Chapter 6
Brainstem Auditory Evoked Potentials

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Overview

Evoked potentials are electrical responses of the sensory pathways in the nervous system to sensory or electrical stimuli. Stimulation and subsequent recording of these potentials allows for evaluation of both peripheral sensory function and integrity of the central nervous system (CNS) sensory pathways. Evoked potentials are used to assess three main stimuli – visual, somatosensory, and auditory via pattern visual evoked potentials (PVEP), somatosensory evoked potentials (SSEP) and brainstem auditory evoked potentials (BAEP), respectively. This chapter focuses on brainstem auditory evoked potentials.

Brainstem auditory evoked potentials (BAEPs) are electrical responses of the nervous system to acoustic stimulation. Despite the name, the first component of the

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response arises outside the brainstem in the auditory nerve. While somewhat of a misnomer, BAEP remains the accepted terminology as it is widely used and understood [1]. The remainder of the response is from the brainstem and possibly higher subcortical structures, although this remains controversial. Responses are measured using electrodes placed on the skin. Measuring potentials with low electrical activity of <1 μV on a background spontaneous brain electrical activity of ~100 μV presents a challenge. Repetitive auditory stimulation allows electrical activity recorded from the scalp to be averaged in order to single out time-locked electrical activity, which is a response to the auditory stimulus [2]. Although distinct waves are recorded, each measured wave is a summation of responses from multiple sources rather than a single wave for each portion of the pathway. BAEPs are useful for detecting and localizing auditory dysfunction. This includes intraoperative monitoring during procedures with potential for hearing loss. It is important to note that performing auditory evoked potentials is a tool to predict hearing, not a definitive hearing test.

Purpose

Intraoperative monitoring of BAEPs is a rapid, effective technique for assessing the integrity of auditory pathway. Real-time monitoring of auditory pathway during surgical procedures allows for correction or elimination of techniques and maneuvers that could cause auditory pathway dysfunction resulting in hearing loss [3–8]. BAEPs can accurately and reliably predict postoperative hearing loss [5, 9]. In some procedures, BAEPs have drastically reduced the rate of hearing loss [8, 10–14]. In particular, BAEPs have nearly eliminated hearing loss in microvascular decompression for both hemifacial spasm and glossopharyngeal neuralgia [3–7, 15].

Qualifications

Training for interpretation of clinical evoked potential studies is accomplished through at least a year-long post-residency fellowship in clinical neurophysiology. A part of the American Board of Clinical Neurophysiology two-part examination is devoted to clinical evoked potentials. Passing this exam and subsequently becoming credentialed demonstrates competency in interpretation of clinical evoked potential studies. Along with interpreters, technologists are necessary to conduct these studies. Becoming an evoked potential technologist requires a formal training program in neurophysiology. Additionally, technologists need training and experience of at least 1 year with proficiency in the following areas: explaining the purpose of the study to the patient, addressing patient fears, obtaining necessary medical history, getting high-quality data, recording all pertinent information, and maintaining

equipment. These constitute the qualifications required to become an entry-level technologist. More prerequisites are necessary for complicated studies including more training, more experience, initiative, and ability for independent assessment [16].

Equipment

To obtain reliable evoked potentials, equipment must comply with certain guidelines. Often, newer commercially available equipment will exceed these requirements, but any equipment that meets the guidelines is satisfactory.

Amplifier

An amplifier is necessary to transform the low voltage electrical responses into signal waveforms. The goal of the amplifier is to amplify stimulus response while filtering out noise. Different specifications are needed based on the context of monitoring (i.e., intraoperative), but there are minimal acceptable criteria. In order to keep background noise to a minimum, the amplifier must have a great common-mode rejection ratio of at least 80 dB with recommendations of above 120 dB for use in the operating room. Likewise, the input impedance should be high, at least 100 MΩ. Lastly, gain should be finely adjustable in steps of no more than 2.5 to 1. Gain should be set to the maximum possible without generating excessive artifact production. Meeting these specifications will allow for enhanced signal recording while reducing noise [16].

Averager

The average allows for compiling the electrical responses of many trials into one output while simultaneously eliminating artifact-contaminated trials. Amplitude resolution of 12 bits at the analog-to-digital converter (A–D) is preferred, but an 8 bit A–D is sufficient. The averager must be capable of averaging at least 4000 trials. BAEP studies require a minimum of two channels and a time resolution of ≤20 μs per data point [16].

