Clinical Usefulness of Auditory Evoked Potentials: A Critical Evaluation

L'utilité clinique des potentiels évoqués auditifs: évaluation critique

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Résumé

Les nombreux potentiels évoqués auditifs différents que l'on peut constater chez l'être humain fournissent des renseignements cliniques importants sur l'audition. A l'heure actuelle, les réponses du tronc cérébral évoquées par un «clic» constituent le plus utilisé de ces potentiels. Ces réponses, comme tous les tests diagnostiques, ont leur limites, qui peuvent être partiellement contournées de trois façons. D'abord, les potentiels évoqués auditifs autres que les réponses évoquées du tronc cérébral peuvent également fournir des renseignements importants. L'électrocochléographie peut aider à évaluer la fonction cochléaire, et les potentiels évoqués auditifs moyens et tardifs peuvent évaluer le système auditif au-delà du tronc cérébral. Ensuite, les potentiels évoqués par des stimuli autres que de simples clics et sons peuvent contribuer à évaluer des processus auditifs précis comme la discrimination des fréquences et la localisation des sons. Enfin, d'autres procédures diagnostiques peuvent compléter les renseignements fournis par les potentiels évoqués. Les émissions oto-acoustiques devraient tenir un rôle important dans la détection de la perte de l'audition. L'imagerie par résonance magnétique (IRM) peut identifier rapidement et précisément les lésions de la voie auditive.

Abstract

The many different auditory evoked potentials that can be recorded from the human subject provide important clinical information about hearing. At the present time the click evoked auditory brainstem responses are the most widely used of these potentials. Like all diagnostic tests, these responses have their limitations. These limitations can be partially circumvented in three ways. First, auditory evoked potentials other than the auditory brainstem response can also provide important information. Electrocochleography can help assess cochlear function, and the middle and late auditory evoked potentials can evaluate the auditory system beyond the brainstem. Second, potentials evoked by stimuli other than simple clicks and tones may help evaluate specific auditory processes such as frequency discrimination and localization. Third, other diagnostic procedures may supplement the information provided by evoked potentials. Otoacoustic emissions should become important in screening for hearing loss. Magnetic resonance imaging can quickly and accurately delineate lesions of the auditory pathway.

Introduction

The purpose of this paper is to engender some discussion on the clinical usefulness of the auditory evoked potentials. Although the evoked potentials are clearly important in the evaluation of hearing, they have definite limitations. The astute clinician should know what they indicate, be aware of what they cannot show, and learn a little about what they might demonstrate in the future since possibilities have a habit of becoming reality.

The paper is organized around several important clinical applications. The discussion generally proceeds along a "now ... but... however" format. For each application, I shall present the current state of knowledge, consider the limitations of present practice, and then suggest what might occur in the next few years.

Identification of Hearing Impairment in Infancy

The general wisdom is that it is important to identify an infant with a hearing impairment as soon as possible, preferably within the first few months of age. Early detection will allow treatment during a period when the brain is particularly sensitive to language development. Although the concept of a language-sensitive period is reasonable, it has not been fully proven. Furthermore, there is no clear experimental evidence for commencing therapy at one age or another or for one type of therapy or another. Nevertheless, it is essential to have a test that will detect hearing loss in the first few months of life so that, if it is better to begin therapy at an earlier age, one can do so.

A possible drawback to knowing that an infant has a hearing loss is that such knowledge might possibly impair the normal interactions between the infant and its family. Learning that one's child has a hearing loss is very stressful. One must therefore be sure of the diagnosis and be able to provide

both a therapeutic program for the infant and the necessary support to help the family through the stress (Durieux-Smith, Manion, & Finkelstein, 1988).

One means to assess hearing in young children is by observing their behavioural responses to sound. A baby may move (or stop movement) when a sound is presented. Such changes in behaviour can be assessed objectively using such instruments as the Crib-O-Gram (Hosford-Dunn, Johnson, Simmons, Malachowski, & Low, 1987) or the Auditory Response Cradle (Sancho & Davis, 1988). Unfortunately, such techniques usually are not very effective (Durieux-Smith, Picton, Edwards, Goodman, & MacMurray, 1985; Davis & Sancho 1988). They require loud sounds and therefore will not detect infants with a mild or moderate hearing impairment, particularly if there is recruitment. Furthermore, although normal infants usually show clear responses, infants that are not completely healthy may not. One then does not know whether the baby is specifically unresponsive to sounds or just unresponsive. Unfortunately, those babies at risk for hearing impairment are often not well for other reasons and may be generally unresponsive to stimulation.

Because behavioural tests are neither reliable nor specific, electrophysiological tests are now recommended as the most appropriate means of identifying infants with a hearing impairment (ASHA Committee on Infant Hearing, 1989). Since electrophysiological tests are too expensive to use in all infants, one concentrates on those infants who are considered at risk for hearing loss. Except for those with a family history of childhood hearing impairment, these infants are usually admitted to a neonatal intensive care unit (NICU). The electrophysiological test of choice for assessing these infants is the auditory brainstem response (ABR). In general, neonates should show a wave V in response to clicks at intensities down to 30 dB nHL (Durieux-Smith, Picton, Edwards, Mac-Murray, & Goodman, 1987; Galambos, Hicks, & Wilson, 1984; Gorga, Kaminski, & Beauchaine, 1988).

There are several issues to discuss about our present procedures for identifying hearing loss in infancy. Is the risk register worthwhile? Is the ABR a valid test? What is the role of oto-acoustic emissions (OAEs)?

Although the risk register selects more babies with a hearing impairment than random selection, it certainly does not catch them all. About one-half the children with a significant sensorineural loss at age 2-5 years do not have a history of any of the risk factors (Hovind & Parving, 1987). Some of these losses will have developed after birth and some will have been present at birth. The best way of finding these children is to respond to any family concern about hearing. If a parent is worried about a child's hearing, the child must be tested.

In recent years, babies who have been tested with the ABR in the newborn period have become old enough to provide full frequency audiograms. Hyde, Riko, and Malizia (1990) reported a follow-up study of 713 children (1367 ears) who were evaluated with click evoked ABRs in the neonatal period. Except for 3 ears all of the audiometric thresholds at follow-up (average HL thresholds between 2-4 kHz) fell within 20 dB of the ABR thresholds. The 3 ears had elevated ABR thresholds in the neonatal period and normal hearing on follow-up.

Hyde and his colleagues also evaluated their data to determine the optimum criteria for identifying a significant hearing loss. Defining a significant hearing loss on follow-up as a sensorineural loss with thresholds above 40 dB HL, the criterion of neonatal ABR thresholds above 40 dB nHL picks up 98% of the hearing impaired babies (sensitivity) and provides only 4% false positives (96% specificity).

The test is much less effective if one considers the conductive hearing losses as well as the sensorineural hearing losses. A conductive loss may occur in the newborn period and get better by the time of audiometric testing. Probably between 20 and 30% of NICU babies will have a transient conductive hearing loss that resolves within the first few months of life (Durieux-Smith et al., 1987; Galambos et al., 1984). Furthermore, conductive hearing losses are common during childhood and may occur at the time of follow-up in a baby who was normal in the neonatal period.

