

Chapter 148: Auditory Function Tests

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The audiologic assessment of patients depends on the clinical question being asked and on the characteristics of individual patients. For example, the hearing of most adults and of children with a developmental age of at least 6 to 8 months may be assessed successfully by the use of behavioral test techniques. In younger children and some patients with additional handicaps, objective measures such as an auditory brainstem response (ABR) assessment can be used to estimate audiometric thresholds. This means that the auditory sensitivity of any patient can be assessed as long as appropriate procedures are used. In addition to the basic audiologic tests, a variety of special diagnostic procedures are designed to assess site of lesion and/or functional integrity of various portions of the auditory system. The link between structure and function is sufficiently strong that audiologic test results often may alert the otolaryngologist to the need for further assessments (eg, radiologic studies, neurologic assessment). This chapter is intended to provide an overview of current audiologic procedures and to describe how these test data might be useful to the otolaryngologist whose practice includes both children and adults.

Identification of Hearing Loss

Audiogram

The audiogram is a grid that plots frequency on the X axis or abscissa and hearing level on the Y axis or ordinate. The typical frequency range is from 250 to 8000 Hz, with vertical lines denoting octave and some half-octave frequencies. Hearing level (HL) is listed in decibels (dB) and is based on national standards appropriate for the test measurement. That is, there are standards for supraaural earphones and different standards for bone vibrators (in reference-equivalent force levels), depending on whether the vibrator is placed on the forehead or on the mastoid process. Thresholds occasionally are measured for frequency above 8000 Hz, especially in an attempt to identify potential ototoxic effects during certain drug therapies. These thresholds, however, are not typically plotted on a standard audiogram form.

An example of the standard audiogram form is given in Fig. 148-1, and the set of symbols that is commonly used to record thresholds is shown in Fig. 148-2 (American Speech-Language-Hearing Association, 1990). The appropriate symbol is recorded on the form at the intersection of frequency and the measured threshold. If no response is observed, an arrow pointing down at a 45-degree angle is plotted at the limits of the instrumentation. The most commonly used symbols are those that describe air and bone conduction thresholds, but other symbols are often used to describe such things as threshold measured in the sound field or acoustic reflex thresholds.

Air-conduction testing

Air-conducted signals generally are transduced by a supraaural earphone (eg, TDH-49), which is calibrated in a standard 6-cm³ coupler (NBS-9A). For certain test populations, however, alternative transducers are needed. For example, test signals may be presented in the sound field via a loudspeaker when testing young children who will not tolerate earphones. Although there is no ANSI standard for sound field calibration, published values are available for normal reference threshold levels (Morgan et al, 1979; Walker et al, 1984). When these values are applied, sound field thresholds should agree with earphone thresholds expressed in dB HL. In some instances, insert earphones (eg, Etymotic ER-3A), which are calibrated in a standard 2-cm³ coupler (HA-2), may be used. Conversion values supplied by the manufacturer are used to provide threshold estimates equivalent to those obtained with TDH-39 or TDH-49 earphones. These insert earphones have been found to be useful in cases of artifactual hearing loss caused by occlusion from collapse of the external auditory meatus under the pressure of a supraaural earphone cushion (Killion, 1984) and have been shown to provide a substantial increase in interaural attenuation of air-conducted signals when testing patients with maximum conductive hearing loss (Killion et al, 1985).

Bone-conduction testing

Bone-conducted signals are presented via a bone vibrator (eg, Radioear B-72), which should be couple to the head with a force of 550 g. Unlike air-conducted signals, a bone vibrator is calibrated by using an artificial mastoid (ANSI S3.26-1981). For clinical testing the vibrator is most commonly placed on the mastoid bone.

Because of clinical test-retest reliability, differences in calibration procedures, and error tolerances for air- and bone-conduction signals, air and bone conduction thresholds will not always agree in patients with normal middle-ear function. In some patients, optimal placement of the bone vibrator may be difficult ue to skull shape or prior operations, which can elevate bone-conduction thresholds. In the low-frequencies (250 and 500 Hz), supraaural earphones may not fit adequately in some patients and air conduction thresholds will be elevated at these frequencies, leading to the incorrect conclusion that a low-frequency conductive hearing loss is present.

Interpretation of results

Type and degree of hearing loss are based on an interpretation of thresholds as a function of frequency for different stimulus conditions. These interpretations typically are straightforward. If air and bone conduction thresholds are within normal limits and similar, as shown in Fig. 148-3, A, then hearing is normal. If air conduction thresholds are poorer than bone conduction thresholds, as shown in Fig. 148-3, B, then a conductive hearing loss is present. This is true even when air-conduction thresholds are at least 10 dB better. If both air- and bone-conduction thresholds are symmetrically elevated, then a sensorineural hearing loss exists. An example of this type of loss is shown in Fig. 148-3, C. If both of these threshold measures are elevate but air conduction thresholds are worse, a mixed hearing loss, including both conductive an sensorineural components, is present. A mixed hearing loss is shown in Fig. 148-3, D.

The importance of understanding the meanings of different audiometric symbols is particularly clear when one considers conditions when no response is observed. Specifically, it is important to recognize that a notation of "no response" does not mean no hearing. "No response" only indicates that no response was observed at the highest level that could be produced within the limits of the instrument used. This upper limit depends on many factors, including the audiometer, the transducer, and the frequency being tested. An example might make this point clearer. Consider a child with a flat hearing loss of 100 dB HL by air conduction with concomitant middle ear dysfunction. In this case, it might be difficult to identify either the presence or magnitude of the conductive component because bone conduction has a lower maximum output than air conduction. Of course, acoustic immittance measurements and physical examination of the ear would alert the otolaryngologist to the presence of middle ear dysfunction. Still, one must understand the meaning of different symbol notations to correctly interpret audiograms.

Finally, magnitude of hearing loss is represented by the extent to which thresholds exceed the normal range. It generally is described that up to 25 dB HL represents normal limits, 25 to 45 dB HL represents mild hearing loss, 40 to 65 dB represents moderate hearing loss, 66 to 85 dB represents severe hearing loss, and losses greater than 85 dB are considered profound.

Fig. 148-4 illustrates how the audibility of average conversation can be affected by a hearing loss. In this case, the patient demonstrates a hearing loss that slopes from near normal in the low frequencies to severe in the high frequencies. The superimposed speech sounds were taken from Nerbonne and Schow (1980) and represent the frequency and intensity at which these sounds occur in average conversation. Some sounds are represented at a number of different places, reflecting the fact that individual speech sounds have energy at more than one frequency. In this example, the low-frequency components of speech are heard at a near-normal sensation level (25-30 dB SL), but the high-frequency sounds occur near or below threshold. This individual will miss many of the consonants of speech and, when listening in noise, the audibility of even the low-frequency speech sounds may be reduced. In counseling the hearing-impaired patient, an overlay with the speech spectrum information shown in Fig. 148-4 can be extremely helpful in explaining the consequences of peripheral hearing loss.

Test techniques

Adults

The test technique used with adults are straightforward, generally requiring a hand-raise or button-push response. For elderly patients, the instructional set may need to be altered and the allowable response time may be lengthened. A psychophysical method of limits is the clinical procedure used most commonly. In this procedure, signal level is decreased in 10-dB steps until the signal is inaudible. Signal level then is increased in 5-dB steps until a response occurs. Threshold is defined as the minimum level at which a response occurs in at least 50% of a series of ascending trials (ANSI, 1978).