Display and Writeout

An easily readable cathode ray tube or similar display shows the average waveforms and the unaveraged EEG. In addition to the display output, there needs to be a permanent printout of the evoked potentials. Any data manipulations should be clearly

and obviously presented on the display as well as the printout because these modifications can affect the study's reliability [16].

Indications

Intraoperative monitoring of auditory function with BAEPs is useful in several surgeries. Removal of acoustic neuromas as well as a number of posterior fossa procedures requires monitoring as hearing loss is a potential complication. Intraoperative monitoring allows for real-time warning and subsequent correction (if possible) of auditory pathway impairment acquired during surgery. BAEPs can also be used to monitor for hearing restoration, albeit much less frequently. Lastly, BAEPs are useful in assessing and monitoring the brainstem function intraoperatively. Specifically, changes in wave V during tumor resection or procedures involving the posterior circulation can signify alter brainstem function [17].

Generation of Potentials

Anatomy

Each wave generated in the BAEP corresponds to synapses in various locations along the auditory pathway. The knowledge of auditory pathway anatomy is critical for understanding the generated potentials, and their significance in lesion localization when abnormal findings are present. The auditory pathway begins in the modiolus of the cochlea. Dendritic processes of the auditory nerve travel from the cochlea through the spiral ganglia to the internal auditory canal. In the temporal bone, the acoustic and vestibular portions merge to form the auditory nerve. The auditory nerve exits the skull, terminating in either the posterior ventral cochlear nucleus or anterior ventral cochlear nucleus situated on the lateral surface of the inferior cerebellar peduncle in rostral medulla. The auditory pathway fibers synapsing at the posterior ventral cochlear nucleus also connects to the dorsal cochlear nucleus. Once fibers reach the dorsal cochlear nucleus, there are a number of available pathways, but most fibers cross to the contralateral brainstem via the trapezoid body. Both the medial and lateral superior olivary nuclei in caudal pons receive some fibers, while others travel through the lateral lemniscus to the inferior colliculus. Of note, the superior olivary nucleus on each side receives input from bilateral cochlear nuclei, more so from contralateral cochlear nucleus, and acoustic information is bilaterally represented from this point onwards in the auditory pathway. The ascending pathway includes synapses at the inferior colliculus, the mediate geniculate body of the thalamus, and finally, the primary auditory cortex [17].

BAEP Waveforms

BAEPs are measured as a series of seven vertex positive waves within 10 msec of the stimulus. Wave amplitude, wave latencies, and interpeak latencies are all useful for assessing hearing function. In the standard recording between the vertex and mastoid or earlobe electrodes, the seven waves are sequentially numbered I-VII. Between the waves, vertex negative components are labeled I-VI. Waves IV and V are often observed as a single complex or barely discernable from one another. Convention states that this can be regarded as wave V [1]. Most studies place the most importance on waves I, III, and V as they serve as the best measurement parameters [1, 18]. Wave I primarily correspond to the synchronous firing of CN VIII fibers in the distal part of the nerve. Thus, Wave I measurement allows for interpretation of nerve integrity. Wave II represents activity in the proximal CN VIII adjacent to the brainstem and/or synaptic activity in the cochlear nucleus. Wave III represents signal transmission to the superior olivary nucleus located in the inferior pons. This is the first potential from the brainstem. Waves IV and V are from the lateral lemniscus and inferior colliculus, respectively. Waves VI and VII are not always measured clinically but indicate transmission to the medial geniculate body and the thalamocortical pathways. These are generalizations as each wave can correspond at least in part to synapses in multiple places. Assessment of the waves includes their presence, reproducibility, amplitude, absolute latencies, and interpeak latencies [18]. The American Clinical Neurophysiology Society Guidelines require several measurements for intraoperative monitoring including: peak latencies for waves I, III, and V; amplitude of waves I and V; interval latencies for I-III, III-V, and I-V; and amplitude ratio of wave IV-V/I [1].

