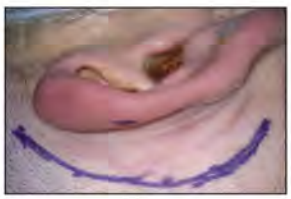
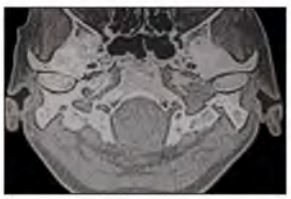
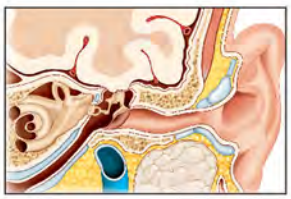

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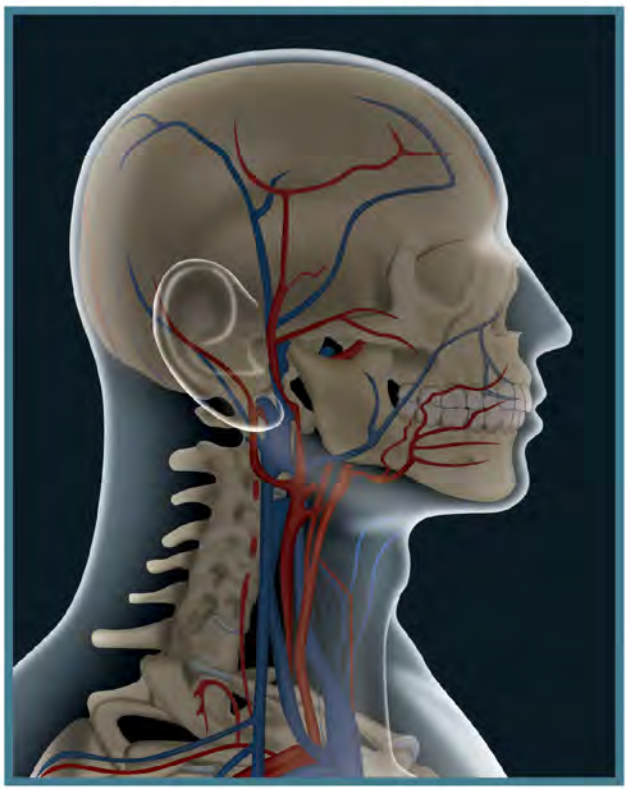

Volume Editor
Anil K Lalwani

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Video Legend

Video 28.1: Transmastoid superior semicircular canal occlusion.

CHAPTER 2

Evaluation of Auditory Function

Janet Koehnke, Faith M Mogila, Maris Appelbaum, Joan Besing

This chapter is designed to provide an overview of the profession of audiology. It begins with a brief history of audiology followed by a description of the scope of practice of audiologists and some facts and figures on the incidence of hearing loss. The remainder of the chapter describes the diagnostic test procedures conducted by audiologists. These include subjective measures such as pure tone air conduction and bone conduction thresholds, speech recognition thresholds, and speech intelligibility tests as well as objective measures such as middle ear immittance, evoked otoacoustic emissions (OAEs), auditory brainstem tests, and vestibular tests. Each procedure is described briefly along with examples of typical test results and a discussion of the interpretation of results. The chapter concludes with some ideas about the future of audiologic assessment.

BRIEF HISTORY

The profession of audiology emerged in the late 1940s as many soldiers from World War II returned home suffering from prolonged exposure to the sounds of artillery, grenades, sirens, aircraft, and the like. The term itself was coined by three different individuals at about the same time in the mid-1940s, an otolaryngologist, Norton Canfield, a speech pathologist, Raymond Carhart, and an auditory scientist, Hallowell Davis.[1] Shortly thereafter, specialized institutions were developed to serve the needs of military personnel returning from active duty who were experiencing difficulty hearing and understanding speech and hearing essential sounds such as alarms, honking horns, and other important auditory information.

