference monopolar configuration. In practice, however, this appears not to be the case. The effectiveness of bipolar stimulation is highly dependent on the orientation of the two tips of the probe with respect to the axis of the nerve [48]. The increased bulk of a bipolar electrode makes maintenance of the desired orientation difficult in the close confines of the posterior fossa. A mono-polar electrode does not have this disadvantage and if the stimulus intensity is kept at the appropriate level (see later) can provide spatial resolution of less than 1 mm.

Several types of monopolar electrode have been described. Møller and Jannetta [37] used a simple malleable wire on a probe handle with the distal tip bared of insulation. Prass and Lüders [49] described a similar electrode except that the insulation was continuous to the flush-tip, which could be bent so that only the central portion of the tip contacted the desired tissue, minimizing spread of current to adjacent structures. Yingling and colleagues [50] developed a probe with a flexible Pt-Ir tip, insulated except for a 0.5-mm ball on the end, which can be used to probe within dissection planes or behind the tumor out of direct visualization without the danger of inadvertent damage to delicate neural or vascular structures (Fig. 2). The flexible tip thus frequently allows the facial nerve to be located electrically before its course is apparent visually, and dissection can then proceed in the most advantageous manner to avoid neural damage (Fig. 3).

These probes are all designed for the single purpose of stimulation, and thus dissection must be temporarily halted each time stimulation is performed. Kartush [51] has developed a set of

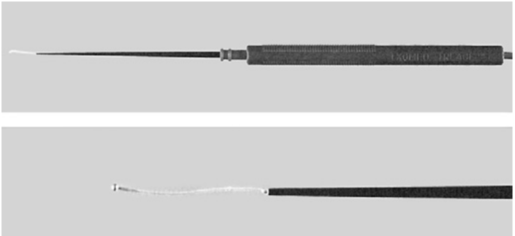

Fig. 2. Flexible-tip probe used for intracranial stimulation. The entire probe and the flexible wire are insulated except for the 0.5-mm ball on the end in order to achieve localized stimulation.

dissecting instruments that are insulated to just above the cutting surface and can be interchangeably connected to the electrical simulator, allowing simultaneous dissection with constant stimulation. According to Kartush [51], sharp dissection, as opposed to traction or prolonged dissection, may evoke little or no EMG response even with complete transection of the nerve. These "stimulus dissectors" are of particular value in removing the last portions of the tumor capsule, which are closely adherent to the nerve. They can also be used for intermittent stimulation during dissection in other regions because they can easily be electrified on desire.

Constant voltage versus constant current

The question of whether to use constant current or constant voltage stimulators has been a source of continuing controversy. Because transmembrane current is ultimately the effective stimulus for a nerve axon, constant current stimulators have generally been preferred for transcutaneous nerve stimulation, since the current delivered to the nerve is maintained at a constant level despite changes in electrode impedance. The same considerations may not apply, however, for intracranial stimulation, in which the degree of shunting of the nerve by blood, cerebrospinal fluid, or irrigant may vary

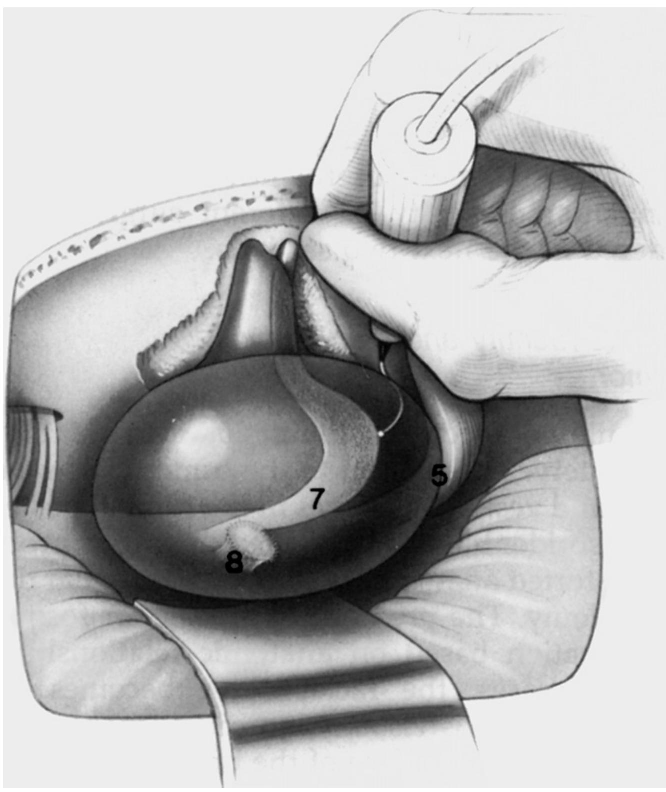

Fig. 3. Surgical view of large acoustic neuroma (suboccipital approach) showing use of flexible-tip probe to locate the facial nerve on the medial surface of tumor, out of direct view. Tumor is drawn as if transparent to show details of anatomy on the hidden surface.

widely from one second to the next. Møller and Jannetta [37] have articulated the case for constant voltage stimulation. Consider a nerve bathed in a conducting fluid. Much of the current delivered through the stimulating electrode flows through the relatively lower impedance fluid, rather than through the nerve. A constant current stimulator may thus have to be turned up to a relatively high level to depolarize the nerve effectively. If the fluid is then suddenly removed (ie, by suction) or a drier portion of the nerve is contacted, the same total current now flows through the nerve, with potentially damaging consequences. The current delivered to a nerve from a constant voltage stimulator depends on the impedance of the nerve itself, according to Ohm's law, regardless of the amount of shunting. A varying total current is delivered as the overall nerve/fluid environment changes, but the current delivered to the nerve itself, paradoxically, is more constant with a constant voltage stimulator.

On the other hand, Prass and Lüders [49] argued in favor of constant current stimulation, claiming that their flush-tip probe design eliminates the problem of current shunting by fluids. Kartush and colleagues [48] offered some data to confirm this view; they compared bare-tip with flush-tip probe designs and showed that significantly greater response amplitudes were obtained with flush-tip stimulators. Note, however, that these results were obtained with constant current stimulators; it is not clear that the same results would have been obtained with constant voltage devices.

Further research, preferably in animal models, is necessary to resolve this debate finally. In the meantime, most groups will probably continue to use the method with which they have the most experience and feel most comfortable. Whether constant voltage or constant current is used, the question still remains as to what actual level of stimulation is most appropriate. Although some have argued for a "set it and forget it" approach, we believe that more useful information can be gained by varying the stimulation intensity in different surgical contexts. These issues are considered in the next two sections.

Use of stimulation to identify and map nerves in relation to tumor

The primary utility of electrical stimulation is to identify the facial or other cranial motor nerves in relation to the tumor. The relations among the facial, cochlear, and vestibular nerves in the normal posterior fossa are relatively constant, so identification produces less of a problem in cases with relatively undistorted anatomy such as microvascular decompression or vestibular neurectomy. The presence of a posterior fossa tumor, however, makes identification based on anatomic relationships difficult or impossible. In many cases, the facial nerve becomes stretched and widened to the extent that it is visually indistinguishable from arachnoid tissue, and vasculature on the surface of the brain stem may even be seen through a gossamer-thin, yet functionally intact nerve. In such situations, often the only way to identify and trace the facial nerve is with electrical stimulation.

