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Section 2: Audiology

Chapter 8: Electric Response Audiometry

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During the past ten years, electric response audiometry, particularly brain-stem response audiometry, has become an important clinical tool. In this chapter the basic principles of electric response audiometry are reviewed. We then describe the various techniques, emphasizing their clinical applications.

Basic Concepts

The aim of electric response audiometry is to record the potentials that arise in the auditory system as a result of stimulation by sound. The basic principles of recording the electric potentials from the auditory system are the same, regardless of the potential that is of particular interest. The recording is made difficult by the fact that the potentials generated in the auditory system are minute in comparison with the background of electric impulses from other parts of the body (brain, heart, and muscles).

The development of computers to sample and average responses made it possible to record the synchronous neural potentials arising from the auditory neural pathway. The further development of small computers dedicated specifically to averaging made it practical to record these potentials in a clinical setting. Now these small averaging computers are giving way to small microcomputers that are capable of performing other kinds of analyses in addition to averaging and of controlling the parameters of the testing procedure. In some instances, they are also capable of performing the normal functions of a microcomputer.

The basic components of equipment for ERA are shown in the block diagram. The stimulus generated depends on the type of responses that are to be recorded. For most types of recordings, the stimuli are acoustic signals of short duration. Variations of clicks, which are produced by applying pulses of voltage of short (eg, 0.1 msec) duration to a transducer (earphone or loudspeaker), and of pure tones of short duration (called tone-pips or tone-bursts) are the most commonly used stimuli. Such brief stimuli produce synchronized discharge of neural elements in the auditory system.

Diagram. Basic Components of ERA

Pulse generator --> Amplifier --> Loudspeaker --> Pre-amplifier --> Amplifier --> Averaging computer --> Recorder.

The types and placement of electrodes to record the evoked potentials also vary with the type of responses that are to be recorded. Aside from a ground electrode, one electrode is generally placed on the promontory, the ear canal, the scalp vertex, or the forehead; a second electrode is placed somewhere appropriate to the first (eg, on the mastoid prominence or earlobe). The minute electrical activity that these electrodes pick up is differentially amplified and filtered before being delivered to the computer for averaging. In some systems, the filtering is performed digitally (digital filtering) in the computer after averaging.

The average response computer consists of a series of memory units, each receiving information a fraction of a second later than the one just before it. We like to think of each point as a small calculator capable of addition and subtraction. The computer is triggered to begin a sweep (sequential processing of electrical activity over a period of time) each time a stimulus is delivered to the ear. The length of the sweep depends on the type of responses being recorded. A response to the stimulus is assumed to be time-locked to the stimulus and, thus, to the computerized processing. Therefore, the response will repeatedly occur in the same group of memory-locations.

The electrical background noise occurring during this response period is reduced by averaging many sweeps, such that the final average value in each memory location represents mostly the response value. (See Picton et al (1984) for a good description of averaging signals in noise.) By averaging many sweeps, the response potentials from the auditory system that singly would be impossible to identify are extracted from the background electrical noise. The averaged response can be transferred to paper for analysis and stored in the patient's chart.

The basic principles for recording are the same in all electric response audiometry. The techniques vary, depending on the response to be measured.

Auditory Evoked Potentials

The most important auditory evoked potentials and probable sites of generation are outlined in Table 1. The actual site of generation of some of these responses is not known. It is likely that there are multiple neural sites

involved in the production of the brain stem responses. In considering these responses, it is important to point out that the measurements obtained from electric response audiometry methods are generally not measures of hearing per se. Hearing is a perceptual process that involves the entire auditory system, and it cannot be measured in terms of electric responses unless these responses can be shown to be related directly to perception. The clinical value of electric response audiometry lies in the correlation of electric responses with auditory pathologic conditions and/or performance.

Table 1. Potentials Evoked in the Auditory System by Stimulation by Sound; Their Probable Sites of Origin; and Typical Latencies for Moderately High Levels of Stimulation

1. Cochlea (hair cells)
    Cochlear microphonics - immediate
    Summating potential - immediate

2. Auditory nerve (nerve VIII action potential, wave I, 2.0 msec)

3. Brain stem
    Wave II - nerve VIII or cochlear nucleus, 3.0 msec
    Wave III - cochlear nucleus or superior olive, 4.1 msec
    Wave IV - lateral lemniscus, 5.3 msec
    Wave V - inferior colliculus, 5.9 msec

4. Middle responses (auditory cortex)
    N_0 - 8 to 10 msec (variable)
    P_0 - 13 msec
    N_a - 22 msec
    P_a - 34 msec
    N_b - 44 msec

5. Vertex potential (auditory cortex)
    P_1 - 50 msec (variable)
    N_1 - 90 msec
    P_2 - 180 msec
    N_2 - 250 msec
    Sustained cortical potential
    Late positive component
    Contigent negative variation.