Children and special populations

Behavioral tests

Behavioral observation audiometry (BOA). For children who have a developmental age of less than 5 to 6 months, it generally is not possible to use operant conditioning techniques to assess auditory function. Historically, BOA has been used to "informally" evaluate these patients. Various signals (eg, noisemakers or calibrated signals presented in the sound field) are introduced and the infant's behavior is observed. Responses include reflexive activity (eg, Moro reflex), eye widening, onset or cessation of crying, or other types of changes in state. Attempts have been made to increase the objectivity of BOA by monitoring changes in infant activity via sensors in the base of an infant crib (Crib-o-gram) (Simmons et al, 1979). Newer techniques (ABR) now has replaced this technique and BOA generally is not recommended for the following reasons: (1) responses can only be observed at relatively high signal levels, thus being insensitive to mild-moderate hearing loss; (2) responses are dependent on patient state; (3) accuracy is subject to examiner bias and experience; (4) the most robust responses will occur to broad-spectrum signals, which do not provide frequency-specific information; (5) the test technique cannot provide individual ear information; and (6) large inter-subject variability makes it difficult to establish meaningful norms using this technique. Although BOA should not be used to rule out significant hearing loss, it may be a useful adjunct to more objective measures on a long-term basis when dealing with multiply handicapped or neurologically impaired children.

Visual reinforcement audiometry (VRA). An operant condition technique known as VRA (Liden and Kankunen, 1969) is the most commonly used test procedure for children in the 6- to 24-month age range (Thompson and Wilson, 1984). Signals generally are presented in the sound field and may be either broadband (eg, speech, music) or frequency specific. The child is seated on the parent's lap and a second examiner maintains the child's attention at midline with interesting toys. With this technique, a head-turn response toward the sound source is reinforced by illuminating and/or animating a toy that is located at eye level near the loudspeaker. When signals are presented in the sound field, test results reflect hearing in the "better ear" only. For some cooperative children, it also is possible to use VRA with either test signals or masking noise presented via supraaural or insert earphones. In this way, behavioral thresholds may be obtained for each ear independently. Because this latter procedure is time consuming and may require repeated visits because of habituation and the child's limited attention span, individual ear information often is obtained only in cases where knowledge of asymmetric thresholds may be important for management (known hearing loss, head trauma, significant visual impairment, preoperative audiologic assessment).

In spite of a variety of potential problems such as habituation, false-positive responses, and examiner bias, behavioral thresholds obtained using VRA have been shown to agree with adult values within approximately 10 dB (Moore et al, 1976).

Conditioned play audiometry (CPA). By the age of 24 to 29 months, approximately 70% of children can be evaluated by CPA (Thompson and Weber, 1974). The child is required to perform a simple motor task (eg, dropping blocks into a bucket) in response to auditory signals. Testing can be performed either with a second examiner in the test room or by using a portable audiometer. In the latter case, flexibility is compromised because the child must accept earphones and speech testing cannot be performed easily. By this age, social reinforcement generally is adequate to keep the child involved in the task long enough to obtain pure tone air and bone conduction thresholds. There are some variants of this procedure that have been developed. Lloyd et al (1968) described a technique for use with difficult-to-test patients known as "tangible reinforcement operant conditioning audiometry" (TROCA). With this procedure, tangible reinforcers such as cereal, candy, or small toys are used in conjunction with social reinforcement. This procedure may require a lengthy conditioning period, and it may be difficult to find motivating reinforcers for some children. More recently, a variety of computer graphics have been used as reinforcers for CPA. This approach allows for rapid changes in reinforcers, thus making the task more interesting to the child, particularly if the evaluation is lengthy.

Conventional audiometry. By the time a child is at a developmental age of 42 to 48 months, they can often perform the test techniques used with adults with little difficulty. The instructional set may need to be altered and social reinforcement continues to be important.

Objective tests. Previous sections of this chapter described the use of behavioral hearing tests with young children. Although successful with cooperative and developmentally normal children as young as 6 months of age, these techniques are not appropriate for many individuals at risk for hearing loss, including newborn, multiply handicapped, and developmentally delayed patients. As a consequence, techniques have been developed that attempt to circumvent the special problems associated with the audiologic evaluation of these difficult-to-test patients.

Auditory brainstem response (ABR) test. The ABR, which represents the sum of synchronous neural discharges from lower portions of the auditory nervous system, is the most accurate and sensitive objective test of hearing loss in difficult-to-test patients. Other evoked potential techniques, such as the middle latency response or the 40-Hz potential will not be discussed here because they have not yet proven to be reliable indicators of peripheral hearing loss in young children as used in a typical clinical environment.

The most robust component of the response is wave V, and the lowest level at which this response can be measured will be used to predict auditory sensitivity. Further information about ABR recording techniques and waveforms will be described in conjunction with a description of its use in the neuro-otologic assessment.

The particular stimulus used to elicit the ABR strongly influences what can be said regarding hearing sensitivity. Although some disagreement exists, the general view is that click-evoked ABR thresholds correlate best with behavioral thresholds at 2000 and 4000 Hz (Gorga et al, 1985b; Jerger and Mauldin, 1978; van der Drift et al, 1987). Our own data also suggest that a relationship exists between the slope of the wave V latency-intensity function and configuration of hearing loss (Gorga et al, 1985a and b). Patients with high-frequency losses often have steep latency-intensity functions whereas patients with flat losses tend to

have more shallow functions. We attribute these effects to an interaction between stimulus intensity and the place of excitation along the basilar membrane that dominates the response. With mild-to-moderate high-frequency hearing loss, intense stimuli still can excite basal regions of the cochlea. Because latency is related to place of excitation, the latency of response may be normal or near normal under these circumstances. As level decreases, however, the response may not be as dominated by these high-frequency regions as it is in normal ears. Thus response latency might be abnormally long at low stimulus levels because of larger contribution from low-frequency regions and because it takes longer to reach the low-frequency places of representation in the cochlea. The resulting wave V latency-intensity function, therefore, would have a steeper-than-normal slope.

Although the click-evoked ABR correlates best with high-frequency sensitivity, there are reports that, under appropriate stimulus conditions, information can be obtained from a range of different frequencies. For example, Don et al (1979) reported on the use of the derived band technique for obtaining estimates of hearing at octave frequencies from 500 to 4000 Hz. Gorga et al (1987a, 1988b) reported on obtaining ABRs to frequencies ranging from 250 to 16,000 Hz, using tone burst stimuli. Stapells et al (1990) recently reported on the relation between pure-tone hearing sensitivity and tone burst ABR thresholds when the tone bursts were embedded in notched noise. All of these reports suggest that although some special conditions may need to be met when attempting to predict the pure-tone audiogram, it appears that a variety of different techniques can achieve this goal successfully.

The application of ABRs to predict hearing loss in multiply handicapped patients also has been demonstrated (Stein and Kraus, 1985). These patients may be particularly difficult to test using behavioral test techniques but are more likely to have hearing loss. The performance of ABR tests during sedation-induced sleep has demonstrated that these techniques will provide reliable information on auditory sensitivity for these patients.

Another special application of the ABR test is with infants who are at risk for hearing loss, such as those who meet any of the high-risk criteria and/or those infants who have spent a significant period of time in the intensive care nursery (Durieux-Smith et al, 1985; Galambos and Despland, 1980; Galambos et al, 1984; Gorga et al, 1987b). Although some reports suggest extremely high failure rates among these patients (Roberts et al, 1982; Shimizu et al, 1985), failure rates of 10% to 15% are more typical and values less than 5% have been reported (Gorga et al, 1988a; Schulman-Galambos and Galambos, 1979).

Test techniques are available that enable us to test the auditory sensitivity of any patient, regardless of developmental level or cognitive skills. If a patient provides reliable test information using behavioral test techniques, then the use of objective tests, such as the ABR, is obviated. On the other hand, any patient who is unable or unwilling to provide reliable behavioral test data can be tested for hearing loss using ABR techniques.