The procedures we use at UCSF are as follows. First, the integrity of the stimulating and recording system must be confirmed at the earliest opportunity to avoid potentially catastrophic false-negative results. The presence of a stimulus artifact is *not* an infallible test; it is sometimes possible to see a stimulus artifact with only one lead connected, either the anodal return or the cathodal stimulator. Conversely, the *absence* of any artifact is usually indicative of an incomplete connection somewhere in the system. To avoid this ambiguity, we try to confirm the functional integrity of the entire system before commencing tumor dissection from the VIIth cranial nerve. In a suboccipital approach, this can usually be done by stimulating the XIth cranial nerve at the jugular foramen as soon as the dura has been opened and the cerebellum retracted, confirming the presence of a response in the trapezius muscle. Fortunately this is usually possible before tumor resection begins except in very large acoustic tumors. With monopolar constant voltage stimulation, using cathodal pulses of 0.2 msec duration at a rate of 5 to 10/sec, the threshold for obtaining an evoked EMG response from normal bare nerves is usually between 0.05 and 0.2 V, averaging about 0.1 V. (Thresholds reported for constant-current stimulation have ranged from <0.1 to 0.5 mA.) If the Xlth cranial nerve cannot be visualized at the outset, the stimulating electrode can be placed directly on any visible muscle and a direct muscular response obtained, although this requires a higher level of stimulation than is necessary to obtain an EMG response from nerve stimulation. In translabyrinthine procedures, the facial nerve can be stimulated within the mastoid bone before the tumor is exposed, although the threshold is higher, depending on the thickness of the overlying bone.

Once functional integrity has been verified, we then attempt to locate and stimulate the facial nerve. In smaller tumors (cerebellopontine angle component of 1 cm or less), the nerve can usually be visually identified and confirmed with stimulation before dissection begins. Once the threshold has been established, the voltage can be increased to 3 × threshold and the stimulator used to sweep across the exposed surface of the tumor to confirm that there are no facial nerve fibers in the area to be dissected. In larger tumors, the location of the facial nerve may not be immediately apparent. In this case, we start with 0.3 V and map the accessible region and, if no response is obtained, try again at 0.5 and 1 V. We do not exceed a stimulation level of 1 V; if no response is obtained at this level, it can be safely assumed that the facial nerve is not in the immediate vicinity, and dissection can proceed.

The dissection is begun at the brain stem end of the tumor, attempting to identify the facial nerve at the brain stem root entry zone before dissecting the lateral aspect of the tumor in or near the internal auditory canal. This is because the most common site of injury to the facial nerve is just outside of the porus acusticus, where it frequently is compressed against the temporal bone by the tumor. If this region is dissected first, the nerve may be compromised to the extent that it is not possible to identify it at the brain stem with electrical stimulation because of a conduction block in the more distal segment. Once the facial nerve is identified at the brain stem and traced as far laterally as possible, with the tumor-nerve interface under direct vision, the dissection can move to the lateral end, working back toward the mid–cerebellopontine angle until the nerve is freed from both ends.

As dissection proceeds, the stimulator is used repeatedly to scan the tumor capsule for the presence of facial nerve fibers as the tumor is mobilized, using stimulus intensities as already described. The flexible tip probe already described is particularly useful in this regard because it can be used to probe within dissection planes and often identify the general location of the nerve before it is visually apparent. The great advantage of the flexible tip is that it can be used to probe portions of the capsule that are out of view on the far side of the tumor, since the VIIth cranial nerve usually courses on the anterior surface of the tumor and the common surgical approaches are from posterior. Once a response is obtained, stimulus intensity is reduced to 0.1 or 0.15 V, and the region where responses are obtained is narrowed. Once the nerve is in sight, the electrode is placed directly on the nerve and a threshold is obtained. Further stimulation for mapping the location of the nerve is carried out at approximately 3× this threshold, which should be periodically rechecked as dissection proceeds.

With monopolar stimulation, spatial resolution of electrical mapping is partly determined by stimulus intensity; thus, for the most accurate localization, the stimulus is kept at a relatively low level as just described. This allows a spatial resolution of less than 1 mm, so that the facial nerve can be easily distinguished from the adjacent vestibulocochlear complex. On the other hand, if the immediate aim is to confirm that the nerve is *not* in an area about to be cut or cauterized, higher levels of stimulation up to 1 V can be used to reduce the likelihood of false-negative results. As more and more tumor is removed, the course of the facial nerve can be mapped from brain stem to internal auditory canal. It is important to note that while the nerve may be relatively cylindrical at each end, it is frequently compressed by the tumor in the cerebellopontine angle to such an extent that it may be a broad, flat expanse of fibers splayed across the surface of the tumor, which can be identified and distinguished from arachnoid tissue only with electrical stimulation.

Another important point is that other cranial motor nerves may often be encountered in unexpected locations, particularly in larger tumors. By noting the distribution and latency of response in the various channels, it is usually possible to distinguish among several nerves and thus gain more insight into the anatomic relationships. The latency of the facial response to stimulation of the VIIth cranial nerve in the cerebellopontine angle (measured to the onset of the first inflection) is 6 to 8 msec in an intact nerve. The exact latency varies depending on the site of stimulation from the brain stem root entry zone to the internal auditory canal. Stimulation of the motor fibers of the trigeminal nerve (Vm) produces EMG activity in the masseter and temporalis muscles; because of the proximity of these muscles to the facial muscles, there is typically considerable crosstalk between channels, so that activity elicited by stimulation of the VIIth cranial nerve may be volume conducted to the masseter channel, and that from stimulation of Vm may be seen in facial channels. Responses to Vm versus VIIth cranial nerve stimulation, however, can be distinguished from one another by their different onset latencies. Stimulation of Vm produces EMG responses that are of a considerably shorter latency (3 to 4 msec to onset) than those produced by VIIth cranial nerve stimulation (6 to 8 msec), allowing these nerves to be distinguished despite overlap in the responding channels. (Mnemonic: CNVII about 7, CNV less than 5). As already mentioned, stimulation of the XIth cranial nerve produces responses restricted to the trapezius channel; because of the greater distance, there is generally no crosstalk between channels with XIth cranial nerve stimulation. Finally the VIth cranial nerve may occasionally be encountered. Stimulation of the VIth cranial nerve produces activity that can be seen as a short latency response (~2 msec) restricted to the orbicularis oculi channel, where it is seen by volume conduction from the lateral rectus. (One of the bipolar electrodes in this pair should be positioned near the lateral canthus to optimize pickup of this response, which is of smaller amplitude than those recorded directly from the lateral rectus muscle.) These patterns are indicated schematically in Fig. 4.

Use of stimulation to assess functional status of nerves following tumor removal

In addition to localizing and mapping the course of cranial nerves in relation to cerebellopontine angle tumors, electrical stimulation may also be used to determine changes in the functional status of these nerves and thus may help to predict postoperative function. We have found that the ability to elicit facial EMG responses by low-threshold stimulation of the VIIth cranial nerve at the brain stem after total tumor resection is usually predictive of good postoperative function, although transient facial palsies may still be seen. Conversely, a substantially elevated threshold or the inability to elicit a response with stimulation up to 1 V is generally associated with significant facial dysfunction, although if the nerve is anatomically preserved there is still the possibility of return of function as the nerve fibers regenerate.

Other methods have been proposed to quantify further VIIth cranial nerve status after acoustic tumor removal. Harner and colleagues [52] stated that a decrease in the amplitude of the compound muscle action potential (CMAP) with

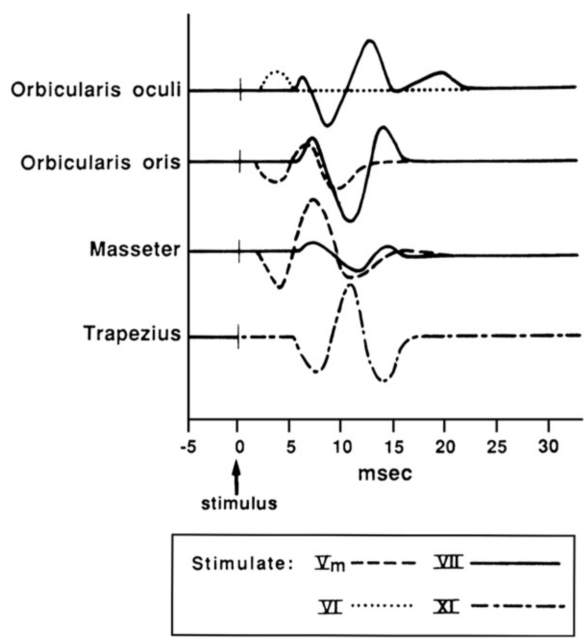

Fig. 4. Schematic representation of responses obtained in four-channel montage (see Fig. 1) with intracranial stimulation of cranial nerves (CN)Vm, VI, VII, and XI. Despite crosstalk in CNV and VII channels, these nerves can be clearly distinguished by the shorter latency of responses to Vm stimulation. Stimulation of CNVI produces a short latency response localized to the orbicularis oculi channel, due to volume conduction from the nearby lateral rectus; responses to CNXI stimulation are restricted to the trapezius channel (see text for details). (*From* Jackler RK, Pitts LH. Acoustic neuroma. Neurosurg Clin North Am 1990;1:199–223; with permission.)