Types of Electric Response Audiometry

The three main types of electric response audiometry (ERA) are electrocochleography, auditory brain-stem response (ABR) audiometry, and cortical ERA (Table 2). They are discussed in detail in subsequent sections. The basic mechanism and advantages and disadvantages of each technique are as follows

Table 2. Comparison of Techniques of Electric Response Audiometry

Technique	Electrocochleography	ABR Audiometry	Cortical ERA
Electrode	Promontory	Surface	Surface
Effect of anesthesia	None	None	Marked
Part of auditory system tested	Peripheral	Brain stem	Entire
Reliability	Excellent	Good	Fair.

Electrocochleography. Electrocochleography is the measurement of the potentials arising within the cochlea and the auditory nerve: the cochlear microphonic, summating potential, and nerve VIII action potential. In most cases, a needle electrode is placed through the tympanic membrane onto the bone of the promontory to make these recordings. Electrocochleography is the most accurate of the ERA techniques, by virtue of the close proximity of the electrode to the generator sites. Accuracy also is enhanced, because the peripheral auditory system is unaffected by sedation or even general anesthesia.

An obvious disadvantage of this technique is the requirement for penetration of the tympanic membrane. Electrodes that can be fitted into the ear canal with minimal discomfort have been developed to avoid the need for penetrating the tympanic membrane. The amplitudes of the responses recorded from the ear canal, however, are still greatly reduced in comparison to transtympanic recordings. It remains to be seen whether such canal recordings are sufficient for the desired electrocochleographic information. A recently developed tympanic drum electrode (Stypulkowski and Staller, 1987) appears very promising in providing good sensitivity with minimal discomfort to the patient. Another disadvantage of electrocochleography is that it measures only the response of the most peripheral portion of the auditory system and, therefore, cannot be equated with hearing as such. Although relatively rare, there are cases in which the cochlea and auditory nerve function normally but brain stem or central defects produce hearing loss.

ABR Audiometry. ABR audiometry utilizes surface electrodes to measure the potentials arising in the auditory nerve and brain stem structures. Usually, one electrode is placed on the scalp vertex and one on the mastoid of the tested ear. The electrical activity is differentially recorded and amplified from these two electrodes. The opposite mastoid is used as ground. The events that occur during the first 10 milliseconds following stimulation by sound are recorded.

The advantage of ABR audiometry is that, because surface electrodes are used, anesthesia is not required. In practice, however, either basal narcosis or anesthesia is often required in children to prevent excessive movement, which interferes with accurate recordings. ABR audiometry, like electrocochleography, is not influenced by basal narcosis or general anesthesia.

Cortical ERA. Cortical ERA involves the measurements of the potentials that arise in the auditory system above the brain stem (the middle and slow potentials). The configuration of electrodes is the same as for ABR audiometry. An advantage of cortical ERA is that in measuring the most central responses, the entire auditory mechanism is tested. Responses can thus be best equated with clinical hearing. This is particularly important when there is a question of a central disturbance. A major disadvantage of cortical ERA is that the potentials also are affected by sleep and sedation. Because of these factors, cortical ERA is more difficult to perform in a clinical setting.

Electrocochleography

Stimulative Techniques

The stimulus most commonly used electrocohleography has been a wide-band click. Acoustically the click comprises a large number of frequencies that stimulate the entire cochlea. With a flat hearing loss, the click is a good predictor of the audiometric threshold. With sloping hearing losses, however, one cannot predict the type of audiogram by using click stimuli. Eggermont (1976) has used tone-bursts for electrocochleography; frequency-specific tone-bursts are more accurate indicators of levels of hearing at different frequencies and predict the behavioral audiogram quite accurately.

Recording Techniques

For transtympanic ECoG, a standard Teflon insulated electromyographic recording needle is positioned onto the bone of the promontory, after induction of anesthesia of the tympanic membrane by means of iontophoresis or application of topical phenol. For extratympanic ECoG, see the article by

Stypulkowski and Staller (1987) for a description of the various types. Responses are filtered below 30 Hz and above 3200 Hz. The computer is set to measure over a window of 10 milliseconds.

Measurable Potentials

As discussed previously, electrocohleography is a measure of the potentials arising within the cochlea and the auditory nerve: the cochlear microphonic, summating potential, and nerve VIII action potential.

Cochlear Microphonic

The source of the cochlear microphonic is the hair-bearing surface of the hair cells. Its onset is immediate, and it mimics the waveform of the acoustic stimulus. Because the response recorded from the promontory is diffuse and gives no definite information regarding specific populations of hair cells, most investigators do not find the cochlear microphonic clinically useful. Gibson and Beagley (1976) are an exception and have used the cochlear microphonic to aid in differentiation of cochlear from retrocochlear lesions. They find a tendency toward a reduction in microphonics in cochlear lesions, whereas in acoustic tumors the cochlear microphonic is often normal. The eighth nerve's action potential is of primary interest in electrocochleography; this can be recorded free of the interfering cochlear microphonic by canceling the microphonic by alternating the phase of the click or the tone-burst stimulus.