A small number of patients with normal ABR thresholds for clicks in the newborn period show a significant hearing loss at follow-up (Picton & Durieux-Smith, 1988). Occasionally, an infant may develop a sensorineural hearing loss after birth. However, most of the children who were missed by ABR testing in infancy have an audiometric pattern with normal thresholds somewhere between 1 and 4 kHz and significant hearing losses at other frequencies. The normal ABR thresholds occurred because the broadband click elicited a response from the frequency region with normal thresholds. There are two approaches to this problem. One is not to worry because normal hearing somewhere within the 1 to 4 kHz range will allow an infant to develop speech. The other is to use some more frequency specific ABR technique rather than just recording the click evoked ABR. Tones in notched noise and derived responses can be used in infants (Hyde, Riko, Corbin, Moroso, & Alberti, 1984; Stapells, 1989; Ponton, 1989).

It may be difficult to use the ABR to assess hearing in infants with neurological disorders. If wave V of the ABR is small or absent due to brainstem damage, one cannot use this wave to assess thresholds. The most common cause for this in the neonatal period is hydrocephalus (Picton & Durieux-

Smith, 1988). Although hydrocephalic babies may have abnormalities of wave V, they usually have normal pure tone audiograms at follow-up. One way to assess their hearing is to consider ABR wave I rather than wave V. This is usually recognizable down to 40 dB nHL in surface recordings from normal neonates.

A nagging issue with the use of the ABR to detect hearing loss in infancy is the existence of patients with no recordable ABRs but with relatively normal hearing (Kraus, Ozdamar, Stein, & Reed, 1984; Worthington & Peters, 1980). These patients probably have some disorder of synchronization in the pathways responsible for the ABR. The desynchronization is sufficient to eliminate the ABR but not sufficient to interfere with auditory perception (at least as evaluated by the usual audiometric tests). If such a child were detected in infancy, would he or she be inappropriately aided? One must be particularly careful in evaluating babies who have suffered from asphyxia in the neonatal period. These babies may not show recordable ABRs on the initial examination and have normal responses on follow-up (Kileny, Connelly, & Robertson, 1980; Stockard, Stockard, Kleinberg, & Westmoreland, 1983).

One controversy in the use of the ABR to evaluate hearing in infancy is the optimum age at which babies should be tested. Several authors (Durieux-Smith et al., 1987; Swigonski, Shallop, Bull, & Lemons, 1987) have suggested that it may be better to evaluate these infants several months after they have been discharged from the neonatal intensive care unit. At this time, most conductive hearing losses will have cleared. Therefore there will be fewer babies with elevated thresholds that return to normal on follow-up testing. The main argument against this delay is that babies at risk for hearing loss might not return for testing after being discharged from the hospital.

One of the most exciting recent developments in auditory physiology has been the recording of otoacoustic emissions (OAE) (Kemp, 1978). An acoustic stimulus can evoke from the ear an acoustic response or echo. This emitted energy is mediated by a process in the external hair cells that converts incoming acoustic energy to electrical energy and then to active movements of the hair cells. These movements return acoustic energy through the basilar membrane and middle ear to give an echo in the external auditory meatus (Brownell, 1990).

Otoacoustic emissions are typically demonstrated by presenting a brief stimulus (click or tonepip) and recording the acoustic energy in the external ear canal over the 20 ms following the click (Kemp, Ryan, & Bray, 1990). The initial few milliseconds of the recording are usually blanked out since during this period there will be ringing of the stimulus in the external auditory meatus. Comparisons between the responses at two different intensities can ensure that the late waveforms are truly cochlear emissions and not late meatal echoes. Averaging is used to detect the small emitted waveforms in the ongoing acoustic background. The signal-to-noise levels of these recordings are somewhat better than those for the auditory brainstem responses; therefore averaging an OAE takes only one half the time as averaging an ABR.

Because the emissions depend upon the normal activity of hair cells, cochlear hearing losses interfere with this activity. OAEs are not recorded when there is a cochlear hearing loss exceeding 30 dB. Thus they can demonstrate quickly whether there is normal cochlear function or not. However, unlike the ABR, they cannot be used to assess the degree of hearing loss. Another relevant factor is that middle ear pathology can interfere with the return of echoes to the external auditory meatus (as well as with the transmission of sound into the inner ear) (Bonfils, Avan, Francois, Marie, Trotoux, & Narcy, 1990a).

Otoacoustic emissions can be recorded from newborn infants at intensities as low as 10 dB above normal (adult) thresholds (Bonfils, Dumont, Marie, Francois, & Narcy 1990b; Johnsen, Bagi, Parbo, & Elberling, 1988). Several laboratories therefore have been evaluating the OAEs as a screening test for hearing loss in the newborn period (Adrian & Sancho, 1988; Bonfils et al., 1990b; Stevens, Webb, Hutchinson, Connell, Smith, & Buffin 1989, 1990). The OAEs are usually evoked by clicks at intensities between 30-50 dB nHL. Two intensities are used to allow the cochlear echoes to be distinguished from meatal echoes. The intensity need not be calibrated accurately because one needs only to determine the presence or absence of a response. All babies who show normal behavioural responses to sound and who have no risk factors for hearing loss will have recognizable OAEs (Bonfils et al., 1990b). About 80% of newborn babies in an intensive care unit will have recognizable OAEs (Stevens et al., 1990). Of the 20% who do not have recognizable emissions, most will have a transient conductive hearing loss.

These results indicate that the OAEs could become an excellent screening test for hearing loss in infancy. Those infants who fail the OAE test then could be assessed with ABRs. However, further validation is necessary. The data necessary for validation is different perhaps for the OAEs than for the ABR. If those who do not show OAEs are tested by ABR to determine the severity of their hearing loss, one must be sure that those who show responses that are interpreted as OAEs are followed closely to ensure that indeed they do have normal hearing.

In summary, the ABR has proven to be a relatively efficient means for identifying hearing loss in infancy. It may be replaced by the OAEs as an initial screening procedure. How-