supramaximal stimulation was associated with an increase in the degree of facial weakness. This is presumably due to a decrease in the proportion of facial nerve fibers remaining functional after tumor removal. Schmid and colleagues [46] have suggested calculating intracisternal latency intervals by noting the difference in latency between EMG responses elicited by stimulation at the brain stem versus internal auditory canal. They obtained a mean intracisternal latency interval of 0.24 msec; three patients with transient postoperative facial palsies had values of 0.5 to 0.54 msec. A combination of methods based on preoperative and postoperative comparisons of threshold, latency, and CMAP amplitude may provide a better predictive index of postoperative facial nerve function.

Spontaneous and mechanically evoked activity

In addition to EMG responses elicited by electrical stimulation, spontaneous EMG activity and EMG responses related to intraoperative events are also frequently encountered. Patients with significant preoperative facial deficits may exhibit tonic EMG activity even before the craniotomy is performed; this may decrease as the nerve is decompressed with opening of the dura and draining of cerebrospinal fluid. Virtually all patients exhibit at least some mechanically evoked facial EMG activity during tumor dissection, retraction, irrigation, or other intraoperative events. Such activity is frequently the earliest indicator of the location of the facial nerve, which can then be more precisely localized with electrical stimulation as described earlier. It is important to note that a simultaneous increase in spontaneous EMG activity on all channels is unlikely to result from localized dissection. When such a generalized increase occurs, the anesthesiologist should be notified immediately because this is frequently an early indication that the depth of anesthesia is too light, and overt patient movement often occurs within a few seconds after the increased EMG activity.

Distinguishing artifacts from electromyographic activity

A number of causes other than muscle activity can produce activity on the oscilloscope screen or loudspeaker, and it is important to distinguish them from true EMG activity. Some of these are obvious artifacts associated with electrocautery equipment, ultrasonic aspirators, and lasers and can be readily identified by their association with use of these devices and generally large amplitude. Such artifacts can be rejected from the audio monitor by use of interlock devices or squelch circuitry, which mutes the audio during their use. More troublesome are smaller artifacts produced by bimetallic potentials as a result of contact between surgical instruments made of different metals; because these may be associated with similar intraoperative events as those producing true EMG responses, they can be difficult to distinguish. Some useful criteria include the fact that artifacts are typically higher in frequency content than EMG activity and thus sound more “crackly” than true EMG activity, which has more of a “popping” sound, and the tendency for artifacts to appear simultaneously on several channels, which is unlikely for an EMG response. Experienced monitoring personnel are in a better position to make such decisions than surgeons who are focused on the operative field.

Phasic versus tonic electromyography

Prass and Lüders [36] distinguished two types of EMG activity associated with intraoperative events. The phasic “burst” pattern, characterized by short, relatively synchronous bursts of motor unit potentials, was thought to correspond with a single discharge of multiple facial nerve axons. Such activity was associated with direct mechanical nerve trauma, free irrigation, application of Ringer’s-soaked pledgets over the facial nerve, and electrocautery and could be easily associated with such events. In contrast, tonic or “train” activity, episodes of prolonged asynchronous grouped motor unit discharges that could last up to several minutes, were most commonly associated with facial nerve traction, usually in the lateral to medial direction. Such train activity was further divided into higher frequency trains (50 to 100 Hz), which were dubbed “bomber potentials” because of their sonic characteristics, and lower frequency discharges (1 to 50 Hz), which were more irregular and had a sound resembling popping popcorn. The onset and decline of “popcorn” activity was more gradual than the more abrupt onset and decline of “bomber” activity.

It should be noted that, particularly in larger tumors in which there is significant compression of the facial nerve, tonic EMG activity may be observed even in baseline recordings. This can complicate the detection of changes in EMG activity associated with intraoperative events as well as the use of stimulus-evoked EMG for nerve identification and mapping. As discussed earlier (under "Technical Issues"), the use of multiple channels can help in identification of changed patterns of tonic activity or of stimulus-evoked activity.

Does tonic electromyographic activity imply nerve injury?

Prass and Lüders [36] suggested that episodes of "burst" activity were probably due to the mechanoreceptor properties of nerve axons, as they tended to be directly associated with intraoperative compression of the facial nerve. Such mechanically evoked activity was distinguished from injury discharges and thought to have no necessary relationship to nerve injury. In fact, they point out that the ability to elicit burst activity with mechanical stimuli indicates functional integrity of the nerve distal to the site of stimulation and that a trend of decreasing burst activity despite continued mechanical stimulation may indicate nerve injury has already occurred.

In contrast, they argued that frequent and prolonged "train" responses, especially of the "bomber" type, were more likely to be associated with either nerve ischemia or prolonged mechanical deformation and thus potentially correspond to injury potentials and poor postoperative function. Daube and Harper [53] have described cases in which prolonged train activity was associated with inability to stimulate the nerve electrically after tumor removal and lack of postoperative facial motility. As with the various methods for determining the functional integrity of the facial nerve with electrical stimulation, described earlier, more work is necessary to associate such intraoperative events firmly with ultimate clinical outcome.

Extension of techniques to other cranial motor nerves, other posterior fossa procedures

The methods described for facial nerve monitoring are easily adaptable to virtually any cranial motor nerve by placing recording electrodes in the appropriate muscles. We have, for example, monitored the IIIth, IVth, and VIth cranial nerves during removal of cavernous sinus tumors with electrodes in the extraocular muscles and IXth, Xth, XIth, and XIIth cranial nerves during a variety of skull base procedures with electrodes in the soft palate, false vocal cords, trapezius, and tongue, respectively. Both mechanically and electrically elicited activity may be observed in such cases, just as described for the facial nerve, with the exception that the characteristic latencies of EMG responses differ depending on the particular nerve studies. For further details on such procedures, see Møller [35], Desmedt [54], and Lanser and colleagues [55].

Effects of neural monitoring on clinical outcome

Several studies have appeared comparing postoperative preservation of facial nerve function in series of cases with and without facial nerve monitoring. Leonetti and colleagues [56] compared 23 unmonitored cases with 15 monitored cases of infratemporal approaches to the skull base, all involving rerouting of the facial nerve in the temporal bone. In the unmonitored group, 11 of 23 (48%) showed a House grade V or VI facial palsy [57] at discharge, whereas none of the monitored group fell into this category, and 12 of 15 (80%) were in grade I or II. Niparko and colleagues [58] reported the outcome for 29 monitored patients with translabyrinthine acoustic neuroma removals versus 75 unmonitored cases using the same approach. A nonsignificant trend for better facial function in the monitored group was seen at the end of the 1st postoperative week. One-year follow-up revealed that satisfactory facial function was significantly associated with monitoring ($p<0.05$); analysis of subgroups showed this effect to be significant only for tumors larger than 2 cm, although there was a nonsignificant trend ($p = 0.08$) in the same direction for smaller tumors.

The best-controlled study to date is that of Harner and colleagues [52] who reported outcome data from 91 consecutive acoustic neuroma removals. The unmonitored control group consisted of 91 patients selected from a larger pool of 173 cases to match the monitored group on the basis of (in order): (1) tumor size, (2) most recent year of operation, and (3) age of the monitored patient. The resulting groups were closely matched for tumor size (median 3 cm) and age (median 54 yr). The facial nerve was anatomically preserved in 92% of the monitored group and 84% of the unmonitored group, a nonsignificant difference. The most meaningful comparisons were at 3 months and 1 year postoperatively. At 3 months, 46% of the monitored and 20% of the unmonitored group had House grade I function; 15% of the monitored and 35% of the unmonitored group had a House grade VI palsy. At 1 year, 45% of the monitored versus 27% of the unmonitored group had no deficit (House grade 1), whereas only 2% of the monitored and

6% of the unmonitored group had no facial function whatsoever (House grade VI).