Summating Potential

The summating potential also is generated by the hair cells and is a direct-current shift of the baseline of the recording, which is almost always negative for all frequencies and levels of intensity, in humans. This potential is thought to represent asymmetry in movement of the basilar membrane, resulting from a difference in pressure between the scala tympani and the scala vestibuli during stimulation by sound (Eggermont, 1976). The source of this direct-current shift is also the hair cells. As we shall see later, this potential may be a means of studying hair cells in Ménière's disease and in other cochlear disorders.

Since the summating potential appears as superimposed upon nerve VIII's action potential, its measurement is sometimes difficult. One technique for separating the summating potential from nerve VIII's action potential is to increase the rate of clicks. As the rate of the clicks is increased, nerve VIII's action potential diminishes because the individual neurons do not have time to recover from their refractory period in order to again respond to the new

stimulus. The summating potential is unaffected by the rate of the clicks given. A recording is first done at a low rate of clicks, and the response, which comprises both the summating potential and nerve VIII's action potential, is stored in the computer. A second recording is then done with a high rate of clicks; the response obtained represents primarily the summating potential and is used as a measure of that response. The second response can then be subtracted from the first response in the computer, and the derived response will represent primarily nerve VIII's action potential devoid of the contaminating summating potential.

Compound Action Potential

The action potential of nerve VIII is the averaged response of the discharging pattern of many auditory neurons. Cochlear dynamics that influence the shape of the compound action potential are extremely complex and beyond the scope of this discussion. The reader is referred to Eggermont's chapter on electrocochleography in the *Handbook of Sensory Physiology* for a review of the subject. In addition to the normal compound action potential, Portmann and Aran (1971) have described four types of electrocohleographic response in patients with sensorineural hearing impairment: dissociated, recruiting, broad, and abnormal. Only the normal response will be described here.

Normal Response

In patients with normal hearing, an action potential can be elicited to within 5 to 10 dB of the patient's behavioral threshold in most cases. At high intensities, the potential is large, consistent, easily recordable, and reproducible. Action potentials are described by three parameters: latency, amplitude, and waveform. Latency is defined as the interval of time from the onset of the click to the maximal negative deflection in the action potential.

Latency normally decreases systemically, from approximately 4 milliseconds at threshold to 1.5 milliseconds at high intensities. Amplitude, on the other hand, characteristically increases in two steps. There is a gradual rise, up to the level of approximately 40 to 50 dB of hearing loss, where there is a plateau, and then there is a rapid increase in amplitude above that level. By convention, latency and amplitude (as a percentage of maximal amplitude) are plotted in relation to the intensity of the stimulus. The maximal amplitude and representative waveforms are plotted on the recording.

Clinical Applications of Electrocochleography

There are three clinical uses for electrocochleography: (1) testing of thresholds, (2) study of Ménière's disease, and (3) study of acoustic neurinomas.

Testing for Thresholds

Electrocochleography is the most accurate of the objective audiometric tests. Thresholds for the click are generally an indication of the audiometric threshold in the 3000 to 4000 Hz range. The electrocochleographic threshold predicts the behavioral threshold to within 5 to 10 dB, at this frequency, in almost all cases. As stated before, however, one cannot predict the audiogram using clicks only. There is a much better correlation with the subjective audiogram when tone-bursts are used rather than clicks. The best correlation is in the frequencies at 1000, 2000, and 40000 Hz, but correlation remains excellent at 500 and 8000 Hz.

The disadvantage of using electrocochleography for determination of thresholds is the necessity for placement of a transtympanic needle. As mentioned previously, it remains to be seen if recordings from electrodes in the ear canal or drum can provide sufficient electrocochleographic information. At the Otologic Medical Group, Inc, we currently use ABR audiometry for determinations of thresholds.

Study of Ménière's Disease

The summating potential and the compound action potential are of interest in the study of Ménière's disease.

Summating Potential

Eggermont (1976) has found an increased negative summating potential during periods of hearing loss in the fluctuant-hearing stage of Ménière's disease. He attributes this finding to either a mechanical displacement of the basilar membrane, which causes nonlinearities in its movement as a result of the presumed endolymphatic hydrops, or to a metabolic disturbance resulting in a larger endolymphatic potential. As fixed hearing loss develops, the summating potential decreases. This indicates a loss of hair cells. Measurement of the summating potential may, therefore, be an indication of reversibility of the hearing impairment in Ménière's disease.