Since then the field of audiology has developed and grown into a flourishing profession, serving the needs of individuals across the lifespan who experience hearing and/or vestibular problems. Dr. James Jerger, one of Carhart's first audiology students, was one of the pioneers of the profession; he developed many of the early test methods and procedures, including the Carhart-Jerger method for the measurement of pure-tone thresholds.[2] This procedure is followed to this day and is the foundation of audiometric threshold testing that is the basis for all differential diagnosis in audiology. Dr. Jerger has also written a book entitled *Audiology in the USA*, which details the history and development of the profession.[1]

Audiology is the study of hearing and balance function and disorders; audiologists evaluate auditory and vestibular function and provide rehabilitation for individuals across the lifespan identified with pathologies of these systems. It is also important to note that audiologists strive to inform and educate people about ways to prevent hearing loss as well as cope with the challenges presented by their hearing loss.

The professional activities of audiologists are clearly defined by the two largest organizations representing them, the American-Speech-Language-Hearing Association (ASHA), and the American Academy of Audiology (AAA). In addition, all 50 states license or certify audiologists and have established guidelines for practicing in those states. According to the ASHA Scope of Practice for audiologists, "The practice of audiology includes both the prevention of and assessment of auditory, vestibular, and related impairments as well as the habilitation/rehabilitation and maintenance of persons with these impairments.

The overall goal of the provision of audiology services should be to optimize and enhance the ability of an individual to hear, as well as to communicate in his/her everyday or natural environment".[3] Similarly, the AAA Scope of Practice states, "Audiologists identify, assess, diagnose, and treat individuals with impairment of either peripheral or central auditory and/or vestibular function, and strive to prevent such impairments".[4] Both of these documents also stipulate that practicing audiologists must, at all times, adhere to the Code of Ethics of the respective organization.

SCOPE OF PRACTICE

The scope of practice for the profession has grown dramatically over the past 30–40 years. It was not until 1977 that audiologists began dispensing hearing aids and other assistive devices. As technology has advanced, hearing aids have evolved from body worn analog devices to completely in-the-ear and small behind the ear digital devices. Along with the progress in hearing aid technology came the development of the cochlear implant and the bone anchored hearing aid in the 1960s. Cochlear implants have evolved from single channel devices that were first available commercially in 1972, to multiple channel systems that were introduced in 1984 and provide remarkably accurate auditory input to individuals with profound hearing loss.[5] All of these advances in remediation have resulted in the expansion of the profession of audiology and the need for skilled audiologists.

Although the middle latency response (MLR) and the late auditory evoked potentials (AEPs) were first discovered in the late 1950s, the introduction of clinical electrophysiologic tests including auditory brainstem testing and evoked OAEs testing did not commence until the late 1970s. Together, these diagnostic procedures have contributed to the growth of the profession of audiology. More recently, audiologists have become involved in the evaluation and treatment of vestibular pathologies and in intraoperative monitoring of brainstem and cortical responses during surgical procedures. Clearly, audiology is a rapidly growing and developing profession. Currently, there are >12,000 audiologists in the United States.[6] According to the US Bureau of Labor Statistics this number is expected to grow to about 17,000 by the year 2020.[7] This is a rate of 37%, which is much more rapid than most professions.

Audiologists work as independent practitioners in a variety of settings including private practice, schools, hospitals, community clinics, otolaryngology offices, industry, university clinics, and the military. They may also be involved in the education of audiology students as well as medical residents and interns and other health professionals. Audiologists serve a diverse population across the lifespan including individuals of all races, genders, religions, national origins, and sexual orientations.

DEMOGRAPHICS OF HEARING LOSS

Along with the expanding breadth of the profession, there is an increased need for audiologists and audiologic services. This is, of course, due to the growing numbers of individuals with hearing loss. According to the National Institute on Deafness and Other Communicative Disorders (NIDCD) of the NIH, 17% (36 million) of American adults report some degree of hearing loss. More specifically, the NIDCD reports that "18 percent of American adults 45–64 years old, 30 percent of adults 65–74 years old, and 47 percent of adults 75 years old or older have a hearing loss".[8] World Health Organization statistics indicate that, worldwide, 360 million people (including 328 million adults and 32 million children) experience "disabling" hearing loss. They define disabling as "hearing loss >40 dB in the better hearing ear in adults and a hearing loss >30 dB in the better hearing ear in children".[9]