A potential confounding factor in all these studies is the fact that the unmonitored cases were always operated on earlier than the monitored ones, raising the possibility that the improvements in outcome could be due simply to greater experience on the part of the surgeons. Harner and colleagues [52] point out, however, that part of the surgeon's technical improvement is directly attributable to the use of monitoring. As surgeons become more aware of the types of maneuvers that produce EMG discharges, they naturally adapt their operative technique to avoid such maneuvers whenever possible. Intraoperative monitoring may thus contribute to improved facial nerve preservation in more than one way. A quote from Harner probably typifies the attitude of most surgeons who have used intraoperative facial nerve monitoring: "I don't think I could convince anybody at our institution (the Mayo Clinic) with experience to give up monitoring under any circumstances." Similarly our surgical team at UCSF refuses to proceed with an acoustic neuroma operation unless cranial nerve monitoring capability is available.

Monitoring the VIIIth cranial nerve modalities for monitoring

Although the VIIIth cranial nerve is the cranial nerve at greatest risk during the majority of cerebellopontine angle surgeries, it is also the most likely to have significant preoperative deficits and is the least important to preserve since vestibular and auditory function remain relatively intact with only one surviving ear. Monitoring of VIIIth cranial nerve function during posterior fossa surgeries is most appropriate for (1) smaller acoustic neuromas (especially those that are confined to the medial portions of the internal auditory canal) with well-preserved hearing (slight pure tone loss and good to excellent speech discrimination scores), (2) nonschwannoma posterior fossa tumors (eg, meningiomas), or (3) microvascular decompression of posterior fossa cranial nerves [35]. In larger acoustic neuromas in which hearing conservation is not a realistic goal but in which the tumor is large enough to displace the brain stem significantly with possible collapse of the 4th ventricle or for other surgical procedures such as vascular aneurysms of the brain stem or resection of arteriovenous malformations, monitoring of auditory function of the opposite (contralateral) ear may be useful in detecting brain stem compromise [50,59,60].

Only the auditory portion of the VIIIth cranial nerve is actually monitored, employing either *far-field* or *near-field* techniques. The two monitoring methods are distinguished by the proximity of recording electrodes to the VIIIth cranial nerve. In far-field methods, electrodes are positioned at a distance from the VIIIth cranial nerve, usually on the scalp surface. The most common method of far-field recording is the scalp-recorded ABR [33]. widely used in clinical diagnosis of auditory system dysfunction. In contrast, near-field methods employ the placement of one or both active electrodes near or actually on the VIIIth cranial nerve. The most commonly used near-field recording in surgical monitoring is the auditory whole CNAP, but transtympanic recording of the cochlear microphonic potential in conjunction with the auditory CNAP has also been used. There are distinct advantages and disadvantages to the use of both near-field and far-field techniques; state of the art monitoring of auditory function may include the use of both techniques during different stages of posterior fossa surgeries.

Intraoperative auditory nerve monitoring techniques used in posterior fossa surgery were first described in 1978 by Levine and colleagues [61]. Since the initial report, other authors have extended the intraoperative use of ABR and CNAP measures and concluded that they were a highly reliable and efficacious test of VIIIth cranial nerve function during posterior fossa craniotomies [62–69]. Further work over the last decade has detailed the application of these monitoring techniques to include a wide range of surgical procedures of the posterior fossa, including acoustic neuromas; other cranial motor neuromas; cerebellopontine, petrous apex, and transtentorial meningiomas; microvascular decompression of the Vth, VIIth, VIIIth, IXth, and Xth cranial nerves, and restricted neurectomies of the vestibular portion of the VIIIth cranial nerve and 2nd and 3rd divisions of the Vth cranial nerve [35,60,70–78].

The ABR is typically elicited by repetitive click stimuli, with 1000 to 2000 trials at repetition rates of 8 to 33/sec averaged to produce a replicable response. The relatively large number of trials is necessary because of the small size of the far-field potentials (200 to 500 nV) in relation to ongoing EEG and EMG activity. Averaged ABRs consist of a sequence of 5 or more reproducible waves occurring within the 1st 10 msec after the stimulus. Of these, waves I, III, and V are the most commonly used. Wave I reflects the compound action potential generated in the distal segment of the cochlear nerve, wave III is probably generated by 2nd order neurons exiting the cochlear nucleus complex, and wave V originates higher in the brain stem, probably at the level of the upper pons bilaterally [79].

In normal subjects, the latency intervals between these peaks are very consistent, and thus increases in latency of the interpeak intervals are evidence of compromised transmission between the sites of generation of each wave. Normal interpeak latencies are approximately 2.1 msec (I to III); 1.9 msec (III to V); and 4.0 msec (I to V). The absolute latency of wave I may be affected by peripheral factors such as conductive or cochlear hearing loss, but the interpeak latencies are usually not affected. In contrast, acoustic neuromas typically produce an increase in the I to III interpeak latency (and consequently I to V as well) owing to compromise of the cochlear nerve in the cerebellopontine angle. The III to V interpeak latency is generally normal in smaller tumors but may also become increased if the tumor is large enough to cause significant compression of the brain stem. In many cases, the waveforms are so degraded by the presence of the tumor that only wave V, the most prominent component, may be recordable. In such cases, the interaural time difference in the absolute latency of wave V (IT5) may be used to help establish a diagnosis of unilateral retrocochlear dysfunction. For a more thorough discussion of ABR basic techniques and their diagnostic use, see Moore [80], and Jacobson [81].

Employing ABR and related techniques in surgery presents some novel problems not encountered in normal clinical application. The goal for the balance of this section is to detail important technical considerations for the successful use of these procedures in a surgical setting as well as discuss how these protocols have been employed by various surgical teams to improve the chances for hearing preservation in acoustic neuroma surgery.

Methodologic considerations

In addition to the general methods for ABR recording, there are special considerations for equipment used in the operating room, the most important of which are as follows:

1. Standard audiometric earphones are not useful in the operating room because they are too large and would interfere with surgical access. Instead, it is necessary to use miniature earphones that fit within the ear and do not compromise the surgical field. Møller and colleagues have successfully used small in-the-ear transducers designed for use with portable cassette players (Radio Shack). Inexpensive earphones, however, may vary considerably in the acoustic waveform delivered for a given electrical input [82], with consequent changes in ABR latencies. Stimulus artifact also poses a problem since such earphones are not shielded. A better solution is to use higher-quality transducers such as Etymotic Tubephones (Etymotic Research, Elk Grove Village, Illinois), which duplicate the frequency response characteristics of standard audiometric ear phones. These can be placed at the level of the neck with acoustic output passed along a short tube that terminates in an ear insert foam plug. Use of such earphones greatly reduces stimulus artifact production owing to the distance between differential leads and the earphone's speaker. If the foam plug is covered with a conductive gold foil (TipTrode, Nicolet, Madison, Wisconsin), it can also serve as a recording electrode. In addition to providing acoustic isolation from operating room background noise, this electrode provides definition of wave I as good as that obtained with a needle electrode in the ear canal, owing to closer proximity to the distal VIIIth cranial nerve than the earlobe or mastoid electrodes routinely used in clinical ABR testing.
2. It is desirable to use a protocol in which stimuli can be delivered to either ear in an alternating fashion, with the recording montage automatically switched to record from the electrode at the currently stimulated ear, with the vertex or forehead electrode always connected to the other input of the differential amplifier. This allows immediate comparison of the ABR from the operated side with that obtained from the contralateral ear, a useful control for nonspecific effects on the ABR from factors such as anesthesia and temperature. Most commercial systems do not have the capacity for such interleaved recording. One of us (JNG), however, has developed such

a system based on a portable IBM-compatible computer, which presents stimuli and records responses in the following manner. The ears are stimulated alternately with 100 μsec, alternating polarity square waves. EEG activity for 15 msec following each stimulus presentation is recorded from electrodes at the vertex and the stimulated ear, automatically selected by the computer. Alternate trials from each ear are accumulated in separate memory buffers, providing an automatic replication for assessment of reliability. The cycle repeats at 33.3 stimuli/sec/ear, so that duplicate 1500-trial averages for each tested ear are obtained roughly every 2 minutes, assuming minimum artifact. With the simple addition of software macro capabilities, this monitoring scheme can be repeated endlessly, with automatic data storage to disk for permanent documentation and to a printer for hardcopy trend analysis.