Stimulation and Recording Technique

Stimuli used to generate evoked potentials can vary; however, for the purpose of intraoperative monitoring certain stimuli are preferred. Click stimuli are most commonly used because of their broad spectrum. Broadband 2 ms long clicks are produced by a 100 μs square wave pulse to the diaphragm of the speaker membrane. Generally, these clicks are at 100 μs intervals, allowing response synchronization resulting in well-defined peaks in the recorded evoked potentials [17]. More than 10 stimuli per second result in decreased amplitude of waves I, II, VI, and VII, so stimuli at rates of 8–10 per second are generally preferred. However, high stimulus rates (50–70/s) may aid in identification of wave V [1]. Stimuli can be at variable frequencies usually between 10 and 40 Hz. One technique is to begin at a fast rate for a timelier response to the surgeon then to progressively decrease the rate if the low amplitude becomes an issue. Generally, the responses from 1000 to 4000 stimuli are averaged to produce BAEPs. Click intensity is determined based upon

hearing threshold using decibel sensation level (dBSL), decibel hearing level (dBHL), or decibel peak equivalent sound pressure level (dBpeSPL). dBSL and dBHL are subjective measures assessing the patient's ability to hear a pure tone stimulus at a given intensity, while dBpeSPL is a more objective measure determined by the amplitude of the headphone speaker's membrane response to a click stimulus. An optimal stimulus intensity is 65–70 dB above dBSL or dBHL or 100 to 110 dBpeSPL. Polarity can also affect the recorded potentials. Rarefaction, or the movement of the speaker membrane away from the ear drum, is typically used due to easier wave I identification along with separation of waves IV and V. Alternatively, condensation, or moving the speaker membrane toward the eardrum, can prolong the latency of wave I and help identify wave V. Alternating polarity can also be used and this is especially helpful in delineating wave I when it is obscured by the stimulus artifact. Stimuli to the ipsilateral ear also affect the contralateral ear through bony conduction, resulting in undesired responses. To avoid this, white noise consisting of an equal mix of frequencies that encompasses the entire human auditory range is applied to the contralateral ear at an intensity of 40 dB less than the click stimulus. Clicks and other broadband stimuli tend to underestimate hearing loss [19]. Responses to clicks may be more precise for interpreting sensorineural hearing loss rather than conductive hearing loss [20]. This makes clicks more useful in intraoperative monitoring in conditions where sensorineural hearing loss is more likely. Frequency-specific stimuli present an alternative. The most commonly used specific frequencies are administered as tone bursts and tone pips [19]. Frequency-specific stimuli are more accurate for pure tone audiometry [21]; however, more research is needed to make a definitive determination in the intraoperative environment [19, 22]. Stimuli should be delivered to one ear at a time [23].

Recording the BAEP waveforms generated by these stimuli involves electrode recording from the scalp. Standard electrode placement involves placing the noninverting (+) electrode on the high forehead or at the vertex (C_z) and the inverting electrode (−) is preferred on the mastoid (M1 or M2) or earlobe (A1 or A2) but may be placed on the skin just anterior to the earlobe or the tragus of the ear if the operating space impedes the desired areas. The ground can be placed anywhere on the body. Other recording channels may prove useful. For instance, hearing can be monitored bilaterally with an additional inverting electrode (−) on the contralateral side [17]. This montage is recommended for intraoperative monitoring to help with identification of waves IV and V by simultaneously recording the ipsilateral and contralateral pathways [1, 23, 24]. The preoperative baseline BAEP data can be obtained in the outpatient clinic (Fig. 6.1) and dBSL/dBHL can be determined. Also, having the outpatient baseline BAEP data is helpful in the case of inability to obtain the BAEP waveforms just prior to the start of the surgical procedure. This signifies a technical error, and all efforts are then made by the neurophysiology team to troubleshoot the technical issue to obtain the BAEP waveforms for intraoperative monitoring.