Figure 1. Tentative strategy for identifying hearing impairment in infancy. The major changes from present practice are the use of otoacoustic emissions (OAE) as a screening procedure and the suggestion of electrochochleography (ECochG) if there is any question concerning the information provided by the auditory brainstem response (ABR). If OAEs are not available, one can proceed directly to the click evoked ABR. The click ABR studies should include bone conduction thresholds if the air conduction threshold are elevated. Masked ABR studies using either tones in notched noise or derived responses can provide information about thresholds at different frequencies.
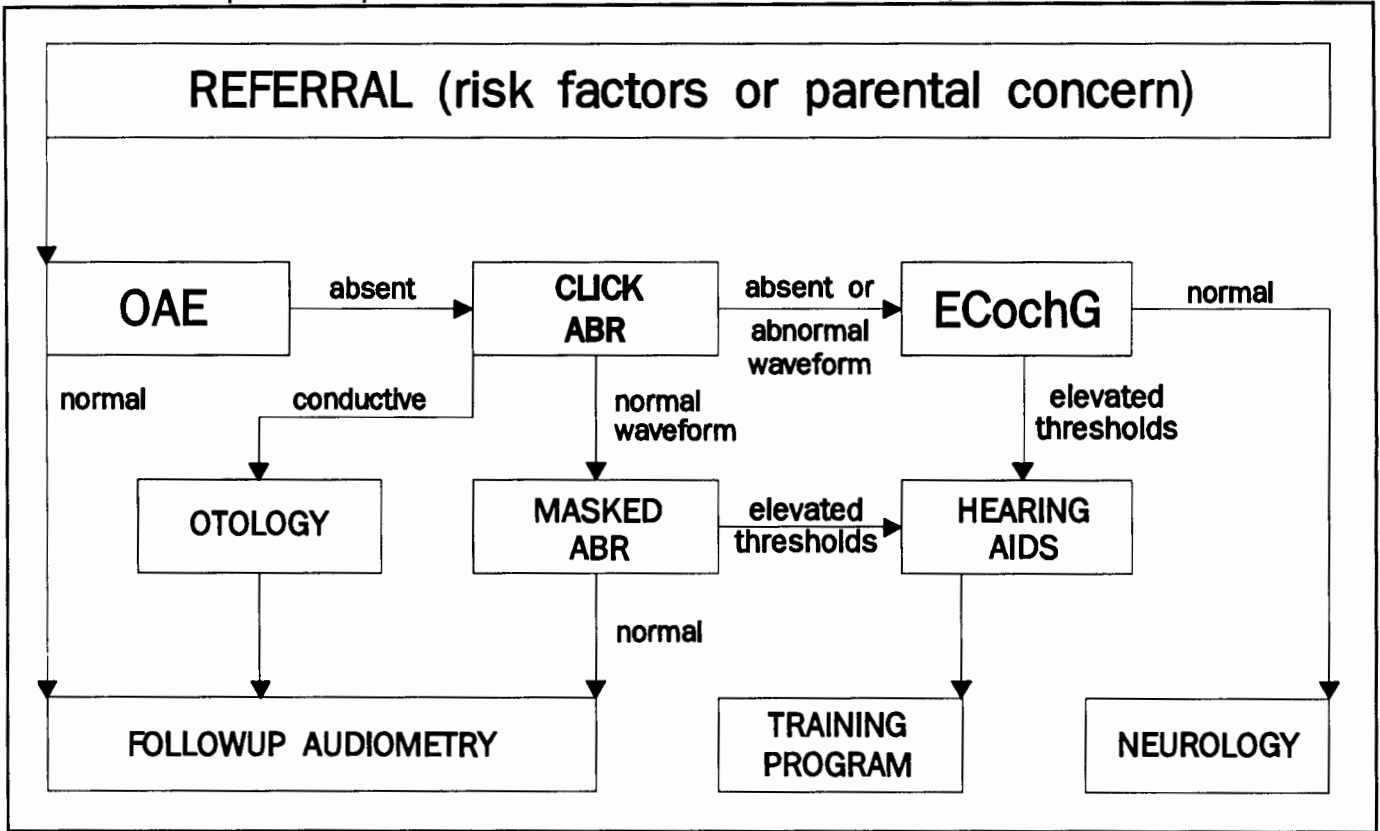
ever, it will remain as the only reliable means of actually assessing thresholds in the first six months of life. Since the ABR may become more concerned with diagnostic assessment than screening identification, ABR procedures should perhaps be altered. Techniques for obtaining frequency specific thresholds should replace clicks. Whatever the approach, it is more efficient to test babies initially at 1-3 months after discharge from hospital when transient neonatal conductive losses have cleared than when they are still in hospital. Another adjunct to present procedures might be to use electrocochleography in babies who have absent or distorted ABRs or for whom there is any discrepancy between the ABR thresholds and behavioural responsiveness. Figure 1 presents a tentative strategy for the identification of hearing impairment in infants.

The figure is diagrammatic and presents only the major paths in the evaluation and treatment. For example, some babies will have a low frequency conductive hearing impairment that may be missed on the click ABR. Referral to otology then could occur after the masked ABR studies.

Furthermore, some babies will have both a hearing loss and a brainstem abnormality and will need to be followed by both neurology and aural habilitation. As well, a few babies with conductive hearing losses may need hearing aids.

Objective Audiometry

The auditory evoked potentials are often used in the objective evaluation of hearing in patients who are unable to provide accurate responses by behavioural testing. Objective audiometry is important in patients who are too young or too emotionally disturbed to respond, in patients who are unable to understand the requirements of the test because of mental retardation or communication disorders, in patients who are stuporous or comatose, and in patients who appear (by their unreliability or inconsistency) to have a functional hearing loss.

Usually the first step in audiometry is to assess thresholds for pure tones of different frequencies, that is, to obtain an audiogram. The question for objective audiometry there-

fore is whether the evoked potentials can provide an audiogram, if not at all frequencies, then at least between the frequencies of 500 and 4000 Hz (Sohmer & Kinarti, 1984). Can one type of evoked potential be used to obtain all these thresholds in all cases? Several criteria must be met for such a perfect evoked potential technique.

First, the response must provide a reasonably accurate assessment of hearing threshold. In a quiet awake adult or older child, the early, middle, and late responses can all be recorded at intensities close to threshold (Stapells, 1983). Wave V of the ABR is closest, coming within a few dB of threshold (Elberling & Don, 1987). The Pa wave of the middle latency response and the N1 wave of the late response also are usually recordable within 10 or 20 dB of threshold. These results occur with the optimal recording conditions. Under general recording conditions one can record the brainstem response down to 20 dB of threshold and the later waves to 30 dB.

Second, the response should be easily recorded during changes of arousal. Evoked potentials are best recorded in quiet subjects because movements cause electrical artifacts in the recording. Thus, objective audiometry using the evoked potentials usually is performed in relaxed or sleeping subjects. The early components of the auditory evoked potential are quite stable during changes of arousal, but the middle and late components are affected significantly by sleep. Although some waves (P2 and N2 of the late response, for example) can become larger during sleep, most of these evoked potentials become smaller. Thus sleep makes them more difficult to recognize by decreasing the signal-noise ratio. This is particularly true of the late components because the background EEG noise also is higher during sleep. Furthermore, the morphology of the response may change with different stages of sleep. Averaging over different sleep stages will distort and attenuate the response. Therefore one cannot always compensate for a small signal-to-noise ratio by increasing the amount of averaging.

Patients who are unable to remain quiet for the testing procedure will have to be sedated or even anesthetized. Although the evoked potentials recorded after sedation are similar to those recorded during normal sleep, anesthesia can cause dramatic changes. The ABRs show little if any effect of anesthesia. The middle latency responses recorded at relatively slow rates are delayed and distorted by anesthesia (Thornton, Heneghan, James, & Jones, 1984). When relatively rapid rates are used in order to obtain steady-state responses, the middle latency responses are dramatically attenuated (Plourde & Picton, 1990). Under general anesthesia the late responses are usually absent.

A third criterion for an all-purpose evoked potential would be that the response be easily recognized at all ages.

The most important age group is infancy because that is where objective audiometry most commonly is required. The electrocochleogram and auditory brainstem response are recognizable at all ages. There are developmental changes in the auditory brainstem response over the first 18 months of life (Hecox & Galambos, 1974), and there are small effects of aging (Allison, Wood, & Goff, 1983). Nevertheless, these responses can be recorded down to intensities near threshold in patients of all age groups.