3. Finally it is imperative to take whatever steps are necessary to minimize or control both electrical and acoustic artifacts. Electrical artifacts, which are of concern for both EMG and ABR monitoring, have already been discussed under "Technical Issues." In addition, acoustic interference becomes a significant issue when either ABR or direct VIIIth cranial nerve action potentials are recorded. Drilling of the skull, especially with high-speed drills used in opening the internal auditory canal, can pose serious obstacles to appropriate interpretation of auditory nerve monitoring results as a result of acoustic masking, which can degrade or even obliterate the ABR or CNAP.

Unfortunately the VIIIth cranial nerve and especially the inner ear itself are at great risk during this period in typical suboccipital approaches. Interpretations of these results can be complicated by erroneous conclusions based on acoustic masking from drilling. For surgical teams who wish to conserve hearing in selected patients, it is important to control for masking effects in two simple ways. First, simultaneous monitoring of the opposite, unoperated ear can serve as a control. Although it is unlikely that ABR wave I through V latency differences and overall peak amplitudes will be equivalent in the two ears, interpretation of relative differences can be a great help. It is also likely that the operated ear may be masked to a greater degree than the opposite ear as a result of the closer proximity of the drilling.

Second, deliberate halting of drilling can be done when it is necessary to obtain unmasked results from the test ear. Unfortunately time becomes a major concern in this regard, and techniques have to be employed to reduce greatly data collection times. This is a primary motivation for the emphasis on near-field recording techniques when attempts are made to conserve hearing. Comparing the amplitude and latency of the Nl response collected over the course of temporal bone drilling can be done in seconds because averaged CNAP recordings can be obtained within 5 to 10 seconds compared with much greater times (1 to 2 minutes) for ABR averages. Therefore the capability to perform both far-field and near-field recordings during attempts at hearing conservation in acoustic neuroma surgeries is desirable.

Routine uses of auditory brain stem responses and VIIIth cranial nerve compound action potentials during acoustic neuroma surgery

Auditory brain stem response

Stimuli for eliciting auditory brain stem response. Although ABRs can be elicited by many auditory stimuli, including clicks and tone pips of various frequencies, broad-band clicks produced by square wave stimulation are the most often employed. Although the electrical waveform is a simple pulse, the mechanical characteristics of most earphones produce an acoustic output with energy distributed over a wide portion of the high-frequency auditory spectrum. Such a stimulus is desirable for clinical use because it activates a wider range of the cochlea than pure tone pips, increasing the signal amplitude and minimizing the potential problem of stimulating at a frequency corresponding to an individual's major hearing deficit.

Typically stimuli consist of 100-*μsec* duration pulses delivered at a rate of from 8 to 33 stimuli/sec. More rapid rates produce a faster updating of the average and thus are desirable for use during surgery, when timely feedback is important. Slower repetition rates have the advantage of increasing response amplitude, however, and may be necessary in cases with poor signal to noise ratio Rarefaction clicks or alternating polarity stimuli are most often used. Alternating stimulus polarity has the advantage of eliminating residual stimulus artifacts when insert

Tubephones are used. Stimulus intensity is always maintained at a high level, usually at 105-dB peak sound pressure level (SPL) or higher, to obtain the best possible signal to noise ratio (this is at least 70 dB above subjective click threshold levels). Although this would be an unacceptably high level for truly continuous stimulation, the short duty cycle with 100-μsec clicks (roughly 0.3% at 30/s) does not appear to pose a problem; we are not aware of any reports of compromised hearing traceable to ABR recording over extended periods. For ABRs, each ear is ideally tested separately in an alternating fashion with averages superimposed to eliminate spurious interpretations caused by noise. For VIIIth cranial nerve CNAPs, only delivery of stimuli to the ear ipsilateral to the surgical site is necessary.

Auditory brain stem response recording. For ABRs, electrodes are placed at the vertex (Cz) or at any point along the midsagittal plane between midforehead (Fpz) and vertex (noninverting lead) as well as in the ipsilateral ear canal or earlobe (inverting lead). The ground may be placed at any convenient location, usually on the forehead contralateral to the surgical field. Electrodes themselves can be scalp electrodes, paste electrodes, or subdermal needle electrodes. Needle electrodes have the advantage of more discrete placement, more stable impedance over the long course of surgery, and equal impedance across differential leads.

For auditory CNAPs, in which the electrode is intentionally placed directly on the nerve, electrodes are one of three basic types. Two are monopolar electrodes with the active electrode either a cotton wick sutured on the end of a malleable wire or a flexible ball-tipped wire (usually platinum-iridium); in either case, the electrode is held in place by a separate adjustable clamp, the cerebellar retractor, or brain cotton or bone wax restraint [35,83–85]. The reference electrode is usually connected to the wound musculature. To take maximum advantage of the near-field electrode to increase signal to noise ratios, accurate placement in close proximity to the auditory portion of the VIIIth cranial nerve at the root entry zone is essential for quick turnaround of averaged CNAPs, especially if the patient has a significant preoperative hearing deficit (Fig. 5).

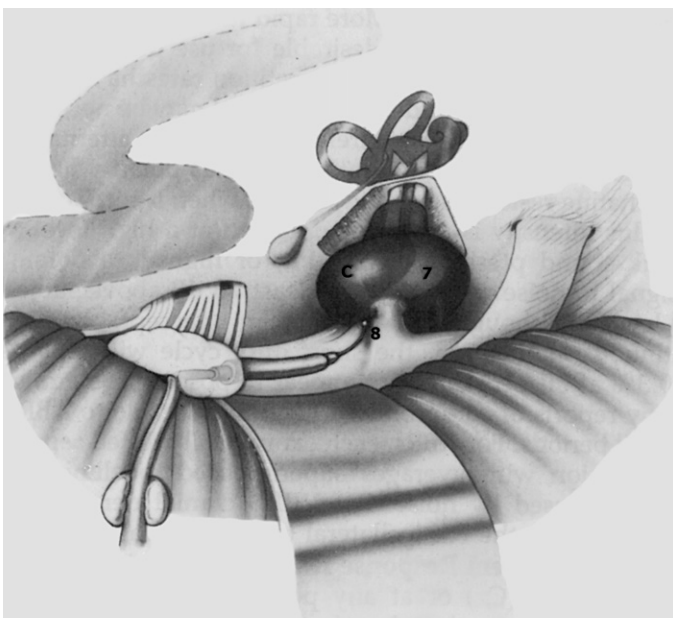

Fig. 5. Surgical view of suboccipital approach to small acoustic neuroma showing flexible-tip electrode in place on cochlear nerve at brain stem for recording of VIIIth cranial nerve compound action potentials. A malleable solid-core wire, attached rigidly outside the craniotomy, is attached to the flexibletip and used to hold the tip in place, slightly indenting the surface of the nerve.

The second type of near-field electrode is a true bipolar electrode with two closely spaced contacts, both of which are positioned on or near the auditory portion of the VIIIth cranial nerve near the root entry zone. In principle, such a bipolar arrangement should provide greater spatial selectivity than a monopolar electrode. In practice, however, this is not necessarily the case; the amplitude and waveform of the CNAP may change unless the orientation of the electrode in relation to the nerve is held absolutely constant. Also, bipolar electrodes are inherently bulkier and thus more difficult to position correctly within the tight confines of the posterior fossa. In our experience, the spatial selectivity of a monopolar electrode is more than adequate to distinguish cochlear from vestibular components of the VIIIth cranial nerve since only the cochlear division produces a CNAP in response to acoustic stimulation.