Compound Action Potential

Compound action potentials in Ménière's disease are generally of the broad type, most likely because of the contribution of a large negative summating potential. In approximately 50 per cent of the patients with Ménière's disease whom we studied, a distinctive type of nerve VIII action potential was found, characterized by a tendency to form multiple negative responses (Brackmann and Selters, 1976). We have not seen this type of response in other types of sensorineural hearing loss, and this may be a means of distinguishing endolymphatic hydrops.

Study of Acoustic Neurinomas

The potential in acoustic neurinomas is much broader than the normal potential. In our study (1976) by electrocochleography of 50 patients with acoustic neurinomas, we found an abnormal action potential in 85 per cent. One of the major difficulties in using electrocochleography for detection of tumors is that patients with tumors often incur a cochlear loss as well, perhaps from vascular compromise by the tumor (Eggermont et al, 1980). Thus, often the conclusion from electrocochleography reflects only that there is cochlear involvement. As observed in the following section, ABR audiometry is a more accurate predictor of acoustic tumors, and we use it exclusively for this problem at the present time.

Future Applications of Electrocochleography

Because of the necessity of penetrating the tympanic membrane for transtympanic electrocochleography, ABR audiometry has replaced it in most clinics. Testing for thresholds is nearly as accurate, with ABR audiometry as with electrocochleography, provided one is dealing with a normal auditory brain stem. ABR audiometry is a more accurate predictor of retrocochlear pathologic conditions than is electrocochleography.

The future of electrocohleography lies in the study of the physiology and pathophysiology of the cochlea and nerve VIII. Changes in cochlear microphonics and summating potentials are an indication of hair cell disease. As outlined above, study of the summating potentials and the compound action potential are means of assessing the state of the end-organ in Ménière's disease. Moffat (1977) has reported changes in these potentials during glycerol dehydration, in patients with Ménière's disease. Gibson, Ramsden, and Moffat (1977) also have demonstrated changes in these potentials with the administration of intravenous vasodilators. Electrocochleography is, therefore,

a powerful new tool in the study of cochlear disease that will have great future application. The disadvantage of transtympanic electrocochleography is the necessity for placement of the transtympanic needle electrode. Because of this, techniques for recording from the surface have become much more popular in the USA. However, the newer extratympanic methods may cause a resurgence in ECoG.

Auditory Brain Stem Response Audiometry

Stimulative Techniques

As in electrocochleography, the stimulus most commonly used for ABR audiometry is a wide-band click. This stimulus presents the same limitations in ABR audiometry as in electrocochleography, in that the entire cochlea is stimulated and one cannot predict the audiogram except in cases of flat hearing impairment. The majority of sensorineural losses are sloping, with the loss greater in the higher frequencies. Errors, therefore, might occur in predicting a more severe loss than is actually present, because of preservation of hearing for the low tones. Relatively frequency-specific stimuli (tone-bursts, tone-pips, filtered clicks) may also be used to elicit the brain stem responses. These stimuli give more frequency-specific information regarding the cochlea and may be used to estimate audiometric thresholds as will be described later.

The addition of high-pass noise with various cut-off frequencies, simultaneously presented with stimulative clicks, is a means of assessing contributions from various areas of the cochlea. With this technique, a good estimation of the audiogram can be made. The principles of this and similar noise-masking techniques will be detailed later.

Recording Techniques

Standard electroencephalographic disk electrodes are attached to the vertex and both mastoids of the patient to be tested. The electrical activity, over a window of time of 10 to 15 milliseconds after onset of the stimulus, is recorded differentially, usually from the vertex electrode (positive input to the amplifier), and the mastoid electrode (negative input to the amplifier) of the tested ear. The mastoid of the nontested ear serves as the ground. The electrical activity is filtered with a passband from 100 Hz to 3000 Hz, and this activity is amplified 100.000 times or more.

Sedation is not used in adults or in small infants, who often sleep during the procedure. Uncooperative children are sedated as follows: 1 mL/25 lb body

weight intramuscularly, of a combination of meperidine (Demerol) (25 mg), promethazine (Phenergan) (6.25 mg), and chlorpromazine (Thorazine) (6.24 mg) per mL. A maximum of 1 mL is used. Chloral hydrate (500 mg/5 mL) in an oral dose of 1 to 2 mL/10 lb body weight may be used in place of the injectable medication.

Normal Brain Stem Responses

Waves

A series of seven waves may be recorded from the vertex-mastoid electrode derivation during the first 10 to 15 milliseconds following moderately intense stimulation with sound. These waves, labeled sequentially with Roman numerals, are thought to represent successive tracts and/or synapses in the auditory pathway (Jewett et al, 1970). It is likely that there are multiple neural sites involved in the generation of these wave components. Generally, wave V is the largest and most consistent component observed at threshold intensities and is used in the clinical assessment of peripheral hearing. The first appearance and latency of wave V are the measures most used in ABR audiometry. Wave V latency is dependent upon intensity of the stimulus: as the intensity increases, there is a systematic shortening of the latency from about 8.5 milliseconds at threshold to about 5.5 milliseconds at the 60-dB hearing level.