The transient middle latency responses are quite different in this regard. Using the normal recording techniques they are often not recognizable in normal children until the age of 10 years (Kraus, Smith, Reed, Stein, & Cartree, 1985). They are particularly difficult to record in newborn infants. It is possible that they may be more easily recorded using slower rates (Jerger, Chmiel, Glaze, & Frost, 1987), but this has not yet been evaluated extensively with respect to how reliably the response can be recorded or how closely thresholds can be estimated. Kraus, McGee, and Comperatore, (1989) have found that the middle latency response is more reliably recorded in wakefulness, stage I sleep, and REM sleep. It is somewhat variable in stage II and III sleep and quite poorly detected in stage IV sleep. The 40 Hz steady-state middle latency response is not reliably recorded in infants (Stapells, Galambos, Costello, & Makeig, 1988).

Because they are remarkably sensitive to the stage of sleep and because sleep itself shows developmental changes, the late auditory evoked potentials are difficult to compare across the different age groups (Kurtzberg, 1989; Rapin, Schimmel, & Cohen, 1972; Taguchi, Picton, Orpin, & Goodman, 1969; Weitzman & Graziani, 1968). Although the response can be recorded in sleeping infants down to 30 dB above threshold, at times the response may not be recognizable at intensities of 50 dB HL or more.

Another requirement for evoked potential audiometry is that the responses be present at all frequencies of the conventional audiogram. The electrocochleogram and the auditory brainstem responses are best recorded with high frequency stimuli. Low frequency thresholds perhaps may be better assessed using the middle or late evoked potentials. Over recent years the 40 Hz response (Galambos, Makeig, & Talmachoff, 1981) has been extensively evaluated as a means of assessing low frequency thresholds. It is best evoked by tones below 1000 Hz because at these frequencies the brainstem responses and middle latency responses overlap more effectively to create the steady state response. Numerous studies (e.g. Fowler & Swanson, 1989; Keleny & Shea, 1986; Rodriguez, Picton, Linden, Hamel, & Laframboise, 1986) have shown that the 40 Hz response provides quite reliable threshold information in waking adults and older children.

The fifth criterion for the perfect evoked potential is that it measure thresholds that are specific to different frequencies on the audiogram. The major problem here is not the response but the stimulus used to elicit the response. A broad band click cannot give frequency specific responses since the stimulus will activate all frequency regions. In general, the click-evoked ABR threshold is most closely related to the 2 kHz and 4 kHz thresholds obtained during pure tone audiometry (Gorga, Worthington, Reiland, Beauchaine, & Goldgar, 1985). However, one should not conclude that the click-evoked ABR can be used to measure these thresholds. For example, a patient with normal hearing at 1000 Hz and a severe hearing loss at 2000 and 4000 Hz will still show an auditory brainstem response. Wave V (elicited through the normally hearing 1000 Hz region of the cochlea) will be delayed, but it will be recordable down to near normal thresholds.

Two basic techniques have been used to obtain frequency specific thresholds with brief stimuli. One technique focuses on the stimulus and makes it more frequency specific. The other technique uses masking to prevent responses from certain frequency bands.

The difficulty with frequency specific stimuli is that most evoked potentials are elicited by brief stimuli or by the onset of longer stimuli. Therefore there are physical limits to the frequency specificity of the stimulus. A brief stimulus has energy in frequency regions other than its nominal frequency. Thus, in a patient with a steep high frequency hearing loss, one can present a high frequency tonepip below the audiometric threshold at that frequency and still obtain a response because there is sufficient low frequency energy in the stimulus to activate the normally hearing low frequency region of the cochlea. It is possible to use special envelopes for the brief tonal stimulus that can concentrate the energy within a small frequency band (Gorga, Abbas, & Worthington, 1985). However, even with these stimuli one must worry about the distortion that occurs within the earphone and within the ear, particularly at high intensities.

Nevertheless, brief tones have some degree of frequency specificity. Tone evoked ABRs show reasonably accurate thresholds provided that the steepness of the hearing loss between octaves is less than 20 or 30 dB. The middle latency and late auditory evoked potentials can be evoked by stimuli of longer duration than those used for the ABR. These responses therefore can provide more frequency specific information. However, one must still consider the fact that the responses are evoked by the onset of the tone. Therefore they will not be as frequency specific as the behavioural responses to pure tones.

Notched noise has been proposed as a possible solution to the lack of frequency specificity of brief tones (Picton, Ouellette, Hamel, & Durieux-Smith, 1979; Stappells, 1989; Stapells, Picton, Perez-Abalo, Read, & Smith, 1985). Brief tones can be mixed with white noise with an intensity 20 dB below the peak equivalent intensity of the tone and with a one-octave notch centered on the tonal frequency. The major difficulty with notched noise masking is that the lower frequencies in the noise may easily mask within the notch. Similar results can be obtained using white noise without the notch, although the amplitude of the response is slightly smaller (Stapells, 1983). Results using tones in notched noise have shown reasonably accurate evoked potential thresholds even in patient with steep hearing losses (Beattie & Boyd, 1985; Purdy, Houghton, Keith, & Greville, 1989; Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990).

One difficulty with the technique is that in patients with a hearing impairment the tuning curves of the auditory neurons may not have a normal sharp tip at the characteristic frequency. Therefore they may not be properly masked by the notched noise when it is presented at an intensity below the peak intensity of the tone. Thus the relative advantage of the notched noise technique may not always be present.

The derived response technique is a way to obtain frequency specific information using broad band stimuli (Don, Eggermont, & Brackmann, 1979). Clicks are presented in high-pass noise with different cut-off frequencies. Sequential subtraction procedures are used to obtain derived responses for the frequency bands between the different cut-off frequencies. This technique can provide quite accurate audiometric information. The major disadvantage is that the noise levels have to be relatively high in order to mask the broad band click. Because of the problem of noise induced hearing impairment, this can limit the intensity range of the technique.

Derived responses and tones in notched noise usually give a clearly recognizable response to low frequency stimuli. There is some question, however, as to whether this response is truly a brainstem response or whether it is a middle latency response. Most of the studies have used stimulus presentation rates near 40/s. In the derived response technique, the stimulus rate was 34/s (Don et al., 1979) and in the original notched noise technique the rate was 40/s (Picton et al., 1979). The response is often seen as a change from positivity to negativity over a 20 ms recording. There may or may not be a superimposed peak upon this slow change in polarity. Thus it is difficult to disentangle the steady state middle latency response from a specific brainstem response. The steady state middle latency response will be present in normal subjects during wakefulness and light sleep but not during anesthesia. This may explain why the ABR to low frequency tones is difficult to record in anesthetized patients (Laukli, Fjermedal, & Mair, 1988). Furthermore, it may explain why the response is difficult to record at stimulus rates near 27/s (Fjermedal &

Table 1. Objective audiometry.

	ECochG	ABR	MLR	40 Hz RESPONSE	SLOW VERTEX POTENTIAL
Threshold (dB nHL)	10 dB	10 dB	20 dB asleep	30 dB asleep	40 dB asleep
			30 db awake	10 db awake	20 db awake
Sleep	no change	no change	small	small	changed
Anesthesia	no change	little change	decreased	absent	absent
Infants	clear	clear	often absent (needs slow rates)	absent	present but quite different
Frequency	better at high frequencies	better at high frequencies	all frequencies	better at low frequencies	better at low and mid-frequencies
Frequency-Specificity	needs masking	needs masking	fair	fair	good

Laukli, 1989) since this is a frequency at which the steady state response is quite small (Stapells, Linden, Suffield, Hamel, & Picton, 1984). Because of the overlapping of the middle latency response one must be somewhat cautious about interpreting the low frequency ABR if the patient is young, asleep, or anesthetized, or if the rate of stimulus presentation is not close to 40/s.