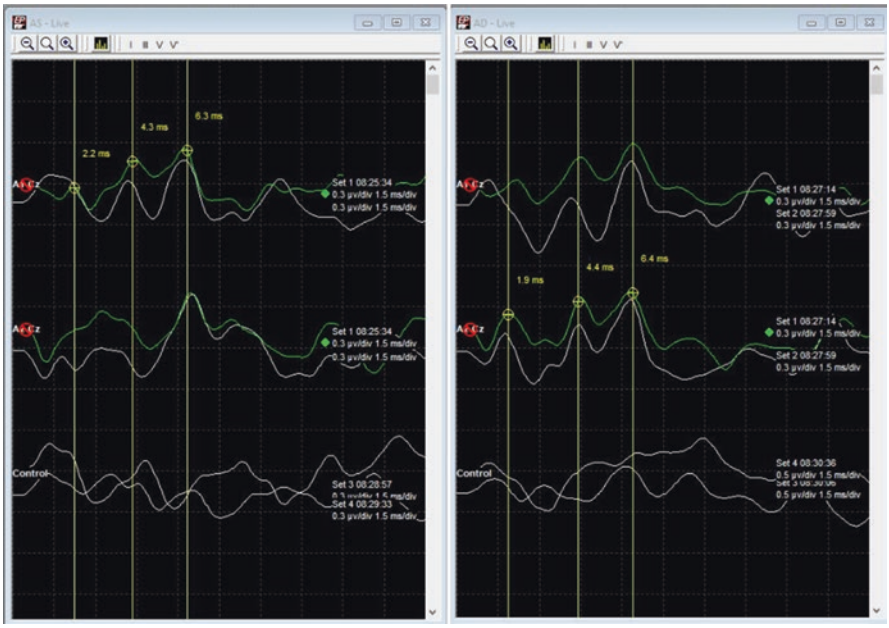

Fig. 6.1 A single set of BAEPs (white) compared to baseline (green) captured in clinic for a patient in preoperative testing before microvascular decompression for trigeminal neuralgia. These are the BAEP waveforms from the left ear (left window) and right ear (right window) at baseline obtained preoperatively in the clinic. This BAEP study shows normal wave I, III, and V peak latencies and their interpeak latencies bilaterally

Warning Criteria

A widely debated question in intraoperative monitoring of BAEPs is when to signal the surgeon. Standard warning criteria according to the American Clinical Neurophysiology Society include: absence of all waves; absence of all waves after wave I, II, or III; prolongation of any of the three aforementioned interpeak intervals; decreased IV-V/I amplitude ratio; and increased difference of interpeak intervals between the two ears [1]. Sensitivity and specificity vary between the measurements. Interpeak intervals are more informative than peak latencies since peak latency is influenced more by age and other external factors [25]. Loss of wave V and prolonged latency of ≥1 ms coupled with a wave V amplitude decrease of >50% have been identified as the most predictive of postoperative hearing loss [7]. Reduction in the amplitude of wave V is the best predictor for abnormal BAEPs. It can be used as a sliding scale warning. A 34% reduction should be monitored, a 46% reduction should be reported to the surgeon, and a 55% reduction should serve as warning of potential postoperative hearing loss. The area under the curve (AUC)

of intraoperative BAEPs for predicting postoperative hearing loss at a cutoff value of 55% is 0.98. For the other cutoff values of 34% and 46%, the AUCs are 0.92 and 0.84 respectively [26]. While these values are accurate for microvascular decompression in hemifacial spasm (HFS), there is evidence that different cutoffs may be more appropriate for different procedures. Cerebellopontine angle tumor resection requires a higher suspicion for warning, while hearing loss in nontumor surgery is usually only at risk with permanent loss of wave V [27]. Some early studies found delay in wave V latency as most important, but this is disputed by larger and more recent studies demonstrating the preeminence of wave V amplitude [3, 7]. In fact, even interpeak latency may be more predictive than wave V latency [26]. Despite these variabilities, the incidence of hearing loss due to posterior cranial fossa surgeries has declined substantially through the use of BAEPs. Please refer to Figs. 6.2, 6.3, and 6.4 for illustrations.