Frequency-Following Response

Similar to the cochlear microphonic response, the frequency-following response follows the frequency of tonal stimulation. It is distinguished from the cochlear microphonic by its onset latency of about 6 milliseconds. This has led to the general consensus that its origin is in the region of the inferior colliculus. Some researchers are still investigating whether the frequency-following response could possibly be a repeated wave V of the transient brain stem response.

SN-10 Response

Davis and Hirsh (1976, 1979) and Suzuki and co-workers (1977a, b) have described another response at around 10 ms after onset of the stimulus. Davis and Hirsh have labeled this the SN-10 response, and they believe that the generation is the primary auditory cortex.

Clinical Applications of ABR Audiometry

There are three major clinical uses of ABR audiometry: (1) testing for thresholds in infants, young children, and malingerers; (2) diagnosis of acoustic neurinomas; and (3) diagnosis of lesions of the brain stem. Two additional uses gaining prominence are (4) screening infants in intensive care units in nurseries who are at risk for hearing loss (Fria, 1985), and (5) monitoring surgical procedures intraoperatively when the auditory nerve is at risk (Kileny and McIntyre, 1985).

Testing for Thresholds

ABR audiometry is used in all cases in which standard behavioral audiometric techniques fail. This technique allows identification of hearing impairment in infancy, so that rehabilitation can be started. As described above, wide-band clicking stimuli stimulate the entire cochlea, so that one cannot predict the audiogram except in cases of flat hearing impairment. Despite this deficiency, this is a valuable technique for early identification of hearing loss. If an error is made, it is usually in predicting a greater hearing loss than is actually present. In either case, early rehabilitation is begun.

Kodera et al (1977) have shown good correlation between the behavioral audiogram and ABR audiometry using tone-bursts as stimuli. As with electocochleography, correlations are better for the high frequencies than for the low. Use of these stimuli better predicts the pure-tone audiogram than does use of broad-band clicks as stimuli. This technique, however, is still deficient in accurately predicting hearing loss in the low frequencies.

Some studies have shown good correlation of the frequency-following response to thresholds for hearing in the low frequencies. The disadvantage of using this response is that its amplitude is very small and it is difficult to separate artifact from response. Some researchers have questioned from which area of the cochlea this response might be initiated, at moderate to high levels of stimulation. Thus, even though this response shows promise of aiding in the assessment of hearing in the low frequencies, many questions remain unanswered regarding its clinical applicability.

We have applied a technique that involves the use of high-pass masking noise, which can reasonably reconstruct the pure-tone audiogram (Don et al, 1979). This technique was first introduced in work with animals by Teas and co-workers (1962) and later applied to electrocohleography by Elberling (1974).

The High-Pass Masking Technique

Don and Eggermont (1978) and Parker and Thornton (1978) have demonstrated that the whole of the basilar membrane contributes to the auditory brain-stem response (ABR) to a click with broad frequencies. The technique of deriving the contribution initiated from each portion of the basilar membrane is illustrated. In this figure, the cochlea is rolled out flat and marked off in sections A through F. Section A represents the area of the cochlea whose maximum sensitivity is 8000 Hz and above; section B represents the area for 4000 to 8000 Hz; section B represents the area for 4000 to 8000 Hz; section C, the area for 2000 to 4000 Hz; section D, the area for 1000 to 2000 Hz; section E, the area for 500 to 1000 Hz; and section F, the region below 500 Hz.

A click presented at moderate hearing levels and above will stimulate the entire cochlea because of its broad-band spectral nature. The ABR (R-1) (line 1) represents the sum of brain stem activity initiated by stimulation of the whole cochlea (ie, sections A through F). Next, as seen in line 2, the level of continuous broad-band noise is determined that is sufficient to desynchronize and thereby to obliterate the response to the click. This masked response is denoted as MR.

After the appropriate level of noise has been determined, the noise is steeply high-pass filtered at 8000 Hz (the high-frequency component of the noise above 8000 Hz is allowed to pass), and the clicks are presented in this noise. As seen in line 3, the ABR (R-2) obtained under these conditions results from click-synchronous activity initiated from the unmasked region below 8000 Hz. Subtraction of this response (R-2) from the response obtained without any masking noise (R-1) in the computer results in the derived narrow-band response (DR-1) seen in line 4. The subtractive procedure eliminates the common contributions from regions below 8000 Hz (the stippled area in line 4) and results in recording the contribution from the cochlea that was masked by the 8000 high-pass noise (section A).