Another issue to consider in relation to low frequency thresholds is the difference between place specific and frequency specific information (Starr & Don, 1988). Pure tones with frequencies less than 1500 Hz specifically activate the middle and apical regions of the cochlea through the travelling wave. However, the asymmetry of the travelling wave will also activate the basal regions of the cochlea, albeit to a lesser degree. This activation can provide frequency specific information through the phase locking of the neurons to the waveform of the low frequency sounds. Because of this dual coding of low frequency information, one cannot get a steep low frequency hearing loss even when the distal regions of the cochlea are completely nonfunctional. Rather, the pure tone audiogram shows slowly increasing thresholds toward the low frequencies. If masking is used to prevent activation of places on the basilar membrane that are not specifically responsive to the low frequencies, one may find a steep low frequency loss and there may be discrepancies between the pure tone audiogram (frequency specific thresholds) and the masked results (place specific thresholds).

Table 1 summarizes the characteristics of some of the auditory evoked potentials. The major conclusion of this discussion is that no one evoked potential can serve to provide all of the information needed for objective audiometry. Perhaps one can tailor the test to the patient. The ABR can provide good audiometric information for the middle and high frequencies. However, it may be supplemented by the 40 Hz response for low frequency thresholds, or by the electrocochleogram for patients with abnormal ABRs. In patients with possible functional hearing loss the late responses may be most relevant because they show activity at higher levels of the auditory system.

Once one has come to the idea that there is more to evoked potential audiometry than the ABR, it may not be hard to accept that there is more to audiometry than clicks and tones. Probably this is where research will lead in the next few years. We need new stimuli and new paradigms so that we can objectively evaluate suprathreshold discrimination. Most importantly we need techniques to show us whether a child has sufficient hearing ability to perceive speech.

Detecting Lesions of the Eighth Nerve

One of the most common uses of the auditory brainstem response is in the detection of acoustic neuromas. Patients presenting with an unexplained unilateral hearing loss, tinni-

tus, and loss of equilibrium may have a tumor in the cerebello-pontine angle.

The ABR is usually abnormal in patients with such tumors (Antonelli, Bellotto, & Grandori, 1987; Barrs, Brackmann & Olson, 1985; Mair, Okstad, Laukli, & Anke, 1988). The classic abnormality is a delay between wave I, generated by the cochlear nerve fibers in the temporal bone, and wave III, generated in the pons. The upper limits of normal for the I-III interval is usually about 2.6 ms. However, wave III may be absent. In these cases one is left with a prolonged I-V interval, the upper limits of which are about 4.6 ms. If wave I is also absent, there is just a delayed wave V. In normal patients wave V shows no more than a 0.4 ms asymmetry between the ears.

Three limitations to identifying retrocochlear problems with the ABR must be recognized. First, the test is not very specific. Increased I-III or I-V intervals can indicate a retrocochlear hearing loss, but they do not demonstrate the pathology. Such delays could be caused by multiple sclerosis and other neurological disturbances, as well as by a tumor in the cerebello-pontine angle.

A prolonged I-V interval is normally considered pathognomic for retrocochlear dysfunction. However, a cochlear hearing loss with a notched audiogram also may cause a delayed I-V (Keith & Greville, 1987). With clicks of moderate to high intensity, wave I derives mainly from the 4-8 kHz region of the cochlea, whereas wave V derives mainly from the 2-4 kHz region. If there is a notch in the audiogram at 4 kHz, wave I may be generated only by the 8 kHz region with a latency that is normal or slightly shorter than normal, and wave V may be generated by the 2 kHz region with a latency that is longer than normal.

A recording with a delayed wave V and no clearly recognizable earlier waves is even more nonspecific than one with a delayed I-V interval. The absence of any wave I means that there is some peripheral hearing loss, but one cannot rule out additional retrocochlear abnormality.

The most common diagnostic problem in patients with acoustic neuroma is to determine whether or not a patient with a high frequency hearing loss has any retrocochlear pathology (Hyde & Blair, 1981). Both a cochlear high frequency hearing loss and an acoustic neuroma can cause a delayed wave V. The main way to differentiate these two problems is to record wave I. In a cochlear hearing loss affecting the high frequencies, wave I is small and delayed and the I-V interval is either normal or decreased. In a retrocochlear hearing loss the wave I-V interval is increased.

Unfortunately, wave I is not recordable in about one third of patients with an acoustic neuroma. Placing the electrodes closer to the cochlea can increase the recognition of wave I. The best technique is a transtympanic electrode (Eggermont, Don, & Brackmann, 1980). However, in deciding whether or not to arrange for electrocochleography, one is faced with the problem of whether it is better just to proceed to MRI studies.

Various techniques have been proposed to compensate for the increased wave V latency caused by a cochlear high frequency hearing loss. Selters and Brackmann (1977) suggested that one might subtract 0.1 ms for every 10 dB hearing loss above 50 dB at 4 kHz. Other compensation schemes have been based upon the normal latency-intensity function when expressed in dB SL rather than in dB HL (Prosser & Arslan, 1987). Some studies have shown that the compensation factors are really only necessary for male subjects (Elberling & Parbo, 1987; Jerger & Johnson, 1988).

A brainstem response may be totally unrecordable in patients with acoustic neuroma. This demonstrates a severe abnormality but cannot help to identify the cochlear or retrocochlear nature of the problem. The incidence of absent responses varies with different series. On average it might occur in about 15% of cases.

A second limitation to the use of the ABR in the identification of retrocochlear hearing loss is that we do not know the cause of the delayed waves. The general interpretation of the delay between wave I and wave III or V is that the pressure of the tumor slows down the conduction of auditory impulses along the auditory nerve. However, this may not be true. The tumor probably mainly affects transmission of the fibers around the outside of the nerve. These fibers come from the first turn of the cochlea and are specifically responsive to high frequency sounds. The tumor may prevent conduction in these fibers or may desynchronize their firing patterns. Since its generators are either absent or desynchronized, wave V from the basal turn is no longer recordable. One is therefore left with a delayed wave V initiated by fibers from the middle and apical turns of the cochlea. Wave I is generated by the auditory nerve fibers in the spiral ganglion and often remains normal. The surface recorded wave I is mainly generated by fibers from the basal turn of the cochlea near the stapes. Derived responses in patients with acoustic neuromas suggest that this selective impairment of the high frequency fibers is the major cause for the prolonged I-V interval in the click-evoked ABR (Eggermont & Don, 1986). There still may be some delays within a frequency band, but these are small relative to the overall effect. It is therefore doubtful that the I-V yield could be improved by using frequency specific techniques.

The third limitation of the technique concerns the sensitivity of the test. Even though the test is not very specific, the consensus of the literature is that the test is quite sensitive.