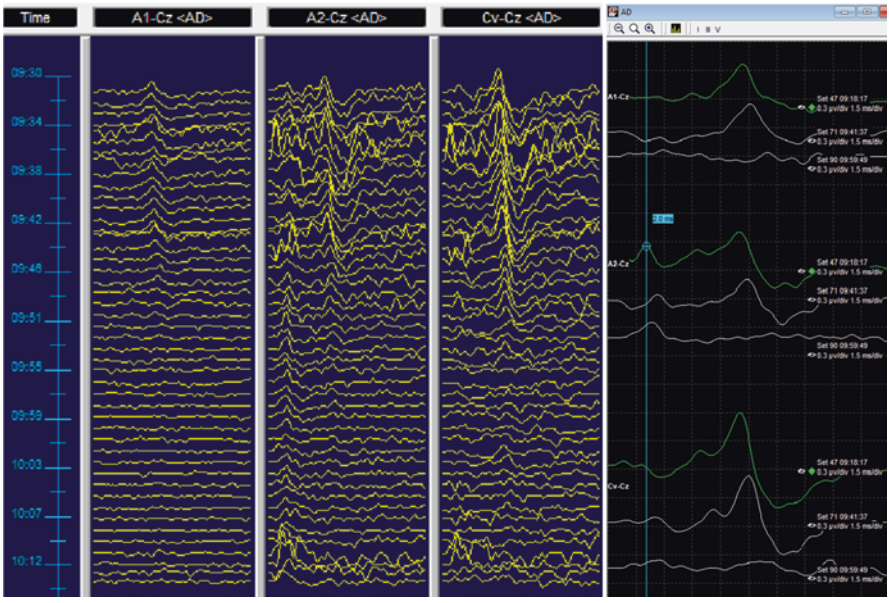

Fig. 6.2 (LEFT) "Waterfall" view of BAEP data during right-sided microvascular decompression showing significant changes. BAEP wave V latency delay from baseline is noted around 9:41, followed by complete loss of amplitude in waves II-V after around 09:59. Wave I was maintained. (RIGHT) displays two sets of BAEPs from the same procedure at 9:41 (set 71) and 9:59 (set 90) (white) compared to baseline (green) for more clarity. This patient suffered immediate postoperative hearing loss in the right ear

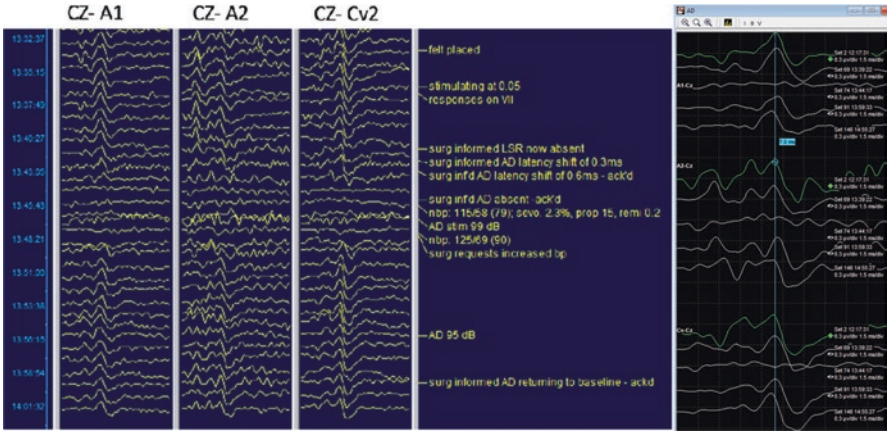

Fig. 6.3 (LEFT) "Waterfall" view of BAEP data during right-sided microvascular decompression. Latency shift of 0.3 ms and 0.6 ms were successively communicated to the surgeon at around 13:43. Subsequent loss of wave I-V amplitude can be observed between 13:43 and 13:45 and was communicated to the surgeon. The surgeon requested increased blood pressure. BAEP returned to baseline after this intervention. (RIGHT) displays multiple sets of data taken at various times during the procedure (white) compared to baseline (green) from the same case. Loss of amplitude in all waves can be observed in the recording from 13:44 with return to baseline by 13:59. The patient suffered no discernable hearing loss after the procedure

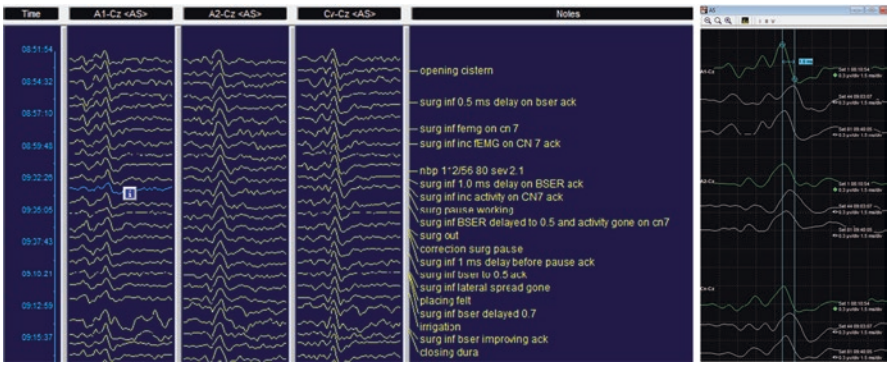

Fig. 6.4 (LEFT) "Waterfall" view of BAEP data during left-sided microvascular decompression. A maximal latency shift of 1 ms without loss of amplitude was observed during this procedure. At this point of time, the surgeon released the retraction on the cerebellum for some time. After the latency delay decreased to 0.5 ms, the procedure was resumed with eventual latency recovery to baseline by closure. (RIGHT) displays two sets of data from different times during the procedure (white) compared to baseline (green) showing the maximal latency shift of 1 ms at 09:03 from baseline which later returned to near baseline by 09:40. This patient did not report postoperative hearing loss

Considerations

BAEPs are useful in sleep or awake states and in infancy through adulthood [1]. Sedation is not problematic and may be preferred in some cases to restrict tension or movement from affecting results. One necessary consideration, however, is that hypothermia may result in BAEP changes similar to those observed in pathological hearing impairment [28]. Anesthesia, drilling, and cerebellar retraction may also affect the recording accuracy, elaborated below. For measurement in children less than 3 years old, special considerations are necessary [29].