Otoacoustic emissions (OAE). In 1978, Kemp showed that, when stimulated, the normal ear emits sound (Kemp, 1978). These emitted sounds can be measured in the ear canal with sensitive microphones, appropriate stimulus paradigms, and signal averaging. The fact that these responses are present in normal ears but absent in ears with significant hearing loss has led to the application of these techniques to the problem of identification and diagnosis of hearing loss (Kemp et al, 1986; Kemp et al, 1990; Lonsbury-Martin and Martin, 1990; and Lonsbury-Martin et al, 1990).

There are two general classes of OAEs: spontaneous and evoked. Spontaneous OAEs are present in about 50% of normal hearing ears. Their presence does not appear to be strongly related to the percept of tinnitus. Given these two facts, the clinical applicability of spontaneous OAEs remains extremely limited.

There are three types of evoked OAEs: transient, stimulus frequency, and distortion product. Of these, stimulus frequency OAEs are technically the most difficult to extract from the stimulus waveform and have not received much attention in terms of clinical problems. In contrast, both transient and distortion product OAEs have been shown to be present in the majority of normally hearing subjects, absent in the majority of patients with hearing loss, and easily measured in relatively short periods of time. Although large clinical databases have not yet been developed, it appears that these test techniques will provide considerable information regarding the integrity of the peripheral auditory system, primarily the outer hair cell system. They may be particularly useful in neonatal screening because responses tend to be larger in the newborn ear and they can be measured within a very short period of time (Bonfils and Pujol, 1988; Bonfils et al, 1988; Kemp et al, 1990; Norton and Widen, 1990; Stevens et al, 1990).

Tests of Speech Perception Ability

Tests of speech perception are critical to the evaluation of auditory function. These tests can be divided into two categories: threshold and suprathreshold measures. As will be described below, the particular test used will depend both on the developmental/language level of the patient as well as the specific purpose of the assessment.

Threshold tests

The speech reception threshold (SRT) is defined as the lowest level at which a listener can identify correctly 50% of test items from a set of two-syllable words (spondees). The spondaic words used for this test are highly familiar and are produced with equal stress on each syllable (eg, cowboy, hotdog). A psychophysical procedure similar to that used for pure-tone testing generally is used to establish the SRT. Adults are expected simply to repeat the test item; a closed-set, picture-pointing task can be used for children as young as 18 to 24 months. For younger children or individuals who are developmentally delayed, a speech awareness threshold (SAT) or speech detection threshold (SDT) can provide similar information. The SAT is the lowest level at which 50% of test items can be *detected* (as opposed to *identified*).

In clinical practice, the primary purpose of the SRT or SAT is to corroborate the pure-tone thresholds. The audiometric calibration of speech signals allows these measures to be related to pure-tone thresholds expressed in dB HL and the relation between pure-tone thresholds and the SRT is well understood (Harris et al, 1956). The SDT (or SAT) generally will be 5 to 6 dB lower than the SRT. The SRT should agree with the three-frequency (500, 1000, and 2000 Hz) pure-tone average (PTA) within 5 to 6 dB (Hodgson, 1980). In the case of sloping hearing loss, however, a two-frequency average sometimes is used. A difference of 12 dB or more between the SRT and PTA would suggest that the pure-tone thresholds may not be valid.

Suprathreshold tests

Purpose and limitations

Historically, clinical tests of suprathreshold speech recognition ability have been used for a variety of purposes: (1) to provide an estimate of functional performance in everyday listening situations, (2) to monitor potential changes in speech perception over time, (3) to compare the ability to perceive speech processed by a variety of different hearing aids, and (4) to distinguish between cochlear and retrocochlear site of lesion. The test materials and methodology used in a particular case will depend on the purpose of the measurement. In addition, many factors (ie, presentation level, word familiarity, mode of presentation, type of competing signals, etc) will influence performance on speech perception tests.

Regardless of the test being used, the presentation level will have marked influence on performance. Fig. 148-5 illustrates how the percentage of words correctly identified will depend on signal level. Idealized performance-intensity (PI) functions are shown for a variety of test materials. Here, spondees show the steepest PI function, denoting that small changes in intensity will produce a large improvement in performance. The term PBmax is used to denote the maximum performance for a given set of speech materials that are phonetically balanced. Sentence materials have a PI function similar to that of spondees. The PI function is less steep for monosyllabic words and will become increasingly shallow as the test materials become more difficult. For certain pathologic conditions (eg, retrocochlear lesion), performance may actually decrease below PBmax at high intensities (Bess et al, 1979; Jerger and Jerger, 1971). It should be clear from this figure that, in order to ensure that maximum performance has been achieved for a given individual, it will be necessary to assess performance over a range of intensities. In clinical practice, it is customary to use a presentation level that is 40 dB above the patient's SRT unless the hearing loss is steeply sloping in configuraion. In those cases, the level should be elevated to ensure that the speech energy is audible at 2000 Hz if possible.

In clinical practice it is often desirable to compare the scores obtained across test conditions, across ears, or with previous test results. Thus it is important that any test of speech recognition yield good test-retest reliability. When scores are expressed as a percentage, the reliability of a given test score is dependent, in part, on the absolute score (Egan, 1948). The variability is greatest in the middle range of test scores and lowest at the two extremes of the scale. In order to determine if two scores are significantly different from one another, one needs to consider the number of test items, the absolute scores, and the confidence level used to interpret results. Table 148-1 illustrates the critical differences

needed for monosyllabic word lists with 25 and 50 entries at a 95% confidence level (Thornton and Raffin, 1978). For example, using a 25-word list, a score of 48% would not be significantly different from a score of 24% or 72% (a range of $\pm 24\%$). At either extreme of the continuum, however, the critical differences are substantially smaller and increasing the number of test items reduces the variability. It is important to understand the clinical implications of the relations shown in Table 148-1. Given the variability inherent in speech recognition testing, attempts to compare scores across various conditions must be approached with caution. It also should be pointed out that it is not possible to compare the scores across different types of tests directly. In fact, the same test items produced by male and female speakers have been shown to produce mean differences in performance of 15% to 20%, depending on signal level (Wilson et al, 1990).

Adult materials

A wide variety of materials have been developed ranging from nonsense syllables to sentence-length materials. For a comprehensive review of suprathreshold speech perception tests, see Bess (1983). The following section will review only the most commonly used tests.

Monosyllabic word tests. The most commonly used tests of suprathreshold speech recognition ability are phonetically balanced word lists such as the CID W-22 word list (Hirsch et al, 1952) or the NU-6 lists (Lehiste and Peterson, 1959). Each list is made up of speech sounds whose occurrence in the lists is proportional to their occurrence in everyday English speech. Test reliability can be maximized by the use of complete (50-word) lists and pre-recorded materials on either audio tape, compact disk, or digitized speech played back through a D/A converter. Test reliability and validity is compromised severely by the use of monitored live-voice presentation (Brady, 1966; Thornton and Raffin, 1978).

Alternative tests have been constructed for use with certain populations. The California Consonant Test (CCT), developed by Owens and Schubert (1977), has been standardized on hearing-impaired listeners. The test is composed of 100 monosyllabic words presented in a four-choice closed-set format. This test has been shown to be sensitive to the difficulties in phoneme recognition often found in listeners with high-frequency sensorineural hearing loss (Schwartz and Surr, 1979).

Although performance in everyday conversation is undoubtedly correlated with one's ability to perceive single words, it is clear that these types of tests cannot be used to predict the communication difficulty a listener may have outside the test environment. Factors such as the listening environment, the listener's linguistic abilities, and speech-reading abilities all play a role in determining communication skills.