Only occasionally does a patient with an acoustic neuroma have a normal ABR. If one adds up the cases reported in the literature, the general incidence of such false negative findings is below 5% (Chiappa, 1990; Picton, 1990). Furthermore, the general feeling is that these patients with normal ABR findings have small tumors. For example, Eggermont et al. (1980) report that 2 out of 45 patients with acoustic neuromas had normal I-V latencies and that these patients had tumors with diameters of less than 1 cm. Thus, the test may be helpful in ruling out a large tumor on the VIIIth nerve.

This conclusion, that the ABR is a sensitive test for detecting lesions of the eighth nerve, might be approached with some scepticism. Most of the published studies used patients who had been diagnosed as having an acoustic neuroma and referred to a surgical center for treatment. Acoustic neuromas are not that common, and it is difficult to obtain a large series of patients by other means. Final diagnoses usually were based on contrast radiography of the posterior fossa. However, the diagnostic techniques leading to referral to the surgical center were most likely computed tomography (CT) and/or the ABR itself. Now, it is possible that some patients with an acoustic neuroma might not have shown abnormalities on CT scanning or ABR testing; these would not occur in the series published in the literature. The incidence of normal ABRs in patients with acoustic neuromas therefore may be higher than that reported. Those patients with normal ABRs could be diagnosed by more sensitive tests such as magnetic resonance imaging (MRI) or contrast CT scans (House, Waluch, & Jackler, 1986; Lo & Solti-Bohman, 1987; Mikhael, Wolfe, Ciric, & Evanston, 1987).

Some recent data cast significant doubt on the efficiency of a normal ABR in ruling out a retrocochlear problem. Joseph, West, Thornton, and Nadol (1987) have reported ABR results in a series of 17 patients with surgically confirmed retrocochlear lesions. Nine of these patients had ABRs that were considered normal or as indicating a cochlear hearing loss. Although 4 of these patients had a wave V latency asymmetry of greater than 0.4 ms, there was no abnormality of I-V interval and no significant differences between the ears for the I-V interval.

Several conclusions can be drawn concerning the use of the ABR in diagnosing lesions of the eighth nerve. With the increasing availability of CT and MRI these lesions are being detected at an earlier stage when the tumors are smaller. This is good because a smaller tumor can be removed more easily, with less risk to the facial nerve, and with a greater chance of preserving hearing. The role of the ABR in the detection of these tumors is uncertain. Although the ABR is almost always abnormal in larger tumors, it can be normal in small tumors - the very ones that are most important to detect if one wishes to operate and preserve function. Contrast CT scanning used to be the best diagnostic procedure. This test is uncomfortable, particularly if gas contrast is used. One might therefore have decided to delay the test if the ABRs were normal. The MRI procedure is sensitive, specific, and painless. It is the diagnostic test of choice, although it is expensive and at present not readily available.

Auditory Evoked Potentials During Surgery

In recent years the auditory brainstem responses have become widely used in monitoring auditory function during posterior fossa surgery (Radtke & Erwin, 1988). The major purpose of this monitoring has been to preserve hearing. The most common types of operation during which monitoring is used are removal of an acoustic neuroma (or some other cerebellopontine angle tumor) and microvascular decompression of the facial or trigeminal nerve. The danger to hearing is of course higher when the surgery is being performed directly on the auditory nerve.

Monitoring the evoked potentials during surgery is technically very demanding (Jacobsson & Tew, 1987; Nuwer, 1986). First, the stimulus must be reliably presented to the ear despite the fact that the stimulating equipment is hidden from view beneath surgical drapes. Insert earphones are probably the most effective way of presenting the stimuli. Second, one must pay careful attention to the recording system because of the high levels of electrical noise in the operating room. The recording electrodes and the ground electrode must be very securely attached. The electrical noise from other equipment in the operating room must be attenuated as much as possible by appropriate grounding, shielding, or distancing the equipment from the patient. Third, the information provided by the evoked potentials must be quickly available so as to allow rapid intervention in case a significant abnormality is detected. Therefore one must use fast stimulus rates, appropriate filtering, and whatever other techniques are available to enhance the rapid detection of significant changes in the response.

Because of these difficulties in the recording environment, it is probably worthwhile to monitor the monitoring system. For example, an insert earphone can be made with two tubes — one to carry the sound to the ear and one to monitor the sound intensity in the external auditory meatus. The recording system can be monitored by determining the response to stimulation in the opposite ear. This can be done without sacrificing any time by alternating or interweaving the stimulation between the two ears (Plourde, Picton, & Kellett, 1988). For example, alternating the stimuli between ears and presenting the stimuli at an overall rate of 50/s can provide the same responses as stimulating each ear individually at 25/s.

Figure 2. Monitoring of the auditory brainstem response during surgical removal of an acoustic neuroma. Auditory brainstem responses were recorded between the vertex and mastoid with negativity at the vertex plotted upward. Clicks were presented at a rate of 11/s and an intensity of 80dB nHL through an insert earphone. The pre-anesthetic recording showed wave I at 1.8 ms and wave V at 6.9 ms. There was a slight increase in these latencies after intubation and a significant increase in wave V to 8.4 ms when the skull was opened. During dissection of the tumour around the auditory nerve, wave V suddenly vanished. Within a few minutes wave I also disappeared. The responses then remained absent during removal of the tumor and closure. There was no hearing after the operation.
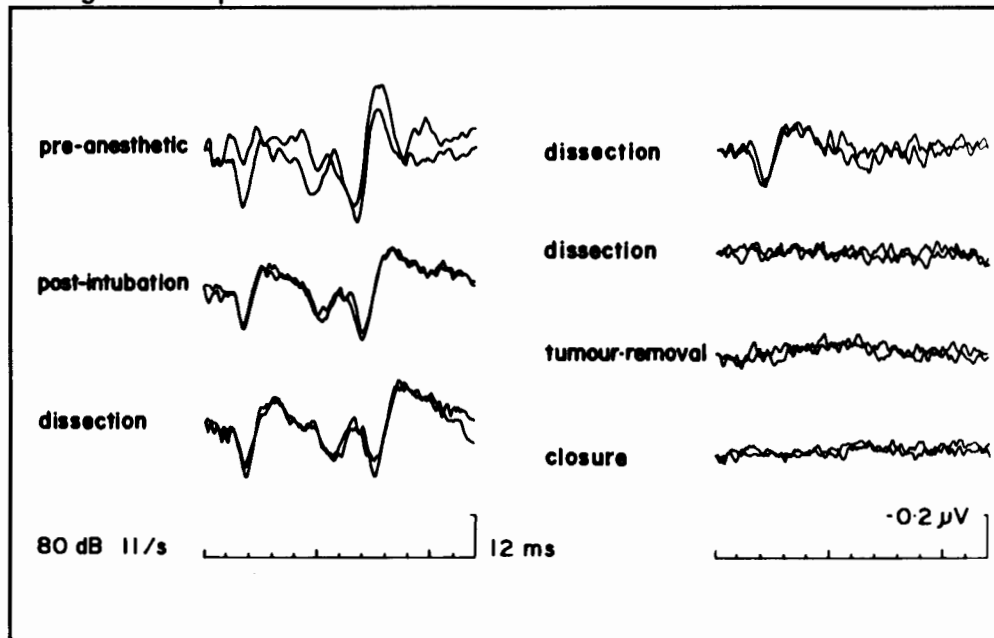

Certain changes in the ABR may occur during an operation in the posterior fossa, seemingly without significance to the outcome of the surgery (Radtke & Erwin, 1988). Latency changes are much less important than decreases in amplitude. The latency of wave V may increase by up to 1.0 ms without increasing the risk of a postoperative hearing loss. Provided the amplitude remains the same, even longer latency prolongations seem to indicate only a mild risk of hearing loss.