In the newborn population, the incidence of hearing loss continues to be reported as two or three individuals per 1000 births in the United States.[8] As a result of the 1993 NIH Consensus Conference on Newborn Screenings, programs to evaluate every newborn have been established in all 50 states. This has led to earlier identification of hearing loss and auditory pathologies, which, in turn, results in appropriate intervention at an earlier age. Despite earlier detection of hearing loss in newborns, according to Niskar et al.[10], about 12.5% of children and adolescents in the United States aged 6–19 years (approximately 5.2 million) experience permanent hearing loss due to exposure to loud sounds. These numbers have likely increased in the past decade due to the use of personal listening systems and the popularity of clubbing and concert-going among teenagers and young adults. According to the NIDCD, approximately 15% of Americans age 20–69 have high-frequency hearing loss due to exposure to loud sounds or noise in some aspect of their daily lives.[8] Other important statistics regarding hearing loss and auditory pathologies can be obtained from the NIDCD, the Centers for Disease Control, the World Health Organization, and the Hearing Health Foundation to name just a few sources.

In our work as audiologists, it is imperative that we collaborate with other professionals to ensure that we provide the best possible care for our patients. Clearly, it is necessary for us to refer to and consult frequently with

otolaryngologists. By working together closely and conferring with each other, we can effectively monitor the auditory status of our patients. Individuals receiving implantable devices and those experiencing pathologies such as Meniere's Disease, acoustic neuroma, or cholesteatoma represent just a few of the many individuals for whom collaborative care between audiologists and otolaryngologists is so essential.

Of course, there are many other health professionals with whom audiologists work on a regular basis. When diagnosing an infant with hearing loss it is imperative to consult with social workers, psychologists, and speech-language pathologists as well as physicians. For children with hearing loss, audiologists confer with teachers and other support personnel in the schools. Adults with gradual or sudden onset hearing loss may need not only hearing aids or other assistive devices, but also help obtaining accommodations in the workplace. In such instances, audiologists are likely to interact with vocational counselors and possibly other individuals in state and local agencies to assist their patients. For geriatric patients, audiologists consult with home healthcare workers, personnel at senior centers and assisted living facilities, and others to achieve optimal auditory input in the environment where these individuals spend their time. Clearly, the overall goal is to work cooperatively to meet the needs of our patients.

CLINICAL AUDIOLOGIC PROCEDURES

A complete audiologic evaluation typically includes assessment, using insert or circumaural earphones, of pure-tone air and bone conduction thresholds as well as spondee thresholds and word recognition testing. In addition to these tests, an immittance battery and OAEs should always be included. The results of these procedures should provide comprehensive evidence for differential diagnosis. These findings also provide direction for habilitation/rehabilitation of the patient.

As with most clinical protocols, changes and adjustments in technique may be required to address any special needs or concerns of the patients. However, these adaptations should not sacrifice the fundamentals on which the following tests are designed and implemented.

Air and Bone Conduction

Audiometric assessment is an integral component in otologic evaluation of a patient who is suspected of having an auditory and/or vestibular pathology. Testing should be completed by a state licensed audiologist in a quiet room with minimal ambient noise. Test results may be recorded on a table or displayed on an audiogram such as the one shown in Figure 2.1.