Sentence tests. Although sentence-length materials may have more face validity and thus be a better indicator of everyday performance, they are not used routinely in most clinics. Kalikow et al (1977) developed an alternate approach to the prediction of everyday performance. Their Speech Perception in Noise (SPIN) Test is comprised of equal numbers of both high-probability (PH) and low-probability (PL) sentences. Each list consists of 50 sentences and scoring is based only on the key word, which occurs at the end of each sentence. An example of a PH sentence is, "She made the bed with clean *sheets*." Alternatively, an LH sentence would not contain contextual clues ("We're discussing the

sheets"). A comparison between scores on PH and PL items can yield an estimate of how the listener uses linguistic information to supplement the acoustic information available.

The Synthetic Sentence Identification Test (SSI) developed by Speaks and Jerger (1965) is perhaps the most commonly used sentence test. This closed-set test is comprised of 10 seven-word nonsense sentences and is usually presented in a background of noise. The sentences are described as third-order approximation to English in that they diverge from the standard rules of grammar and syntax (eg, "small boat with a picture has become"). Scoring is based on the number of sentences identified correctly.

Children's materials

When assessing speech perception ability in young children, both the type of speech materials used and the mode of test administration will depend on the linguistic level of the child. For young children, the results of speech perception tests can yield information not only about the auditory system but also about the language level of the child. For example, if a 3-year-old child who hears normally cannot identify familiar pictures accurately, a referral for a speech / language evaluation may be warranted.

A closed-set picture-pointing format is the most appropriate option for young children. The two most commonly used tests at the present time are the Word Intelligibility by Picture Identification Test (WIPI) and the Northwestern University Children's Speech Perception Test (NU-CHIPS). The WIPI (Ross and Lerman, 1970) consists of 25 test items in a six-item multiple-choice format. The test items are monosyllabic words (eg, ball, boat) and the test is appropriate for children in the 4- to 6-year age range. The NU-CHIPS test (Katz and Elliott, 1978) consists of 50 test items in a four-choice format. This test has been normalized on hearing-impaired children and is appropriate for children as young as 2.8 years of age. A relatively large number of tests have been developed for use on children and many of these are commercially available. For a comprehensive review of children's speech perception tests see Bess (1983).

Central auditory tests

The speech recognition tests discussed previously are intended to assess the function of the peripheral auditory system, including the cochlea and the primary auditory neurons. The accurate coding of acoustic information, however, involves a variety of complex processes within the central auditory nervous system (CANS). In order for acoustic information to be represented accurately at the highest level of the CANS, the peripheral auditory system, brainstem, ascending auditory pathways and subcortical centers, interhemispheric connections, and the auditory cortex must be functioning properly. If the system is not functioning properly, difficulties in attention, recall, and processing of speech in quiet or in noise may occur even though performance on pure-tone tests and standard speech perception tests is within normal limits.

The current approach to assessment of central auditory function is based on the assumption that various levels of the CANS serve specific functions. A wide range of tests have been developed to assess the functional integrity of a particular level of the CANS. At present, CANS testing is not routine in most audiologic clinics. There are a number of factors that limit the clinical utility of these tests. Most tests tend to be time-consuming and the tasks can be quite complicated, generally involving competing signals or some form of degraded speech. As such, performance on these tests can be complicated by language level, attention span, and the age appropriateness of the task, thus limiting their utility with young children and elderly patients. In cases where a peripheral hearing loss also exists, the interpretation of test results is difficult. Finally, very little work in this area has been validated radiologically, surgically, histologically, and the reliability of specific tests with various classes of patients has not been investigated thoroughly. Nevertheless, work in this area continues. It is beyond the scope of this paper to review the vast body of literature on this topic. For a review of central auditory tests see Musiek (1984, 1985), Beasley and Rintelmann (1979), Noffsinger and Kurdziel (1979), and Sloan (1985).

Acoustic Immittance Measures

Although routine pure-tone air-conduction and bone-conduction measures can be used to identify and quantify the magnitude of a conductive component, they generally do not yield information about the nature of middle ear pathology. Acoustic immittance measures provide information about middle ear function that often cannot be derived without invasive measures. The currently available measurement systems are relatively inexpensive, easily tolerated by most patients, fast, and require no behavioral response. As a result, immittance measures have become a routine and indispensable part of the clinical audiologic battery.

Equipment and method

The middle ear system is not a perfect transducer of energy and thus will offer some opposition to the flow of energy. This opposition is known as *acoustic impedance* (ZA). Alternatively, the flow of energy through the middle ear is known as *acoustic admittance* (YA). *Acoustic immittance* is a term used to describe the transfer of acoustic energy through the middle ear system, regardless of whether the measurement is made in terms of impedance or admittance. A simplified block diagram of an acoustic immittance measurement system is shown in Fig. 148-6. The sound delivery and measurement system is coupled hermetically to the ear canal via a flexible rubber cuff. A known acoustic signal is introduced to the ear and the SPL in the ear canal is measured under various conditions. This SPL is taken as an indirect measure of acoustic immittance. For an overview of the basic principles of acoustic immittance see Wiley and Block (1985).

Test battery

The clinical acoustic immittance battery consists of a wide variety of tests intended to assess the integrity and function of the middle ear as well as the afferent portion of CN VIII and part of the motor portion of CN VII.

Tympanometry

Tympanometry is the most commonly used test in the acoustic immittance battery. A tympanogram is a graphic representation of how the immittance of the middle ear is altered by changes in air pressure in the ear canal. Tympanometry yields information about resting middle ear pressure (tympanometric peak pressure) and is helpful in identifying both low-impedance (eg, ossicular disarticulation, tympanic membrane scarring) and high-impedance (eg, otosclerosis, otitis media). Until relatively recently, most acoustic immittance devices allowed measurements at only one or two probe frequencies (usually 226 and 678 Hz). The vast body of data relating various tympanometric patterns to specific pathologic conditions is based on measures at these two frequencies. The clinical utility of multifrequency tympanometry currently is under investigation and is yet to be established (Lilly, 1984; Margolis et al, 1985; Shanks et al, 1987). Several schemes for classifying and interpreting tympanograms have been suggested. The most common scheme, developed by Liden (1969) and later modified (Jerger, 1970; Jerger et al, 1972; Liden et al, 1974), is shown in Fig. 148-7. Type A is a normal tympanogram with peak pressure at or near 0 daPa. Type As is a shallow tympanogram with normal peak pressure and may be indicative of ossicular fixation or certain types of middle ear effusion. Type AD also has normal peak pressure but an unusually high amplitude, suggestive of tympanic membrane anomalies or a possible ossicular disarticulation. A Type B tympanogram is flat and is indicative of middle ear effusion or cholesteatoma if impacted cerumen, tympanic membrane perforation, and/or an improperly placed probe have been ruled out. A Type C tympanogram is characterized by a negative peak pressure and suggests eustachian tube dysfunction. A type D tympanogram is consistent with tympanic membrane anomalies or a possible disarticulation of the ossicular chain. This classification is appropriate only for single component systems that use a low-frequency probe tone. Vanhuysse et al (1975) have proposed a more complicated classification system that considers both the reactance and resistance components of immittance. Attempts also have been made to quantify the tympanometric shape in the region of the peak (Brooks, 1969; Liden et al, 1974). The clinical utility of various measures of tympanometric gradient has been investigated, and gradient appears to be a good indicator of middle ear effusion (de Jonge, 1986; Koebse and Margolis, 1986; Shanks and Wilson, 1986). Using the measurement scheme described by Liden et al (1974), Margolis and Heller (1987) reported the mean normal values and 90% ranges shown in Table 148-2. Abnormally wide tympanometric widths are suggestive of middle ear effusion.