During surgical monitoring most cases will proceed without any significant change in the response. In operations to remove small acoustic neuromas and preserve hearing, the success rate for preserving hearing is between 40 and 90% (Cohen, Hammerschlag, Berg, & Ransohoff, 1986; Ojemann, Levine, Montgomery, & McGaffigan, 1984; Rowed, Nedzelski, & Cashman, 1990; Tator & Nedjelski, 1985). Other cases may show a deterioration in their response, and the surgeon will not be able to alter the procedure so as to bring the response back. In both of these conditions, evoked potential monitoring does not change the outcome of the operation. Evoked potentials make their contribution if a deterioration is recognized, the surgeon is notified, the surgeon changes some

aspect of the operative procedure, the evoked potentials return to their previous status, and the hearing is preserved after the operation. The incidence of this varies with the type of patient that is monitored. Raudzens and Shetter (1982) report that out of 46 procedures in the posterior fossa (27 of which were tumors or vascular lesions), 74% showed no change in the auditory brainstem responses, 10% showed a loss of the response and a post-operative hearing loss, and 15% showed transient deterioration in the ABR during the operation and no significant post-operative hearing impairment.

It is difficult to evaluate whether evoked potential monitoring improves the outcome of patients who show a transient deterioration in the response. The major problem is to determine whether what the surgeon does, once notified of the deterioration, causes the return of the ABR to its previous state. It is possible that, in certain cases at least, the transient deterioration may have been related to self-limited causes such as vascular spasm, electrolyte changes with irrigation, and fluctuations in temperature. Radtke and Erwin (1988) compared the incidence of profound hearing loss during the same operation (microvascular decompression) performed by

Figure 3. Auditory brainstem responses in a patient with multiple sclerosis. These responses were recorded from the vertex to ipsilateral mastoid with negativity at the vertex plotted upward. The filter bandpass for the recording was 30 - 3000 Hz. The responses were evoked by clicks presented at an intensity of 80 dB nHL and a rate of 11/s to left (L) or right (R) ears. The response to right ear stimulation shows clearly recognizable waves I, III, and V. The latency (ms) between wave III and V is just beyond the upper limits of normal. The response to left ear stimulation shows a very distorted wave V with two or three small peaks instead of one.
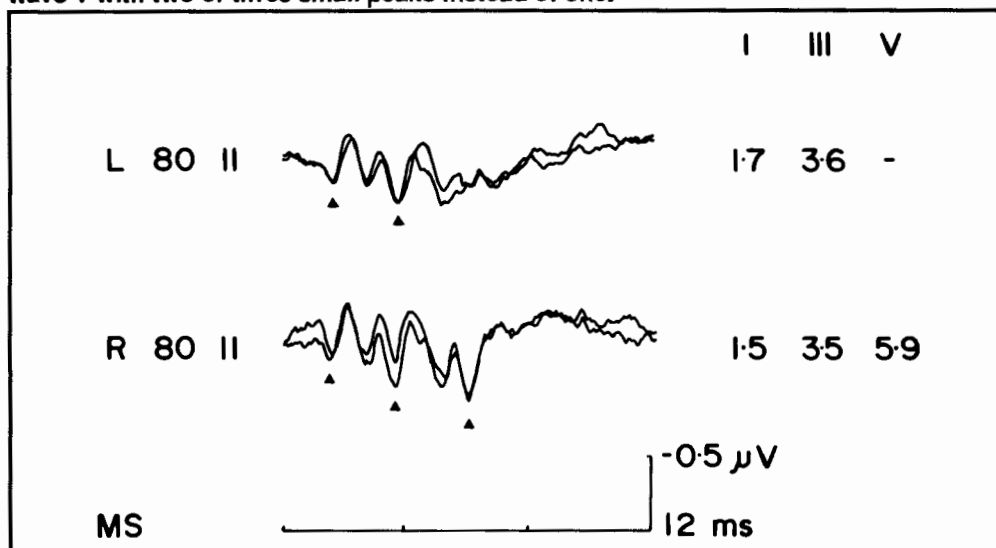
the same surgeon when monitoring was used and when it was not. They found a small but significant decrease in the incidence of profound hearing loss with monitoring. It has not yet been proven that monitoring improves the outcome after surgical removal of an acoustic neuroma.

The ABR is not the only way that auditory function can be monitored during posterior fossa surgery. Cochlear nerve action potentials can be recorded from the external auditory meatus or using transtympanic electrodes (Rowed, Nedzelski, Cashman, Stanton, & Harrison, 1988). The advantage of electrocochleography is that the signal-to-noise ratio is far greater than for the auditory brainstem response. One can therefore detect changes in the auditory function much more quickly. The disadvantage is that damage to the nerve (causing abnormalities of the ABR) may occur before it becomes manifest in an abnormality of the cochlear nerve action potential. Figure 2 illustrates such a case.

It is also possible to measure the auditory nerve action potential using electrodes placed on the auditory nerve within the surgical field (Janetta, Moller, & Moller, 1984; Linden, Tator, Benedict, Charles, Mraz, & Bell, 1988). The advantage of this is that it records the response immediately beyond the point of danger from the operation and that the signal to noise ratio is quite high. The disadvantage is that the electrode itself

may interfere with the operation and may be subject to transient changes in the recording situation due to movement or irrigation.

It is important to realize that auditory function is not the only thing that may need to be monitored during the posterior fossa operations. One might also wish to monitor the function of the facial nerve. This can be done by stimulating the nerve and recording from the facial muscles (Linden et al., 1988).

One might also consider the possibility that the auditory evoked potentials can be used to monitor the depth of anesthesia during operations. The 40 Hz steady-state middle latency response is particularly sensitive to the anesthetic medication. It is rapidly attenuated as the patient goes into anesthesia and returns quickly during recovery (Plourde & Picton, 1990).

In summary, the auditory evoked potentials are probably a helpful way of monitoring auditory function during posterior fossa surgery. However, they probably cause only a small change in outcome, and it will take a while to demonstrate this conclusively. There is still room for improving the recording procedures. Furthermore, one must not lose sight of the fact that monitoring is not limited to the auditory pathway.

Auditory Evoked Potentials in Neurology

The auditory evoked potentials can provide information about the central auditory pathways as well as about the ear and the auditory nerve. Before the ABR, neurologists paid little attention to the auditory system. The central auditory pathways are bilateral, and information travels up both sides of the brainstem. This redundancy of information transfer (at least for simple parameters that can be tested easily in clinical patients) means that unilateral lesions will not cause auditory symptoms. Special tests can bring out abnormalities, but these are difficult to use with many clinical patients. Abnormalities of the ABR can demonstrate involvement of the auditory pathways in the pons and the midbrain. This information is not available to clinical examination and is not always demonstrable by imaging techniques. Rather than consider a multitude of neurological disorders, I shall illustrate the usefulness of the response in demyelinating disorders and in coma.