Next, the high-pass cut-off of the noise is lowered by an octave to 4000 Hz, and the clicks are presented in this noise. The ABR recorded (R-3), shown in line 5, results from click-synchronous activity from the unmasked portion of the cochlea; that is, the region below 4000 Hz. Subtraction of the response (R-3) from that obtained with the 8000 Hz high-pass noise (R-2) eliminates the common contribution from the region below 4000 Hz (the stippled area in line 6). The response derived from this subtraction (DR-2) is initiated from the narrow-band region of the cochlea that is not masked by the 8000 Hz high-pass noise but was masked by the 4000 Hz high-pass noise (section B). In a similar

fashion, by successive subtraction of the responses, one obtains the derived narrow-band contribution to the ABR for the other sections of the cochlea. This procedure is repeated for various intensities of clicks, and in this manner the contribution from each portion of the basilar membrane at each intensity is derived.

In patients with normal hearing, contributions to the ABR to the click can be detected, down to the 30-dB level of sensation, for the region for 8000 Hz and above and for the region for 500 Hz and below. Contributions to ABR from those octave-wide regions for 4000, 2000, and 1000 Hz can be detected, down to at least the 10-dB level of sensation. The differences in levels of threshold between a patient and a person with normal hearing for each of the derived frequency regions are used as the estimate of the hearing loss, for constructing an estimate of the audiogram (Don et al, 1979).

The major advantage of this technique is that it provides information concerning the place in the cochlea in which the losses occur, which is not always the case for techniques using tonal stimuli at moderate to high levels of sound. The major disadvantages are that it requires a little more time than most other procedures, special filters for the masking noise, and equipment capable of storing and subtracting records of waveforms. Most newer equipment, however, has that capability, either in the hardware or the software. These are small prices to pay for a technique that can often accurately assess peripheral hearing function in the very young - the otherwise difficult-to-test patient.

There are other ABR techniques used in estimating the audiogram, and some include noise-masking strategies. A good description of these alternative techniques and their advantages and disadvantages can be found in the review by Stapells et al (1985).

Use of a Combination of Techniques

Davis and Hirsh (1979) have proposed that a combination of techniques be used to approximate the pure-tone audiogram. They use ABRs to 2000 and 4000 Hz tone-pips to estimate the audiogram at those frequencies. The later SN-10 response to 1000 and 500 Hz tone-pips is used to estimate hearing at those frequencies. Moushegian and colleagues (1978) have proposed that the ABR be used to assess the more basal portion of the cochlea and the frequency-following response, the apical region.

Current State of Testing for Thresholds

At the present time, we are using broad-band stimulation with clicks to elicit ABRs. From this, we estimate hearing in the regions of the cochlea for 3000 to 4000 Hz. We estimate hearing in the low frequencies with the use of impedance audiometry. The presence of an acoustic reflex to a low-frequency stimulus indicates preservation of hearing in the lower frequencies. This finding, with an absent ABR to stimulation by clicks of high frequencies, would indicate a sloping type of high-frequency hearing loss and would be an indication for caution in fitting of a hearing aid. In such a case, we might well prescribe a low-gain hearing aid with high-frequency emphasis.

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On the other hand, the absence of an acoustic reflex to a stimulus of low frequency, combined with an absent ABR to a click of high intensity, implies a profound hearing impairment and indicates the need for a high-gain hearing aid. There are recent attempts to utilize ABR audiometry recordings in children to help determine the settings of various parameters for hearing aids (Mahoney, 1985).

Clinical verification of the various techniques is still needed. Some combination of these techniques may give promise of accurate prediction of the pure-tone audiogram by objective measuring techniques.

Diagnosis of Acoustic Neurinomas

ABR audiometry has proved to be the best audiometric test for detection of acoustic tumors (Selters and Brackmann, 1977). Table 3 compares the ABR with other techniques for detecting tumors. The success of ABR audiometry depends on the fact that acoustic tumors stretch or compress the auditory nerve, producing a delay in the response latency, which ABR audiometry can detect. This delay may occur in an ear with normal hearing. Conversely, cochlear lesions have little effect on the brain stem response latencies for stimuli at high

intensities until the hearing loss becomes rather severe.

There are several techniques in which the latency of wave V is used for detection of a retrocochlear lesion. The first is to measure the absolute latency of the wave and compare it with normal latency. The normal latency for wave V is between 5 and 5.7 milliseconds. Because of this rather large variability among normal patients, we have not found the measure of the absolute latency of wave V to be very useful in diagnosis of acoustic neurinomas.

Table 3. Four Screening Test failures Listed as Percentages of Test Performed

	ABR	X-ray	ENG	ART
False-negative (tumor missed)	4	11	23	30
False-positive (false alarm)	8	27	28	28

ABR = Auditory brain-stem response audiometry;
ENG = electronystagmography; ART = acoustic reflex threshold.