Regardless of the classification system used, there will always be patterns that do not fit well-defined criteria and will be difficult to interpret. In addition, the relationship between tympanometry and middle ear dysfunction is extremely complex. For example, tympanometry with a low-frequency probe tone has not been shown to be extremely sensitive to ossicular fixation (Margolis and Shanks, 1985). Tympanometric shape is influenced greatly by abnormalities of the tympanic membrane and these anomalies may dominate the pattern, thus making it difficult to diagnose pathologic processes medial to the tympanic membrane. Tympanometry in infants under the age of 6 to 7 months also has been found to have a high false-negative rate (Paradise et al, 1976), possibly because of the complex interaction between the properties of the external and middle ears. Therefore, when possible, tympanometric results should be viewed within the context of the entire clinical picture.

Equivalent volume measures

An equivalent volume measure of the external ear canal can be derived from the tympanogram. In ears with a tympanic membrane perforation or patent ventilating tube, this measure also will include the middle ear space and mastoid air cells. The test is performed by introducing either a high-negative or high-positive pressure (usually + 200 daPa) into the hermetically sealed ear canal, thus creating a rigid-walled cavity. In such a cavity, there is a predictable relation between cavity size and sound pressure level. Table 148-2 shows the mean and 90% range of normal equivalent volumes obtained with an ear canal pressure of + 200 daPa (Margolis and Heller, 1987). In adult ears with a tympanic membrane perforation (and normal middle ear mucosa), these values will increase by a factor of 2 or more. In young children, the increase is not as large and values greater than 1 cm³ (with a flat tympanogram) suggest a possible perforation. This test is particularly useful in diagnosing small perforations that may be missed otoscopically and in determining the patency of ventilation tubes, particularly in persons on whom pneumatic otoscopy may be difficult to perform. For young children, the preoperative equivalent ear canal volume always should be recorded for comparison with postoperative values. These two measurements will not differ in children as much as they will in adults.

Static acoustic immittance

Peak-compensated static acoustic immittance is a term used to refer to the height of the tympanogram relative to its tail. As such, this value also can be derived directly from the tympanogram. Although this information has not been used widely in clinical settings, it can provide important objective information that can be used in conjunction with tympanometric shape. These measures also allow for a direct comparison of data across clinics or across clinical instruments. The mean and 90% range of normal values are shown in Table 148-2 (Margolis and Heller, 1987).

Eustachian tube function tests

The purpose of eustachian tube function (ETF) testing is to assess the ventilatory capability of the eustachian tube in both passive and nonpassive states. The test requires a perforation of the tympanic membrane or patent ventilating tube.

In the passive ETF test, positive pressure is gradually applied to the ear until the eustachian tube opens spontaneously (usually at > 200 daPa). If the eustachian tube is completely obstructed, it usually will not open within the limits of the equipment and if it is abnormally patent, it will not be possible to pressurize the ear. This latter case can be difficult to distinguish from the failure to seal the external ear hermetically. If a seal can be obtained with *negative* pressure only, then a patulous eustachian tube should be suspected.

It also is possible to assess the function of the eustachian tube under more physiologically relevant conditions. Bluestone (1983) has suggested that the ear be pressurized to + 200 daPa (or less if necessary) and that the patient be asked to swallow five times. The remaining pressure is known as the *residual positive pressure*. The procedure is repeated with a - 200 daPa. According to Bluestone, both positive and negative pressures should be equilibrated in a normal ear. At present, both the test-retest reliability and the long-term

diagnostic significance of these tests have not been established.

Acoustic reflex measures

Although there are two middle ear muscles (tensor tympani and stapedius), in humans only the stapedius muscle contracts in response to sound. Contraction of the stapedius causes a change in the axis of rotation of the stapes footplate, thus increasing the immittance of the middle ear system. This change in conductivity through the middle ear can be measured indirectly as changes in acoustic immittance. The neural pathway includes CN VIII, the ventral cochlear nucleus, the trapezoid body, the medial superior olivary complex, the medial portion of the facial motor nucleus, and the stapedius muscle. When either ear is stimulated by a loud signal (70-90 dB HL), both the ipsilateral and contralateral stapedius muscles contract. Acoustic reflex tests are a very powerful clinical tool in that these measures can provide diagnostic information about CN VII and CN VIII function as well as the reflex pathways in the lower brainstem.

Testing is performed with the external ear canal pressure set to middle ear peak pressure and requires only passive cooperation from the patient. Measurements cannot be made in a very active or crying child or in the presence of a tympanic membrane perforation or patent tympanostomy tube. Stimulation may be either ipsilateral or contralateral to the ear which the responses are being measured (probe ear). For each ear, reflex thresholds can be measured ipsilaterally to assess the integrity of the uncrossed pathways and contralaterally to assess the crossed pathways, for a total of four test configurations. Stimuli may be pure tones, narrowbands of noise, or broadband noise. Reflex threshold is defined as the lowest stimulus level that elicits a time-locked change in acoustic immittance. For normal-hearing listeners, acoustic reflex thresholds in response to pure-tone stimuli occur between 70 and 100 dB HL for frequencies in the 500 to 2000 Hz range. The presence or absence of acoustic reflexes at 4000 Hz has not been found to be clinically significant. In the presence of even a mild conductive hearing loss, acoustic reflexes usually will be absent with the probe in the test ear. In patients with cochlear hearing loss, acoustic reflexes may be present at normal levels, present at elevated levels, or absent, depending on the degree of hearing loss. When the pure-tone thresholds exceed 75 dB HL, 90% of patients with cochlear hearing loss will not exhibit reflexes at any stimulus level (Silman and Gelfand, 1981). This information can be useful in identifying patients with nonorganic hearing loss; that is, if acoustic reflexes are present at level near or below the voluntary behavioral thresholds, a functional hearing loss should be suspected.

Test interpretation is based on the pattern observed across the four test conditions. Fig. 148-8 depicts some typical patterns. In panel A, reflexes are absent when the probe is coupled to the left ear. This pattern is consistent with a conductive problem in the left ear or a left CN VII disorder. Panel B illustrates the case where reflexes are absent when stimulating the left ear. This is consistent with a left cochlear or retrocochlear lesion. The pattern of acoustic reflexes as well as acoustic reflex decay measures are important parts of the site of lesion battery and are discussed in detail in the following section. In Panel C, reflexes are absent bilaterally only when the measurements involve the crossed pathways. Because reflexes are present in the uncrossed mode, both the afferent branch of CN VIII and the motor branch of CN VII must be intact. This pattern is suggestive of a brainstem disorder. Finally, Panel D illustrates an absent reflex when stimulating the right ear in the crossed mode only. This

pattern is extremely rare and also is suggestive of a brainstem lesion.

Historically, attempts have been made to use acoustic reflex measures to identify and quantify the magnitude of sensorineural hearing loss in young children for whom behavioral estimates of threshold could not be obtained (Popelka, 1981). Although this approach did appear to be promising in the mid-1970s, improved electrophysiologic techniques (eg, frequency-specific ABRs) have replaced this method.

Nonacoustic middle ear stimulation

Both the stapedius and tensor tympani muscles can be activated by nonacoustic stimulation such as electrical or cutaneous stimulation of specific regions of the head and neck. Transient changes in immittance time locked to the stimulus can be measured by using standard immittance devices. The primary advantage of the technique is that middle ear status can be evaluated independent of the degree of sensorineural hearing loss in the test ear. This information may be useful in the differential diagnosis in some cases, but results are often ambiguous or difficult to interpret and the techniques are not widely used clinically. For a detailed discussion of this subject see Djupesland (1976) and Fee (1981).

Special Tests for Site of Lesion

Many different tests have been used in an effort to distinguish between cochlear and neural abnormalities that affect the auditory system. In many ways technologic advances have obviated the need for many of the behavioral tests used in the past. However, the tests traditionally included in audiometric test batteries will be reviewed briefly, followed by a comparative analysis of their performance.