Some of these techniques have been combined in useful ways. For example, the use of a transtympanic electrode on the promontory of the cochlea has been coupled with a scalp electrode on the midline of the forehead or vertex to increase signal to noise ratios and avoid placement of a near-field electrode on the VIIIth cranial nerve root entry zone [74,86]. Another variation of this scheme is placement of one electrode of a bipolar pair at the root entry zone and the other on the cochlear promontory, thus allowing simultaneous CNAP and cochlear microphonic or summating potential recording [83]. In this case, rarefaction pulses rather than alternating polarity pulses are used as acoustic signals. Electrodes are flexible, ball-tipped bipolar, or concentric bipolar. The ground remains the same as that used for ABRs. Possible complications with either of these techniques include infection or cerebrospinal fluid leaks owing to the violation of the eardrum. The ability to assess independently cochlear versus neural function, however, may add new and potentially useful information. For example, if the cochlear microphonic or summating potential is preserved but the CNAP lost, the likely site of damage is the nerve itself, with little that can be done to reverse the deficit. On the other hand, if the cochlear microphonic and summating potential are also lost, transient cochlear ischemia is another possible mechanism, which is potentially reversible by raising systemic blood pressure or administering vasodilators.

Finally we have occasionally encountered patients with good to excellent hearing, using bipolar electrodes with both contacts placed in the near-field directly on or adjacent to the VIIIth cranial nerve, in whom the CNAP signal is so large that the need for signal averaging is eliminated. (We are not aware of any such cases in the literature.) In these fortunate cases, changes in CNAP amplitude can be played over a loudspeaker for feedback to the surgeon in real time, analogous to how spontaneous EMG signals are monitored for cranial motor nerves.

Cautions in interpreting auditory brain stem response changes. ABRs and CNAPs are relatively unaffected by the level of anesthesia or the type of anesthetic agents used, provided that normal core temperature or, more importantly, brain temperature is maintained. Core temperature rarely drops below 31 to 32°C over the course of surgery. Within this range, ABR absolute and interpeak latencies increase as a function of decreasing temperature at a rate of about 0.17 to 0.2 msec/°C [87,88], so that below 32.5°C, the values become abnormal relative to normothermic normal subjects [89]. Below 27°C, waveforms become difficult to identify [89] or disappear [82], although response amplitudes may also increase before being lost at about 18°C [90]. Even though core temperature is well controlled and maintained near normal values, brain stem temperature may decrease, especially within tissue bordering the exposed cerebellopontine angle if it is repeatedly irrigated with saline that is insufficiently warmed to body temperature. To the extent that core temperature is *not* maintained, recording ABRs from the contralateral ear can be of some value in determining whether any changes are systemic or localized.

Another factor that can affect the ABR is the change in pathways for current flow accompanying surgical exposure of the tumor. The craniotomy itself, changes in the local environment of the VIIIth cranial nerve with removal of cerebrospinal fluid and exposure of the nerve to air, and insertion of metallic retractors into the opening all create differences in the geometry of the relationship between the sites of ABR generation in the VIIIth cranial nerve and brain stem and the recording electrodes. These changes, which are of no clinical significance, can nevertheless lead to differences in amplitude, latency, and waveform configuration, which may be as large as those associated with intraoperative events significantly affecting the auditory pathway. Fortunately most of these changes occur relatively early in the procedure before the VIIIth cranial nerve is in serious jeopardy; they may, however, necessitate obtaining a new intraoperative baseline because the ABR may be changed enough that the preincision baseline is no longer appropriate.

Typical auditory brain stem response findings in acoustic neuroma surgery

Changes in auditory brain stem response latency and amplitude. Fig. 6A shows typical ABR results encountered in a posterior fossa exposure with cerebellar retraction for removal of a small (< 1.0 cm) intracanalicular acoustic neuroma. Postanesthesia, pre–initial incision results show well-defined ABRs with reproducible wave I, III, and V peaks to both right and left stimulation. There is almost always a significant difference in interpeak I to III and I to V latency values in the test ear (see left in Fig. 6A) compared with those from the opposite ear (see right in Fig. 6A). Initial ABRs are often much worse than the example shown here, depending on the degree of preoperative hearing loss and the extent to which the tumor compresses the nerve within the internal auditory canal or stretches it in the cerebellopontine angle.

Fig. 6B shows initial ABR results from another case in which wave V is desynchronized and greatly reduced in amplitude, wave III is absent (presumably as a result of lack of sufficient neural synchrony), and the I to V interpeak latency value is considerably extended (> 5 msec). In the majority of acoustic neuroma surgeries, test ear ABR findings progressively worsen over the course of surgery as a result of one or more variables, mimicking the results shown in Fig. 6B. Retraction of the cerebellum, dissection of arachnoid support tissue, acoustic trauma, decreasing localized brain temperature, and disruption of cochlear blood supply may all affect ABR peak I, III, and V amplitude and latency values [62,75]. Retraction of the cerebellum is thought to be one of the

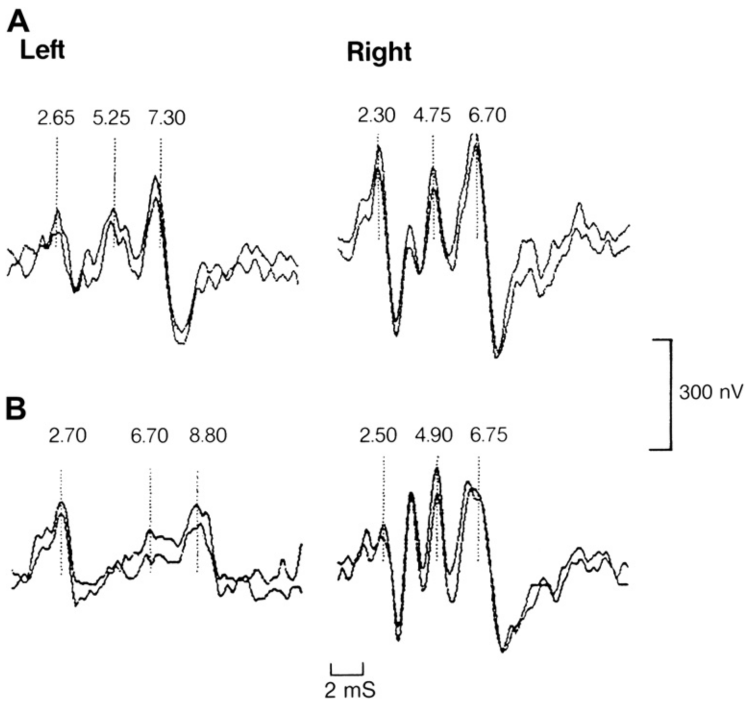

Fig. 6. Representative examples of intraoperatively recorded auditory brain stem responses (ABRs) from two patients. Recordings were obtained post induction, but before first incision, (*A*) 38-year-old woman with an 0.8-cm L acoustic neuroma, mild high frequency hearing loss, and speech discrimination scores of 92% (L.E.) and 100% (R.E.). (*B*) 52-year-old woman with a 1.8-cm L acoustic neuroma, moderate to moderate-severe sloping hearing loss, with speech discrimination scores of 56% (L.E.) and 90% (R.E.). Stimuli were alternating polarity, 100-µsec square wave pulses, presented at 80 dB nHL, 33.3/sec; 0.9-msec acoustic delay; averaged responses (n = 4000) were recorded vertex to ipsilateral ear canal. Duplicate averages are overlaid.

principal maneuvers responsible for significant ABR degradation [62,63]. It is often possible to reverse some of these effects by adjusting the cerebellar retractor, by temporarily halting dissection of tumor capsule, or by attempting dissection from a different angle or direction [66]. Occasionally wave I amplitude is enhanced, presumably because of mechanical trauma to inhibitory auditory efferent fibers, which travel with the vestibular nerve. This is usually followed by a rapid decrease in wave I amplitude values, suggesting disruption of the blood supply to the cochlea.