Another approach has been to measure the interval between waves I and V. This so-called measure of central conduction time has the advantage of removing the error that occurs when there is a sensorineural hearing impairment in the high frequencies that produces a cochlear delay, as described below. Prolongation of the interval between waves I and V should reflect only the delay in propagation of the neuronal impulse along the auditory nerve, secondary to compression by the tumor.

The difficulty with use of this technique is that patients with either sensory hearing loss or an acoustic tumor often do not have a recordable wave I. Thus, this technique cannot always be used. Coats (1978) has increased his ability to use this method by doing simultaneous recordings with an electrode in the ear canal and electrodes on the scalp. The electrode in the ear canal more frequently detects wave I, while the electrodes on the surface are used to record wave V. This procedure, however, requires placement of an electrode in the ear canal. Another difficulty in using central conduction time as the only measure of a retrocochlear lesion is that a tumor may cause delay in wave I; latencies for waves I to V would be normal, with all of the waves delayed. Part of the reason for the delay in both waves I and V is that a cochlear loss in the high frequencies often occurs secondary to the tumor, perhaps through vascular compromise by the tumor (Eggermont et al, 1980).

The technique we use for detection of acoustic tumors is to compare the patient's nonsuspect ear with the ear that is suspected of having the acoustic tumor. With this technique, the patient acts as his own control, to reduce the variability seen among normal patients.

Differences in Latency Interaurally in Patients with Normal Hearing

ABRs to a broad-band click at an 83-dB hearing level are recorded. The nontested ear is masked by 78 dB of white noise. The responses are studied for detection and determination of the latency of wave V, the largest and most recordable of the peaks. Comparison is made between latencies of the two ears (IT_5). In studying a group of normal patients, we found a difference of no more than 0.2 millisecond between latencies in wave V for the two ears.

Differences in Latency Interaurally in Patients with Unilateral Hearing Loss

Sensory Loss. Sensory losses of less than 55 dB do not significantly alter the latency of the wave V response to a click at 83 dB; however, as the sensory hearing loss at 4000 Hz increases above 50 dB, wave V latency gradually increases at the approximate rate of 0.1 millisecond per ten dB. It is necessary to correct for this cochlear delay to decrease the number of otherwise false-positive retrocochlear findings. This factor adjusting the latency was devised to eliminate as many false-positive results as possible without creating additional false-negative results (tumors missed), an error that would be more serious. Our adjustment of the latency subtracts 0.1 millisecond for each 10 dB of loss above 50 dB at 4000 Hz, when the stimulating click is at about an 85-dB hearing level. The data are recorded.

Cases with Tumors. Up to half of patients with acoustic neurinomas have no detectable wave V, regardless of the degree of hearing impairment. We consider this finding indicative of neural desynchronization caused by the tumor. Of 300 of our patients with tumors, 98 per cent have shown an adjusted interaural difference (IT_5) of more than 0.2 millisecond. Five patients, all of whom had tumors smaller than 2 centimeters, had normal ABRs.

Prediction of Size of the Tumor. Large acoustic tumors press against the brain stem. If significant pressure is exerted on the auditory tracts in the brain stem, abnormalities in brain stem response are detectable when testing the opposite (nontumorous) ear. This effect is best detected by measuring the interval between waves III and V. Normally, this interval (T_{3-5}) will be 1.9 ± 0.1 milliseconds. A T_{5-3} of 2.1 to 2.8 milliseconds has been found on 71 per cent of

55 patients who had tumors larger than 3 centimeters. Thus, ABR audiometry may not only predict the presence of an acoustic tumor, but also the general size of the tumor. There is some indication that derived ABRs using the high-pass noise-masking technique can sometimes help predict whether the tumor is in the internal auditory meatus or in the pontine angle (Eggermont and Don, 1988).

Conductive Hearing Losses. One word of caution is in order. Conductive hearing impairments will produce shifts in latency that mimic those of an acoustic tumor. Standard audiometric tests to rule out conductive losses should first be performed. There have been efforts over the last several years to record ABRs using bone-conducted signals to assess the extent of the conductive impairment. The techniques and interpretation are still problematic, but useful clinical information from such recordings has been reported. Further research is still needed.

Current Use of ABR Audiometry in Neuro-Otologic Evaluation

Our routine evaluation of a patient suspected to have a tumor includes (1) x-rays of the petrous pyramid, and (2) ABR audiometry. If the x-rays show definite enlargement of the internal auditory canal on the suspect side or if the ABR is abnormal, a definitive study is obtained. Recently, we have used magnetic resonance imaging (MRI) as our primary definitive test for the diagnosis of tumors. If MRI is not available, computerized cranial tomography (CCT) with an intravenous contrast medium is used. If the intravenously enhanced CCT is normal, air-contrast CCT is necessary to exclude a small acoustic neurinoma. Occasionally, small-dose Pantopaque study is necessary, when air-contrast CCT is not diagnostic.