It is important to recognize that cochlear and neural abnormalities may occur concurrently, such as in the case of a patient with longstanding history of noise exposure and an acoustic neuroma. In addition, space-occupying lesions such as acoustic neuromas may cause cochlear damage by compromising the blood supply to the cochlea. Thus ambiguous results for some tests may occur because cochlear and neural abnormalities can exist concurrently. This possibility should be considered as one reviews the results presented in subsequent sections of this chapter.

Prior to site-of-lesion testing, basic audiometric data, such as air-conduction and bone-conduction pure-tone thresholds and tympanometry, should be obtained. This information is critical to the interpretation of special test results because peripheral hearing loss (conductive and/or cochlear) can affect results of tests designed to evaluate more central parts of the auditory pathway.

Speech tests

Speech recognition ability, which typically is assessed at suprathreshold levels, has been used to provide indications for dysfunction involving the central portions of the auditory pathway. Typically, a set of 25 to 50 monosyllabic words are presented either at one suprathreshold level, or using a number of suprathreshold levels, a performance intensity function is constructed. If the number of words correctly identified is less than 30%, dysfunction central to the cochlea is suggested (Penrod, 1985). An additional criterion includes a marked decrease in performance (known as *rollover*) at high presentation levels (Bess et al, 1979; Dirks et al, 1977; Jerger and Jerger, 1971). Diagnostic criteria are calculated by subtracting the minimum score (in percentage of correct identification) from the maximum score and dividing by the maximum score. If this ratio exceeds 0.45, the results are considered positive for neuropathy.

Tests of abnormal response growth and abnormal adaptation

Cochlear and neural disorders characteristically demonstrate fundamentally different patterns of response with increases in stimulus intensity. Typically, cochlear lesions are thought to produce an abnormally rapid growth of response with increases in intensity. As an example, pure tones or speech presented at only 20 dB above threshold to the ear of a hearing-impaired individual might be judged as comfortably loud, whereas sounds are judged comfortably loud by normal individuals at 40 to 60 dB above threshold. Similarly, very small increases in stimulus intensity may be easily detectable by patients with cochlear hearing loss. Compared to patients with either normal hearing or cochlear hearing loss, patients with neural abnormalities are thought to have abnormally rapid decay or adaptation in response to sustained stimuli. A signal that was easily audible immediately following stimulus onset might soon become inaudible because of adaptation.

A number of tests have been developed over the years to capitalize on these observations in order to separate hearing loss caused by lesions within the cochlea from those which have as their cause pathologic processes in the CN VIII or central auditory pathways in the brainstem. Several tests were usually administered as a site-of-lesion battery. Until recently, the principal tests in the battery were those that attempted to ascertain abnormal growth of loudness, such as the Short Increment Sensitivity Index (SISI), the Alternate Binaural Loudness Balance (ABLB), and the Bekesy test, and tests that sought to identify abnormally rapid decay in response to continuous sound, such as the Tone Decay Test and the Bekesy test. These tests are discussed in the previous edition of this text, but are not further considered here because, by and large, they have been replaced by acoustic reflex threshold and decay testing and auditory brainstem response testing.

Acoustic reflex thresholds and decay

Both acoustic reflex thresholds and acoustic reflex decay (ARD) have been used in the site-of-lesion test battery. Middle ear muscle responses also have been used in tests of facial nerve function; however, these applications are beyond the scope of a chapter devoted to tests of auditory function. Similarly, tests of facial nerve function, such as electroneuronography, will not be described under the section on electrophysiologic tests of auditory function.

If a hearing loss is purely cochlear and is no greater than moderate in magnitude, one would expect to see either normal or slightly elevated acoustic reflex thresholds. As a consequence, acoustic reflex thresholds occur at reduced sensation levels in relation to the pure-tone behavioral threshold (Metz, 1952). If the magnitude of the loss is severe, reflexes may be significantly elevated or absent, even for cases of cochlear lesions (Jerger et al, 1972). However, in the case of a retrocochlear lesion (eg, acoustic neuromas), reflexes may be unexpectedly elevated or absent, even though the magnitude of the hearing loss would not preclude a response (Jerger et al, 1974; Olsen et al, 1975).

In tests of acoustic reflex decay or adaptation (Anderson et al, 1969), a sustained stimulus is presented at a suprathreshold level (typically 10 dB SL) and the change in immittance is measured for 10 seconds. If the magnitude of the response decays by more than 50% in this interval, the test is considered positive for retrocochlear abnormality. Although this test theoretically can be performed for many different stimuli, the observation of decay at 2000 or 4000 Hz is not considered clinically significant (Givens and Seidemann, 1979). Thus the test typically is performed only at 500 and 1000 Hz.

Electrophysiologic tests of auditory function

There are many electrophysiologic tests of auditory function; these tests are thought to evaluate different levels within the auditory nervous system. Unfortunately, insufficient data currently exist for many of these tests, so it is not possible to describe their false-positive and false-negative rates for clinical populations. These problems tend to occur more frequently for tests that assess function of the highest levels of the central auditory system. Thus their value in the clinical assessment of auditory dysfunction is limited. It is hoped that future developments will lead to more sensitive tests of central auditory dysfunction because there is little doubt that disorders in these portions of the nervous system exist.

There are, however, two electrophysiologic tests that have proved to be both reliable and valid following many years of clinical use. Electrocochleography (ECochG) and Auditory Brainstem Response (ABR) measurements provide useful information about the status of peripheral portions of the auditory system up to and including the brainstem. These tests will be described in greater detail below. In the interest of brevity, only click stimulation will be considered. However, it is important to recognize that other stimuli can be used to elicit electrophysiologic responses; indeed, there are many clinical situations when these other stimuli have significant advantage over clicks.

Electrocochleography

The term *electrocochleography* refers to the measurement of electrical events generated either within the cochlea or by primary afferent neurons. Thus it includes measures of summing (SP) and cochlear microphonic (CM) potentials from the cochlea, and whole nerve or compound action potentials (AP) from the auditory nerve.

There are many different ways these potentials can be recorded. In the most invasive recording technique, a needle electrode is passed through the tympanic membrane and placed against the promontory. This electrode placement results in very robust and easily measured responses; however, it is not without risk, it requires that the tympanic membrane be anesthetized (typically using iontophoresis), and a physician is required to place the needle. In one variation on this procedure, needle electrodes are placed in the external ear canal wall. This placement results in smaller responses than those observed with transtympanic electrodes, but has virtually identical restrictions, such as requiring local anesthetic.

Over the years attempts have been made to record these potentials using noninvasive electrode placements. One of the first attempts to record these potentials from the ear canal used a leaf electrode designed by Coats (1974). This electrode has not been used widely because it can be very uncomfortable. Other electrode designs have been developed, and two versions are quite popular. The first, referred to as a *tympanic membrane (TM) electrode*, initially was described by Cullen et al (1972), and has since been modified (Durrant, 1972; Ferraro et al, 1986; and Lilly and Black, 1988). This electrode typically consists of a beaded, chlorided silver wire that has a wisp of rayon, cotton, or foam attached to the ball, which is placed against the tympanic membrane. Although reports vary, it appears that this electrode can be placed with relative ease and without discomfort, and even though its electrical impedance may be high, the recorded potentials usually are well formed and clearly identifiable.

Recently, an ear canal electrode has become available that is easy to place, comfortable, results in fairly low impedances, and increases the amplitude of the AP in relation to the values typically observed with earlobe and/or mastoid electrodes (Bauch and Olson, 1990). These "tip-trode" electrodes are used in conjunction with insert earphones (Etymotic ER-3A). Unfortunately, the responses measured with these earphones typically do not result in clear SP or CM, and may not increase AP amplitude sufficiently to make it measurable in cases of moderate or severe high-frequency hearing loss.