Correlation with postsurgical auditory evaluation. In the majority of cases in which ABR wave V is preserved after the tumor has been completely removed, subjective reports of preserved hearing are obtained. Even with such a favorable intraoperative outcome, however, hearing may still be lost; in some cases, hearing may be present immediately after surgery only to disappear within the next 2 or 3 days. The mechanism of this delayed loss is unclear but may involve vasospasm of the cochlear artery. If only ABR wave I is preserved, preservation of subjective hearing is much less likely. In more than one case, we have recorded an intact and unchanged wave I for more than an hour after complete transection of the cochlear nerve at the brain stem, a condition that is unlikely to be compatible with hearing preservation! Complete loss of waves I and V almost always results in loss of hearing; however, even this indicator is not infallible, and a surgeon should not decide to cut an otherwise healthy-looking cochlear nerve solely on the basis of ABR findings.

It is relevant to note that following surgical recovery, it is possible that postsurgical hearing is adversely affected even in patients who report subjectively unchanged hearing and in whom a reproducible ABR wave V peak is maintained (although of longer latency than presurgical controls). Administration of psychoacoustic tests of central auditory function, which rely on preservation of neural synchrony, is likely to pinpoint these deficits, especially dichotic listening tasks. Little effort has been directed at addressing such questions because most surgical and monitoring teams are pleased if there is little change in presurgical and postsurgical pure tone thresholds and speech discrimination scores.

Real-time analysis of VIIIth cranial nerve activity. In an attempt to make auditory nerve monitoring more reflective of real-time changes, most monitoring teams attempting to preserve hearing have turned to near-field recording paradigms in which VIIIth cranial nerve CNAPs are recorded in real time or with little averaging, allowing for updates on nerve status to be communicated within 5 or 10 seconds [70,74,83]. If manipulation of tumor and nerve or dissection of support tissue begins to affect the amplitude of the CNAP, it may be possible to switch surgical tactics to lessen these effects. An example of such a successful maneuver is shown in Fig. 7. The surgeon's manipulation of the tumor produced a decrease in CNAP amplitude, which returned when the tumor was released and approached from a different angle.

Other authors have decreased averaging time by employing strategies of optimal digital filtering [35,91,92]. In studies such as these, traditionally recorded (vertex to mastoid) ABR baseline waveforms are established postinduction and spectrally decomposed to determine optimum filtering for waveform reconstruction. It is important that the filter characteristics be individually determined for each patient, since the baseline ABR is typically abnormal and filters based on normative data might not be optimal in a given case. Subsequently ABRs are acquired by applying this unique filter to each single trial before averaging, allowing for reduction in the number of sweeps necessary for identifying critical waveform features such as changes in amplitude or latency for given peaks. Digital filtering may allow ABRs to be collected with as few as 128 sweeps, allowing updating of the averages within 10 seconds or less. Although these techniques are computationally intensive and generally not available in commercial devices, they hold the promise of extending successful hearing preservation outcomes to patients with larger tumors that cannot be easily monitored using near-field VIIIth cranial nerve CNAPs. They also have the advantage over near-field recording techniques because placement of an electrode within the surgical field is unnecessary.

Used in tandem, ABR and CNAP recordings may help increase the likelihood of hearing preservation in small acoustic neuromas [77]. Certain limitations of the successful use of these techniques must be kept in mind, however. Placement of a near-field electrode near or on the VIIIth cranial nerve at the root entry zone is critical for real-time recordings of the CNAP. This limitation greatly reduces the number of tumors in which this technique can be used.

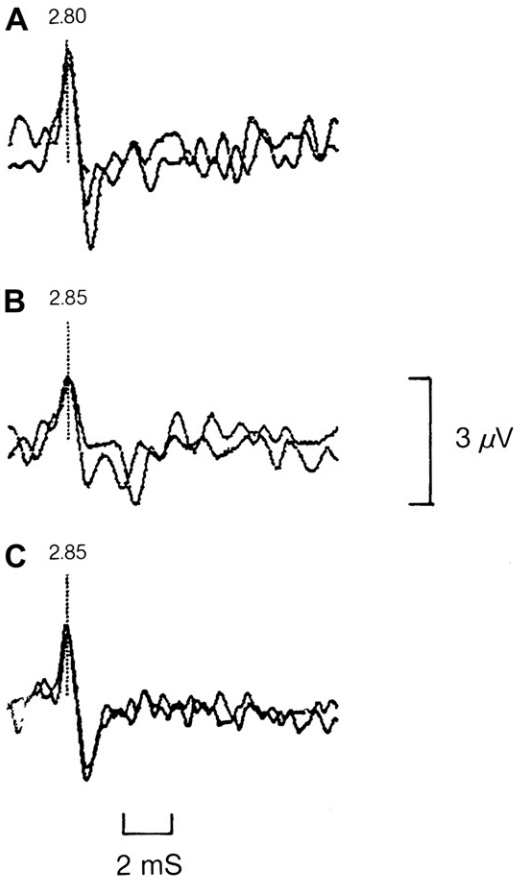

Fig. 7. Representative examples of changes in near-field VIIIth cranial nerve compound action potentials (CNAP) over the course of 30 seconds from a patient with an 0.6-cm intracanalicular acoustic neuroma, (*A*) Just prior to mobilization of tumor tissue adherent to the VIIIth CN, (*B*), mobilization of tumor caused a sharp reduction (>50%) in N_1 amplitude, (*C*), followed by partial recovery. Stimuli same as described in Fig. 5. CNAPs (100 trials/ average) were recorded from a flexible, ball-tipped electrode placed on the auditory portion of the VIIIth CN adjacent to the brain stem root entry zone. The indifferent electrode was placed in wound musculature. Duplicate averages are overlaid.

The use of ABR and VIIIth cranial nerve CNAP techniques is also appropriate in other posterior fossa surgeries and may be particularly helpful in such cases when the cochlear nerve is not as adherent to the tumor as in the typical acoustic neuroma. Microvascular decompression procedures, especially of the Vth, VIIth, and VIIIth cranial nerves and cerebellopontine angle meningiomas in which the VIIIth cranial nerve root entry zone is free, are the other most common surgical procedures that benefit from auditory nerve monitoring.

Impact of VIIIth cranial nerve monitoring on success in preservation of hearing

Five major confounding issues in published reports make it difficult to assess clearly the usefulness of VIIIth cranial nerve intraoperative monitoring techniques in regard to hearing preservation.

1. There is little agreement concerning the definition of success in preservation of hearing in the literature. Some authors consider any useful speech discrimination or pure tone thresholds less than 70 dB between 0.5 and 2.0 kHz as preservation [93], whereas most others define preservation as pure tone thresholds less than 50 dB and speech discrimination scores greater than 50% [94]. Others suggest a classification scheme in which hearing preservation is expressed as a percentage of patients whose postoperative hearing remained in one of three categories compared with preoperative assessment: (1) good = speech reception threshold (SRT) <30 and speech discrimination score (SDS) >70%, (2) serviceable = SRT <50 and SDS >50%, (3) measurable = any measurable hearing [95]. An excellent qualitative scheme for classification of hearing following acoustic neuroma surgeries can befound in Silverstein and colleagues [96].
2. Many reports on attempts at hearing preservation in posterior fossa surgeries do not correlate electrophysiologic data obtained intraoperatively with behavioral data obtained postsurgically [60,97].
3. Well-designed studies employing presurgical and postsurgical behavioral data may lack intraoperative correlates [98].
4. Many electrophysiologic reports group hearing preservation results from acoustic neuromas with other surgeries of the posterior fossa [60,78].
5. Preservation of hearing is directly related to presurgical hearing status and tumor size, making comparisons of results difficult across studies in which there are no controls for these independent variables.