Nonacoustic Tumors of the Cerebellopontine Angle

Twenty-eight patients with tumors of the cerebellopontine angle (not acoustic tumors) have been studied using ABR audiometry. ABR audiometry has identified the tumor in cases in which there has been pressure on the cochlear nerve. Because some nonacoustic lesions of the angle do not produce pressure on the cochlear nerve, the rate of detection for nonacoustic tumors is not as good as that for acoustic neurinomas (Table 4).

Table 4. Rate of Detection for Nonacoustic Tumors of the Cerebellopontine Angle (28 patients)

Wave V - absent or delayed	75%
Wave V - normal	25%

3 of 10 meningiomas
1 of 5 cholesteatomas
2 of 4 neurinomas of the facial nerve arachnoid cyst.

Diagnosis of Lesions of the Brain Stem

ABR audiometry is of distinct value in the diagnosis and localization of lesions of the brain stem. Intra-axial pontine masses that impinge on the auditory tracts produce loss in ABRs. The level of the mass can be predicted on the basis of the presence or absence of succeeding ABRs (Starr and Achor, 1975).

A number of studies have demonstrated that patients with multiple sclerosis often have abnormal ABRs (Keith and Jacobsen, 1985). For example, there are claims that absence of ABRs is an early indication of multiple sclerosis in a large percentage of those patients (Parker and Thornton, 1978). Lesions in the auditory tract produce desynchronization of the responses, which makes then nondetectable, despite the presence of normal audiometric results for pure tones and speech, in many cases. It should be remembered that a given abnormality in the ABR is often found in many types of neuropathies, such that a particular neuropathy cannot usually be diagnosed from the abnormality in the ABR alone.

Cortical Electric Response Audiometry

At the present time we are not using the cortical responses in our clinical practice. Nevertheless, a brief review of possible clinical application of these potentials is presented.

Slow and Late Potentials

Initially, the vertex potentials were explored for use in determining thresholds. Some reasons for recording these potentials are: (1) they represent activity of higher central levels and therefore are apt to reflect more of the "hearing process"; (2) stimuli that are more frequency-specific than clicks (eg, tone-bursts) can be used to elicit a response; and (3) the responses are relatively large and require only a small number of trials.

After several years of research and application, however, it was evident that vertex potentials do not result in accurate determinations of thresholds. They seem to correlate well with the audiogram (within 10 dB of threshold) in waking adults, but they are affected by the patient's physiologic state and by medications and anesthesia. More important, these responses are not reliable in children, the population most in need of an electric response audiometric technique. In general, the slow and late cortical potentials may be reliable in waking adults; in children, these responses are unreliable either because they vary or, as with "expectation waves", they require some behavioral interaction. Thus, these responses can occasionally be used for gross testing, but must be interpreted with great caution.

Middle Components

After the slow and late cortical responses lost their appear, electric responses in the range of 12 to 50 milliseconds began to be examined. These middle-latency responses (MLRs) were thought to be more stable than the slow and late cortical responses and were considered better for predicting thresholds of various frequencies when using clicks and filtered tone-pips (Davis, 1976). The long latencies of the MLR components do not generally allow rates of stimulation greater than 10 per second. Over the past few years, a special way of recording MLRs has developed. It involves presenting the stimuli at a faster rate, nearly 40 per second. At this rate, the MLR to one stimulus is not complete before the next stimulus arrives; but the spacing of the stimuli is such that an early wave component of the MLR to a succeeding stimulus coincides with a late wave of the MLR to the previous stimulus. This superimposition of two response components results in a component of large amplitude in the resultant recording, which is called the 40-Hz response (Galambos et al, 1981). Recent studies of this middle-latency 40-Hz response indicate that, like the late and slow responses, it is sensitive to the state of the subject (Shallop and Osterhamel, 1983). Thus, estimation of thresholds in sedated children through the use of MLRs is problematic.

Another major disadvantage of responses in this middle time domain is contamination by myogenic responses. For testing thresholds, whether the response is myogenic or neurogenic may be irrelevant as long as both responses are mediated by the auditory pathway. At high levels of stimulation, however, some of these myogenic responses from the muscles of the scalp are thought to be mediated by other portions of the labyrinth. Because of the difficulty of recording these later responses, the earlier brain stem responses recorded at the surface are of much greater clinical usefulness.

Summary

Electric response audiometry is an exciting new development with broad implications in the fields of otology, audiology, and neurology. At the present time, it is the best objective audiometric test for predicting hearing thresholds in infants or uncooperative patients. Electrocochleography offers a means for study of the function of the inner ear and for differentiation of types of sensorineural hearing impairment. Auditory brain stem response audiometry is a valuable addition to the battery of audiologic tests for the diagnosis of acoustic tumors. It also offers a means of studying brain stem function in a variety of neurologic disorders.