There are two applications of electrocochleographic measurements. In one application, measurements of SP and AP amplitudes are compared to determine if there is an abnormal ratio between these two potentials. In normal ears or ears with cochlear hearing loss unrelated to a pressure imbalance in the cochlea, the ratio of SP/AP amplitude typically is less than 0.30. In patients in acute symptomatic stages of endolymphatic hydrops, the amplitude of the SP increases in relation to the amplitude of AP, thus resulting in abnormally large SP/AP amplitude ratios. Although many investigators have reported the clinical utility of the test in the diagnosis of Ménière's disease, in our experience there are problems with this application. First, it often is difficult to identify the SP, and it remains unclear whether what often has been referred to in the past as SP is actually only uncanceled CM. Second, and probably more importantly, abnormal ratios have been reported in only about 70% of ears diagnosed with

Ménière's (Coats, 1986), and then only if the hearing loss is between about 30 and 60 dB HL. Accuracy is reduced in cases of lesser or greater hearing loss.

The other application of ECohG is to assist in the identification of the AP, which also is wave I of the auditory brainstem response (Durrant, 1977). In many patients with high-frequency hearing loss, it is difficult to observe wave I, even at high stimulus levels. If wave V latency is normal and symmetric with wave V latency from the opposite side, it is unnecessary to know the exact latency of wave I, regardless of whether hearing loss is present. Unfortunately, this often is not the case. In many ears with high-frequency hearing loss, wave V latency may be prolonged in relation to published norms or in relation to the latency from the opposite side. Although a number of investigators have suggested the use of wave V latency corrections whenever hearing loss is present (eg, Selters and Brackmann, 1977), many patients with hearing loss that would appear to require the use of a correction have completely normal wave V latencies. Thus it becomes difficult to know which ears require the use of these corrections and which do not. In these cases, identification of wave I is important because it will determine which portion of the delay in wave V latency is the result of peripheral hearing loss. If wave I can be clearly identified, then there is no ambiguity in the ABR evaluation, whether or not hearing loss is present or wave V is delayed. In this regard, the use of electrocochelographic techniques can greatly enhance the accuracy of the ABR test. Even the "tiprode" electrode results in a two-fold increase in wave I amplitude as compared to what is observed at the mastoid or earlobe. The newer wick electrodes, which also are easily placed and completely uninvasive, result in five- to eight-fold increases in wave I amplitude over mastoid placements (Lilly and Black, 1988). Indeed, it is not uncommon to observe wave I amplitude equal to or greater than wave V amplitude when a TM electrode is used.

Auditory brainstem responses

The ABR represents the aggregate responses of many neurons from lower portions of the auditory pathway. It is recorded from sets of surface electrodes placed typically at the vertex, mastoid processes or earlobes, and the forehead. The combined effects of low-noise differential amplification and signal averaging permit the routine measurement of these low-level electrical signals. In normal ears, the response consists of a series of waves, labeled from I to V, with wave I being generated by primary afferent fibers (and therefore representative of the output from the periphery) and wave V being generated at some higher level in the nervous system, probably at the pathway of the lateral lemniscus (Moller and Janetta, 1985). The response sometimes includes later components, but these responses have not been shown to be of much clinical value. Similarly, waves II and IV sometimes are present but are not typically considered in clinical assessments.

In normal ears, high-level stimulation results in a wave I latency of about 1.5 msec with the latencies of each subsequent response component delayed by about 1 msec relative to its predecessor. Thus, the interval, or interpeak latency difference, between waves I and III and between waves III and V should be about 2 msec, with an interval between waves I and V of 4 msec. As stimulus intensity decreases, the amplitude of the early components in the response tend to decrease until only wave V remains. Additionally, response latencies increase in a systematic manner. The interval between waves I and V tends to decrease as intensity decreases, but this effect is small.

These latencies are stable and reliable, both between and within subjects. Thus, latencies that are as little as 0.3 msec longer than those observed in normal subjects can be considered abnormal. Similarly, differences between ears that also exceed 0.3 msec are considered abnormal. The effects of peripheral hearing loss and age, however, must be considered in these decisions.

In developing ears, wave I occurs at adultlike latencies very early in life but wave V may take as long as 2 years to reach adult latency values (Gorga et al, 1987b; 1989). In older ears, there is a tendency for longer response latencies, some of which are related to decreases in peripheral response acuity with age.

Regardless of age, conductive hearing loss acts as an attenuator for those frequencies affected by the disease. We know that response latency increases as we decrease intensity. Similarly, conductive hearing losses result in increased response latencies because they attenuate the signal reaching the cochlea. However, the effects are generally uniform for all components in the response. Thus response latencies are delayed the same for wave I as they are for wave V. As stated above, the interval between waves I and V tends to shorten slightly as the level decreases. This same effect is often observed in ears with conductive hearing loss, probably for the same reasons. Conductive hearing loss all will result in threshold elevations, which can be detected by the ABR provided that the frequencies affected are in the 2000 to 4000 Hz range.

The effects of cochlear hearing loss on the ABR will depend on the magnitude of the hearing loss. In ears with mild or moderate hearing losses, high-level stimulation often results in normal absolute latencies and interpeak latency differences. As the loss increases, response latencies become prolonged and earlier components of the response often drop out, leaving only wave V. When these results are observed, interpretation is more ambiguous. For example, an acoustic neuroma is unlikely if the latencies are comparable to those observed on the opposite side because these tumors seldom occur bilaterally. If, however, the latency of wave V is prolonged in the test ear relative to norms and/or results from the opposite ear, and if wave I is absent, the interpretation is more difficult. These effects could be due either to the magnitude of the hearing loss or to the presence of a space-occupying lesion. As stated previously, the use of correction factors to account for peripheral hearing loss has not produced consistently valid results.

Alternatively, this problem of diagnosis can be solved by using recording techniques that enhance wave I, as discussed above. The use of tiroprades or extratympanic or transtympanic electrocochleography might sufficiently increase wave I amplitude such that this component can be measured reliably. Prolongation in wave V latency can be accurately interpreted if wave I is observed, because it will serve as a benchmark for any effects of peripheral hearing loss on response latency. If waves I and V are prolonged equally, then the results are more consistent with peripheral hearing loss. If wave V is prolonged relative to wave I (ie, the interpeak latency difference is abnormal), then the results would suggest the presence of neuropathy, whether or not peripheral hearing loss is present.

There are a variety of ABR abnormalities that can reflect auditory pathway neural dysfunction. The most powerful interpretations of ABR results can be made when wave I is present. Prolongation in wave V latency and in the interval between waves I and V are hallmarks of acoustic tumors. If wave I is not observed, then an asymmetrically prolonged wave V latency that is unlikely to be the result of asymmetric hearing loss also strongly suggests retrocochlear pathology. Other less reliable criteria include abnormal increases in response latency with increases in stimulus rate (presumably causing greater adaptation) and abnormal amplitude ratios between waves I and V. Increases in stimulus rate do not, however, appear to provide any increase in sensitivity compared to response measurements at lower stimulus rates (Campbell and Abbas, 1987). Response amplitudes are highly variable, and electrode configuration and type would need to be considered in order to develop these criteria. Of course, in the extreme, amplitude ratios can be very important. For example, if wave I is observed but wave V is not, then it is likely that something has disrupted the pathway between primary afferent fibers and portions of the brainstem.

Comparison of test techniques

To this point, we have described how different tests are performed and some of the principles behind their development. Next, we will present data on the extent to which these tests can differentiate patients with cochlear lesions from those with acoustic tumors.

Jerger (1983) and Turner et al (1984) provide statistical summaries describing the performance of many different audiologic tests. Both papers rely on data from a number of published reports. We will rely on the paper by Turner et al (1984) for the following discussion because it is somewhat more comprehensive.