The diagnosis of multiple sclerosis (MS) requires evidence of lesions to the nervous system that are separate in time or in space. The ABR may help to make this diagnosis by demonstrating a lesion that may not have been apparent on clinical examination. The ABR is therefore only helpful if the patient has symptoms or signs indicating involvement at locations other than the brainstem or if brainstem symptoms or signs are mild or equivocal.

The demyelinating process in MS does not affect the auditory brainstem pathways as commonly as the visual or somatosensory pathways. Chiappa (1988) has reported that 46% of patients with multiple sclerosis have abnormal ABRs, whereas 63% have abnormal pattern reversal visual evoked potentials, and 58% have abnormal somatosensory evoked potentials. The decreased sensitivity of the ABR may be related to some increased sensitivity of other pathways to the demyelinating process (the optic nerve) or to their increased length (the somatosensory system).

Comparison of the MRI and the ABR show that the tests are complementary (Cutler, Aminoff, & Brant-Zawadzki, 1986). In a small number of cases the MRI will show lesions of the brainstem that do not affect the ABR, and in another small number of patients the ABR may show evidence for dysfunction in the auditory pathways without the MRI demonstrating any brainstem lesions. Although more expensive, the MRI gives a far greater yield of information than the sensory evoked potentials because it evaluates the whole brain rather than just the sensory pathways and it shows abnormalities that can be more specifically related to demyelination.

The patterns of ABR abnormality in multiple sclerosis are variable. A common pattern in MS is illustrated in Figure

3. Wave V is distorted and difficult to recognize, and there is no clear aftergoing negative wave. This pattern may be difficult to interpret because one could arbitrarily identify as wave V one of the wiggles in the normal latency range of wave V. The abnormality shows up better when recording with a low frequency cut-off of 100 Hz rather than 30 Hz because the latter obviously makes the wave V small in amplitude. The abnormality is probably related to desynchronization of transmission in the lateral lemniscus.

The ABR is also helpful in evaluating patients in coma. An essential step in the diagnosis of coma is to determine whether the patient has a brainstem lesion or not. The ABR evaluates the auditory pathways that run around the edge of the brainstem tegmentum. It therefore complements the vestibulo-ocular reflex which evaluates the more central areas of the brainstem (vestibular and ocular motor nuclei and medial longitudinal fasciculus).

There are clear limitations to the use of the ABR in evaluating patients with coma. First, it is possible that certain small lesions of the midbrain or thalamus may cause coma and yet spare the auditory brainstem response (and the vestibulo-ocular reflexes). A normal ABR therefore cannot rule out a brainstem lesion causing coma. Second, there is a high incidence of peripheral hearing loss in comatose patients. Head trauma may damage the auditory nerve or cochlea by fracturing the temporal bone, or may damage the middle ear by causing hemotympanum or ossicular dislocation. Intubation for respiratory support can lead to middle ear problems. Disorders such as anoxia, which affect the brainstem and lead to coma, can also damage the ears.

Several studies (Goldie, Chiappa, Young, & Brooks, 1981; Hall, Mackey-Hargadine, & Allen 1985; Starr, 1976) have noted that wave I may be absent in a significant proportion (20-80%) of patients who are being considered for the diagnosis of brain death. When wave I is not clearly recognizable, one can conclude that there is some degree of hearing loss, but one cannot determine whether or not there is additional brainstem dysfunction. Thus the absence of any components of the ABR cannot differentiate between deaf and dead. Hall et al. (1985) suggest that wave I is perhaps more frequently recorded if the potentials are studied within a few hours of the event leading to brain death.

The ABR may help in assessing the prognosis of a comatose patient. However, one must not simply relate the ABR to outcome. The ABR shows whether there is dysfunction in the auditory pathways. The outcome from coma is determined by many factors, and damage to the brainstem sufficient to affect the auditory pathways is but one of these.

In general, severely abnormal ABRs are a bad prognostic sign, particularly if they are persistent. However, there are

occasional instances in childhood when these responses may return to normal (DeMeirleir & Taylor, 1986). Normal ABRs are usually a good prognostic sign. However, here we are limited by the fact that only the brainstem pathways are being evaluated. Patients may have extensive damage to the cerebral hemispheres and yet preserve brainstem function. The somatosensory evoked potentials are far more informative in assessing comatose patients than the ABR. These potentials provide both brainstem and cortical responses. Furthermore, they are less liable to damage of the receptors.

One new development that could improve the neurological usefulness of the auditory evoked potentials is to extend the recordings beyond the brainstem. In recent years, there has been a renewed interest in the possible use of the middle and late auditory evoked potentials as a means to determine the function of the auditory thalamus and cortex. Several reports suggest that the middle latency responses may be affected by lesion to the cortex (Kileny, Paccioretti, & Wilson, 1987; Kraus, Ozdamar, Hier, & Stein, 1982). The difficulty in using the MLR in neurological evaluations is that at the latency of the MLR many different processes are simultaneously generating fields with overlapping scalp distribution. Areas of the thalamus, both temporal lobes, and various scalp muscles all can generate fields that are recorded from the scalp. It is difficult to disentangle these processes even when the recordings are normal.

Recent developments, such as dipole source analysis (Scherg, 1990; Scherg, Vajsar, & Picton, 1989), may help us to analyze the complex electrical fields generated by the auditory cortices. Scherg and von Cramon (1990) have suggested how lesions of the auditory radiation and auditory cortex can be classified using these techniques. The ABR brought the auditory pathways into the view of the clinical neurologist. They are now as important to the evaluation of the brainstem as the ocular pathways. The new approaches to analyzing the auditory cortex may make a similar impact. The middle and late auditory evoked potentials may become as important to the neurologist as the visual fields.

Another development would be to use stimuli that are specifically designed to test processes that occur in the central auditory system. The simple onset of a tone is not a very sophisticated stimulus and cannot fully evaluate the specialized functions of the human auditory system. For example, stimuli that change in frequency (e.g. Durant, 1987; Maiste & Picton, 1989) or change in spatial localization (McEvoy, Picton, Champagne, Kellett, & Kelly, 1990) may provide access to the cerebral processes that discriminate between different frequencies or that localize sounds in space.

With better techniques to record the auditory evoked potentials beyond the brainstem and with new paradigms to

stimulate these responses more specifically, one might enter into a whole new clinical world. Such elusive problems as "central auditory dysfunction" (Jerger, Martin, & Jerger, 1987; Pinheiro & Musiek, 1985) and "obscure auditory dysfunction" (Saunders & Haggard, 1989) may come into diagnostic focus.

Conclusion

What lessons can be derived from this evaluation? First, we should not lose sight of the fact that the ABR represents but a small part of the auditory evoked potentials that can be recorded from the human subject. Other audiometric evoked potentials may sometimes be more effective in assessing hearing thresholds. Furthermore, they can provide a much more extensive evaluation of the human auditory system. Second, we should realize that the world of auditory stimuli is far more exciting than clicks and tones. Sophisticated stimuli may evoke potentials that can evaluate specific auditory functions. Third, the auditory evoked potentials should be used in conjunction with other tests. Evoked potentials in other modalities are particularly helpful in neurology. However, perhaps the most exciting new tests that have developed in recent years are the OAEs and the MRI.

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