Anesthesia

Anesthesia and core body temperature are major considerations for any intraoperative monitoring procedure. BAEPs are mildly affected by inhaled halogenated anesthetic agents in a dose-dependent manner [30, 31]. Both amplitude and latency are affected. However, non-halogenated anesthetic agents minimally affect BAEPs and therefore are preferred for use where intraoperative monitoring is required [32]. A technique to trivialize this effect is to record the baseline measurement while the patient is under anesthesia. This helps mitigate any changes that are a result of the anesthesia. Body temperature may also affect the responses, with temperatures below 35 °C resulting in prolonged interpeak intervals and latency with decreased amplitude [28, 33].

Drilling and Cerebellar Retraction

Monitoring BAEPs while drilling should be avoided to avoid false warnings. Drilling creates bone conducted noise masking the desired acoustic stimulation. It is important the surgeons understand that BAEPs are ineffective while drilling to avoid any expectations. Likewise, retraction of the cerebellum, indicated in many posterior fossa procedures, can increase the I-V interpeak interval. Typically this increase is transient, although it may sometimes be related to hearing loss [3, 34].

Children

BAEPs are generally higher amplitude in children and neonates because of electrode proximity to waveform generators due to thinner skulls and smaller heads. However, these factors do not reduce interpeak variability in normalized data. In children, BAEPs are significantly altered by age, with the effect decreasing as age increases. In neonates, wave I is particularly variable. Wave V and interpeak latency are less variable and should be preferred indicators for this age group. The higher variability of wave I is due to the presence of amniotic fluid in the middle ear cavity

causing a transient conductive hearing loss in some children [35]. A multicenter database for BAEPs in children has established normative values at different age groups, allowing for BAEPs to effectively assess hearing function in children [36]. Premature infants may lack BAEPs, however by 3 to 6 months of age the values should be approximately normal. Abnormal BAEPs at 6 months of age in a premature infant may indicate developmental delay [37].

Efficacy

There are five potential outcomes for BAEPs measurement: 1 – No change; 2 – reversible significant change; 3 – irreversible significant change; 4 – reversible loss of response; and 5 – irreversible loss of response. It is widely debated whether significant change has an effect, or if loss of response should be the sole measurement for predicting postoperative hearing loss [38–40]. In a recent meta-analysis of microvascular decompression surgeries, an overall incidence of hearing loss was 4.88% [9]. Hearing loss occurred in 1.81% of patients without any change in BAEPs. Change in BAEPs was demonstrated to be correlated with hearing loss as 8.97% of patients with significant change and 31.14% of patients with loss of response suffered hearing loss. Overall, hearing loss occurred in 15.01% of patients with some significant change or loss of BAEPs. Specificity and sensitivity of hearing loss with loss of response of BAEP are 98% and 74% respectively. The high specificity shows that loss of response should be avoided and reversed if possible. Low sensitivity indicates that hearing loss is still a risk without BAEP loss. Adjusting the alarm criteria to include significant change increases the sensitivity to 88%. Positive likelihood ratio is higher when measuring loss of response alone, while negative likelihood ratio is higher when including significant change and loss of response. Based on this analysis, both criteria have merit for predicting postoperative hearing loss in microvascular decompression surgery. Intraoperative monitoring of BAEPs is currently classified by the American Society of Neurophysiological Monitoring as a Guideline, Type C, Class III recommendation for assessing brainstem function in procedures involving the brainstem, assessing brainstem function in procedures involving risk of injury to the posterior circulation, and assessing function of CN VIII in surgeries involving the cerebellopontine angle [17]. This classification indicates there is consensus expert opinion in favor of monitoring.

Limitations

The effectiveness of monitoring BAEPs is limited by certain factors. Monitoring of BAEPs is unable to completely eliminate hearing loss as an adverse outcome. Certain surgical manipulations, such as injury to a perforator, may result in

immediate and irreversible loss of BAEPs. This limits the usefulness of monitoring as damage can occur without the opportunity for correction. Hearing loss may also occur without loss of BAEPs through unknown mechanisms.

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