Table 148-3 represents an abbreviated version of a table presented in the aforementioned paper (Turner et al, 1984). Three measures of test performance are presented: hit (H) rate, false alarm (FA) rate, and d' . Hit rate refers to the percentage of acoustic tumors that were correctly identified by the test. False alarm rate is defined as the percentage of ears having only cochlear abnormality that were identified as having a tumor. The measure d' is an index of the extent to which the two distributions of scores (ie, from patient with cochlear abnormality or acoustic tumors) overlap on any given test. High values of d' indicate that the distributions of scores are well separated, making it easier to distinguish between the two groups. In Table 148-3 the tests are presented in relation to hit rate because this measure can be more generally understood. Additionally, it may be clinically preferable to optimize correct identification of tumors, even if one must tolerate a slightly higher false alarm rate than with some other test whose hit rate was lower.

A review of this table indicates that the ABR test has the highest hit rate and d' , but does not achieve the lowest false alarm rate. Tests with lower false alarm rates (BCL, PIPB, ARD, and ABLB) achieve these rates at the expense of the hit rate. However, some of these other tests perform fairly well. In contrast, loudness balance procedures and speech discrimination scores are particularly inaccurate at identifying acoustic tumors. The measures summarized in Table 148-3 would indicate that these latter tests should not serve as sole screening measures for acoustic tumors.

As expected, sophisticated radiologic tests such as magnetic resonance imaging (MRI) with gadolinium contrast will exceed the performance of even the best audiologic test (ABR), but the costs of such tests are significantly greater. Given the low prevalence of acoustic tumors in clinical populations, it may be more cost effective to perform tests like the ABR as an initial screening measure, and to proceed to more expensive radiologic tests when there is sufficient evidence to suggest a high probability of an acoustic tumor.

Special Test Considerations

High-frequency audiometry

In recent years there has been an increased interest in the measurement of auditory thresholds in the 8.000 to 20.000 Hz range. From a clinical standpoint, these measures have been most useful in monitoring potential changes in auditory sensitivity during the course of ototoxic drug therapy (Dreschler et al, 1985; Fausti et al, 1984). Because ototoxic effects usually will cause damage to the basal portion of the cochlea first, high-frequency testing can serve as an early detector of cochlear damage. In this class of patients, changes in hearing sensitivity can be extremely useful in the medical management of the patient or in planning aural rehabilitation. Other suggested uses include monitoring the effects of noise exposure (Fausti et al, 1981) and monitoring hearing sensitivity in patients with suspected progressive hearing loss. At the present time, however, there is no standardized system for either the calibration or the measurement of high-frequency thresholds. As a result of technical difficulties, the calibration and subsequent expression of thresholds in absolute physical units (ie, dB SPL at the tympanic membrane) is very difficult. The most common approach at present is to use lightweight circumaural earphones that can be calibrated in a flatplate coupler. Although this calibration method does not attempt to predict the SPL at the tympanic membrane, it does allow potential changes in instrumentation or earphone sensitivity to be monitored. Because the primary clinical use is threshold monitoring over time, each patient serves as his or her own control. The test-retest reliability of this approach has been found to be acceptable for clinical purposes (Stelmachowicz et al, 1989b).

Compared to measures in the 250 to 8.000 Hz range, it is difficult to establish high-frequency normative values because thresholds vary widely with age; within a specific age group the inter-subject variability is considerably larger than it is below 8.000 Hz (Stelmachowicz et al, 1989a). In addition, test-retest reliability is poorer in the high frequencies and decreases as a function of frequency. From a practical standpoint, testing often is complicated by a subjective loss of tonality in the high frequencies, interference from tinnitus, and abnormally rapid adaptation to the test stimulus (Viemeister and Bacon, 1983). Despite these problems, high-frequency testing serves an important function and may be a useful part of the audiologic evaluation in centers serving large numbers of patients referred from infectious disease or oncology services.

Nonorganic hearing loss

For a variety of reasons, some patients will feign a hearing loss or will attempt to exaggerate the degree of an existing hearing impairment. The referral source, patient history, and/or interview often will alert the clinician to the potential of a nonorganic hearing loss before testing begins. If the patient is referred from an occupational health program or is in the process of litigation, the test approach should be altered to include the tests necessary to rule out a nonorganic component to the hearing loss. Although financial gain often is the motivation for adult patients, nonorganic hearing loss often is seen in children (particularly those between ages 11 and 16) as a means of getting attention or as an excuse for poor academic performance.

If initial pure-tone or speech testing yield results that are inconsistent with the patient's communication ability during the interview, a nonorganic loss should be suspected. As discussed earlier, there is a predictable relation between the SRT and the PTA and a significant SRT/PTA discrepancy can substantiate the need for further testing. Similarly, poor test-retest reliability may be indicative of nonorganic hearing loss.

Historically, a large number of tests have been developed but only a few are used clinically today. These tests can be divided into two categories: those that confirm the existence of a nonorganic component and those that can estimate auditory thresholds without the patient's cooperation.

Nonthreshold tests

Once a nonorganic hearing loss is suspected, the test approach should be altered immediately. Unless the hearing loss is completely unilateral (see the following discussion of the Stenger test), an SRT should be established by using an ascending approach. These results should be compared to the voluntary pure-tone thresholds at 500 and 2,000 Hz. Speech perception tests administered at a low sensation level relative to the voluntary thresholds (eg, 10 dB SL) also can be used to confirm a nonorganic hearing loss. Patients will not realize that monosyllabic words cannot be perceived with a high degree of accuracy at these low levels (see Fig. 148-5). A Lengthened Off Time (LOT) Bekesy test also can be used. This test requires the patient to track thresholds for a continuous tone and for a pulsed tone. The patient with a nonorganic hearing loss will base his voluntary responses on loudness rather than on signal detectability. Perceptually, the pulsed signal will not be as loud as the continuous signal and thus, the threshold estimates will be 10 to 20 dB higher for the pulsed signal.

Threshold tests

Without a patient's cooperation there are only two methods that can be used to estimate threshold. The problem of establishing hearing thresholds in noncooperative patients has been simplified considerably by the availability of frequency-specific ABR measures. This approach is the only method that can be used reliably in patients with nonorganic hearing loss that is bilaterally symmetric. In the case of a unilateral or asymmetric hearing loss (a difference of more than 20 dB between ears) a Stenger Test can be used to estimate threshold in the poorer ear. The test is based on the fact that a signal presented binaurally at different sensation levels in each ear will be perceived as heard in one ear only. For this test, a tone is introduced to the "good" ear at 10 dB SL and at a level considerably below the voluntary threshold in the "poorer" ear. The test signals are introduced simultaneously, and the patient is instructed to respond whenever a signal is heard in either ear. The intensity of the signal in the "poorer" ear is increased systematically. As soon as the sensation level of the signal in the "poorer" ear exceeds that in the "good" ear (10 dB SL), the patient will perceive the signal as being delivered to the "poor" ear only and will stop responding. Similar techniques can be used to establish a SRT. A Stenger test is the most expedient method for patients who present with suspected nonorganic unilateral hearing losses and this approach has been shown to produce threshold estimates that agree with actual thresholds within 15 to 20 dB or less.

Summary

Audiologic tests can provide the otolaryngologist with useful information related both to the identification and quantification of hearing loss and to the appropriate medical and nonmedical rehabilitation. Although audiologists typically provide interpretations of tests, the otolaryngologist still needs to understand basic principles related to these tests in order to integrate test results into the clinical picture and optimally serve their patients. The summary provided in this chapter is not exhaustive, but does reflect our own experience regarding the usefulness of audiologic tests in the identification and diagnosis of hearing loss in a large clinical setting that serves a full age range of patients having a variety of hearing disorders.