Therefore, certain cautions have to be exercised in drawing conclusions from published reports. The most useful reports are those that contain both intraoperative electrophysiologic data and postsurgical behavioral follow-up data. Furthermore tumor size and preoperative hearing status need to be well documented.

In general, if tumor size is controlled for and restricted to less than 2 cm, useful to adequate hearing preservation is maintained in roughly 30% to 45% of patients as determined by preoperative and postoperative pure tone averages and speech discrimination scores [78,93,94,96,98,99]. ABR and CNAP results obtained intraoperatively suggest that if waves V and I are preserved, there is an excellent chance that hearing will be preserved [78,93,100], although exceptions have been reported [78]. If waves I and V are lost intraoperatively, there is little or no chance of hearing preservation [78,93], although rare exceptions have been reported. When wave V is lost with preservation of wave I, hearing conservation is not always maintained and cannot be accurately predicted. Furthermore, even if the response recovers over the course of surgery, transient changes in wave I and the cochlear microphonic potential may reflect pathogenic changes to the nerve with serious long-term consequences for hearing preservation [74,83]. Recovery of wave V without loss of wave I over the course of surgery does not always appear to lead to hearing loss [93].

The predictability of hearing conservation based on identifiable waves V and I at the end of surgery has been best addressed in a study by Watanabe and colleagues [78]. Their patient group included acoustic neuromas as well as other, nonacoustic surgeries, but it points up the utility of electrophysiologic assessment in a large group of patients. Out of a group of 80 patients in whom ABR wave V could be recorded at the onset of surgery, 68 patients had identifiable wave Vs at the end of surgery and 12 did not. Of these 68, 66 had hearing preservation at the conclusion of surgery and 2 did not. Of the 12 patients without wave V at the conclusion of surgery, 2 patients demonstrated postoperative hearing preservation despite the loss of wave V. Likewise, out of a group of 75 patients in whom wave I could be recorded at the onset of surgery, 62 patients had identifiable wave Is at the end of surgery and 13 did not. Of these 62, 57 had hearing preservation and 5 did not. Of the 13 patients without wave I at the conclusion of surgery, 3 patients demonstrated postoperative hearing preservation despite the loss of wave I.

These results taken together suggest that only four predictions (5%) were inaccurate based on wave V methods and only 8 predictions (10.6%) were inaccurate based on wave I methods. It is likely that some of these errors are due to changes in auditory nerve status subsequent to surgical recovery. For example, a certain small percentage of pathologic changes in the auditory nerve may only manifest themselves over a long time course (ie, >14 days), whereas other changes, including spontaneous recovery [101,102], may explain discrepancies in which hearing was preserved despite loss of wave I or V responses.

There are several possible outcomes of ABR monitoring, each with distinct consequences for hearing prognosis and pathogenic mechanisms. Preservation of both waves I and V after total tumor removal, even with increased I to V interpeak latency, indicates that the cochlea, VIIIth cranial nerve, and lower auditory brain stem pathways are intact and should be predictive of at least some preserved hearing postoperatively; however, even this most favorable outcome may still be associated with delayed hearing loss. Preservation of wave I with loss of wave V is more problematic. Wave V may be lost simply because the cochlear fibers are disrupted enough that the volley entering the brain stem is no longer synchronous enough to produce a recordable wave; in this case, good postoperative hearing may still be obtained. On the other hand, wave I can be preserved even with transection of the cochlear nerve at the brain stem; thus interpretations of such a pattern should be made cautiously and in the context of the degree of anatomic preservation of the VIIIth cranial nerve. Finally loss of all waves including wave I generally indicates an outcome that is incompatible with preservation of hearing; however, even this seemingly straightforward prediction is not foolproof. If wave I is gradually lost during a long and difficult dissection, the loss may still represent only desynchronization of the afferent volley and be compatible with intact transmission into the brain stem and some recovery of hearing postoperatively. Sudden and precipitous loss of wave I, however, is likely to be associated with compromise of the cochlear blood supply and represents an outcome unlikely to result in any useful hearing.

Electrophysiologic monitoring of the VIIIth cranial nerve is technically challenging, but when performed by skilled professionals who work as a team with their surgical colleagues, VIIIth cranial nerve morbidity can be significantly reduced in selected acoustic neuroma cases.

Conclusions and future directions

The introduction of techniques for cranial nerve monitoring in acoustic neuroma surgery has led to significant improvements in surgeons' ability to identify and preserve the function of the VIIth and possibly VIIIth cranial nerves while achieving total tumor removal. It is equally obvious that the state of the art is still developing and that further improvements are likely as techniques become more refined and integrated.

Part of the improvement will come as integrated hardware-software systems, optimized for intraoperative monitoring, become available in the marketplace. Computer-based systems with simultaneous capacity for EMG and ABR recording, rapid data collection with online digital filtering, better artifact rejection, automated control of stimulation and recording parameters, and user-friendly interfaces and displays of current data as well as trends during the operation will bring the full range of currently available techniques into more widespread use.

In addition, there is still much to be learned about the relationship between intraoperative recordings and ultimate clinical outcome. More well-controlled studies, with carefully characterized patient populations and standardized monitoring techniques, need to be carried out to address many of the ambiguities discussed here. Various techniques need to be compared in terms of their predictive efficacy. For example, is the best predictor of postoperative facial nerve function likely to be (1) the threshold for obtaining any evoked EMG response with stimulation of the VIIth cranial nerve after tumor resection, (2) the amplitude of the surface EMG response to supramaximal VIIth cranial nerve stimulation, (3) the total amount of mechanically elicited EMG activity during the case, (4) the intracisternal conduction velocity obtained by comparing the latency of facial responses to stimulation of the VIIth cranial nerve at the brain stem root entry zone versus the porus acusticus, (5) the shape of an input/output curve relating EMG amplitude to stimulation amplitude, (6) the recovery function of the response to paired stimuli at short intervals, (7) some combination of the above-mentioned, or (8) some measure not yet envisioned? Similarly what aspect of the intraoperatively recorded ABR or VIIIth cranial nerve CNAP will prove the best indicator of postoperative hearing preservation? The answers to such questions will be obtained only by more systematic studies, using the full range of techniques now available. The only certain outcome is that improvements in monitoring techniques and routine integration of professional monitoring personnel into the surgical team, coupled with advances in early diagnosis and microsurgical techniques, will continue to improve the prognosis for preservation of cranial nerve function in patients undergoing acoustic neuroma surgery.

Summary

The likelihood of successful preservation of facial and cochlear nerve function during acoustic neuroma surgery has been improved by the advent of intraoperative monitoring techniques. The facial nerve is monitored by recording EMG from facial muscles, with no muscle relaxants used; mechanical irritation of the nerve during surgery causes increased EMG activity, which can be detected in real time using a loudspeaker. Brief episodes of activity associated with specific surgical maneuvers aid the surgeon in avoiding damage to the nerve, whereas prolonged tonic EMG activity may reflect significant neural injury. Electrical stimulation with a hand-held probe elicits evoked EMG responses, which can be used to locate and map the nerve in relation to the tumor. The threshold for eliciting evoked EMG responses provides a rough indicator of the functional status of the nerve. Different nerves in the posterior fossa (trigeminal, facial, spinal accessory) can be identified in multichannel recordings by the spatial distribution and latency of responses to electrical stimulation. The ability to elicit EMG responses from low amplitude stimulation of the facial nerve at the brain stem after tumor removal is a reasonable predictor of postoperative facial function. Cochlear nerve function is assessed by recording the ABR from ear canal and scalp electrodes or the CNAP with an electrode placed directly on the nerve at the brain stem root entry zone. The ABR is a well-known, noninvasive technique that can be adapted to intraoperative use relatively easily but is of limited utility owing to the delay inherent in signal averaging. Direct CNAP recordings require placement of an intracranial electrode in such a way as to contact the cochlear nerve without interfering with surgical access but have the distinct

advantage of rapid feedback on changes in cochlear nerve status.

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