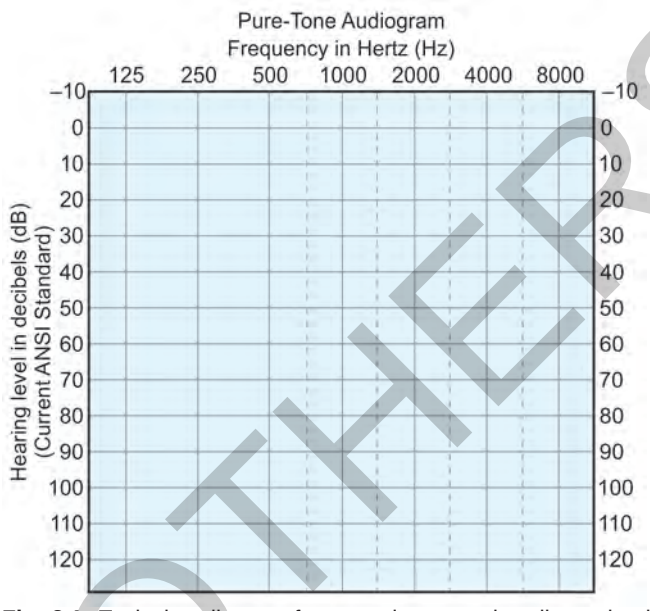


Fig. 2.1: Typical audiogram form used to record audiometric air and bone conduction thresholds.

Prior to audiometric testing, a case history and otoscopy should be performed. Any obstruction in the outer ear could potentially affect pure tone responses. The tympanic membrane should be visible bilaterally during otoscopy. Obtaining a case history can provide information to assist the audiologist in determining the order in which the tests are conducted.

Optimally, air conduction, as well as bone conduction testing, is completed in a double-walled sound-treated booth with the patient wearing insert or circumaural earphones. All equipment utilized for testing should be calibrated annually. Air conduction stimuli pass through the outer, middle and ultimately, the inner ear on the way to the auditory cortex. Bone conduction stimuli are delivered directly to the cochlea through a bone oscillator placed on the mastoid bone. Pure tone signals are used to establish thresholds at specific frequencies. For air conduction, the octave frequencies from 250 to 8000 Hz are tested. In addition, if there is a 20 dB or greater difference between the thresholds at these adjacent frequencies, the interoctaves, 1500, 3000, and/or 6000 Hz, should be tested. Bone conduction thresholds are obtained in response to signals at the octave frequencies from 250 to 4000 Hz. Threshold testing should follow a standardized method such as those outlined by the American National Standards Institute,[11] the American Speech-Language-Hearing Association,[12] or the Carhart-Jerger procedure.[2]

Once air conduction and bone conduction thresholds are obtained, it is standard clinical practice to calculate the pure tone average (PTA) for each ear. In most cases, this is the average of the pure tone air conduction thresholds at 500, 1000, and 2000 Hz. However, if the air conduction threshold at one of these three frequencies differs from the others by >20 dB, then a two frequency PTA is calculated using the two best thresholds at these three frequencies. It has been found that that this approach results in better agreement with the spondee recognition threshold (SRT) described below.

In certain situations, the signal presented to the test ear is sufficiently intense to stimulate the cochlea of the nontest ear, causing inaccurate responses. This is known as crossover; the nontest ear actually responds when the tone is presented to the test ear. This occurs when the intensity of the test ear stimulus is at least 40 dB or greater (circumaural earphone) or 55 dB or greater (insert earphone) than the bone conduction threshold in the nontest ear. The term interaural attenuation is used to describe the amount of sound absorbed by the head before the sound presented to the test ear is intense enough to stimulate the opposite cochlea. The specific value varies as a function of frequency as well as the transducer used for testing. The values cited above are conservative estimates used clinically to ensure that crossover is not occurring during testing. To be certain the nontest ear is not being stimulated resulting in inaccurate responses, masking procedures must be employed. Thus, if the presentation level of the pure-tone in the test ear exceeds the bone conduction threshold in the nontest ear by these values (40 and 55 dB for circumaural and insert earphones, respectively), masking is presented to the nontest ear via air conduction using an insert or circumaural earphone.

For bone conduction testing, the interaural attenuation is 10 dB. This means that if the bone conduction stimulus level and the air conduction threshold differ by >10 dB in the ear being tested or in the nontest ear, masking is necessary at that frequency. The reason for this value is because when a stimulus is presented via bone conduction, all of the bones in the skull are stimulated, not just the ones in the cochlea closest to the bone oscillator. The interaural attenuation is thus minimal resulting in the use of the 10 dB value for determining the need for masking. Use of appropriate masking techniques is essential to obtain accurate threshold measurements.

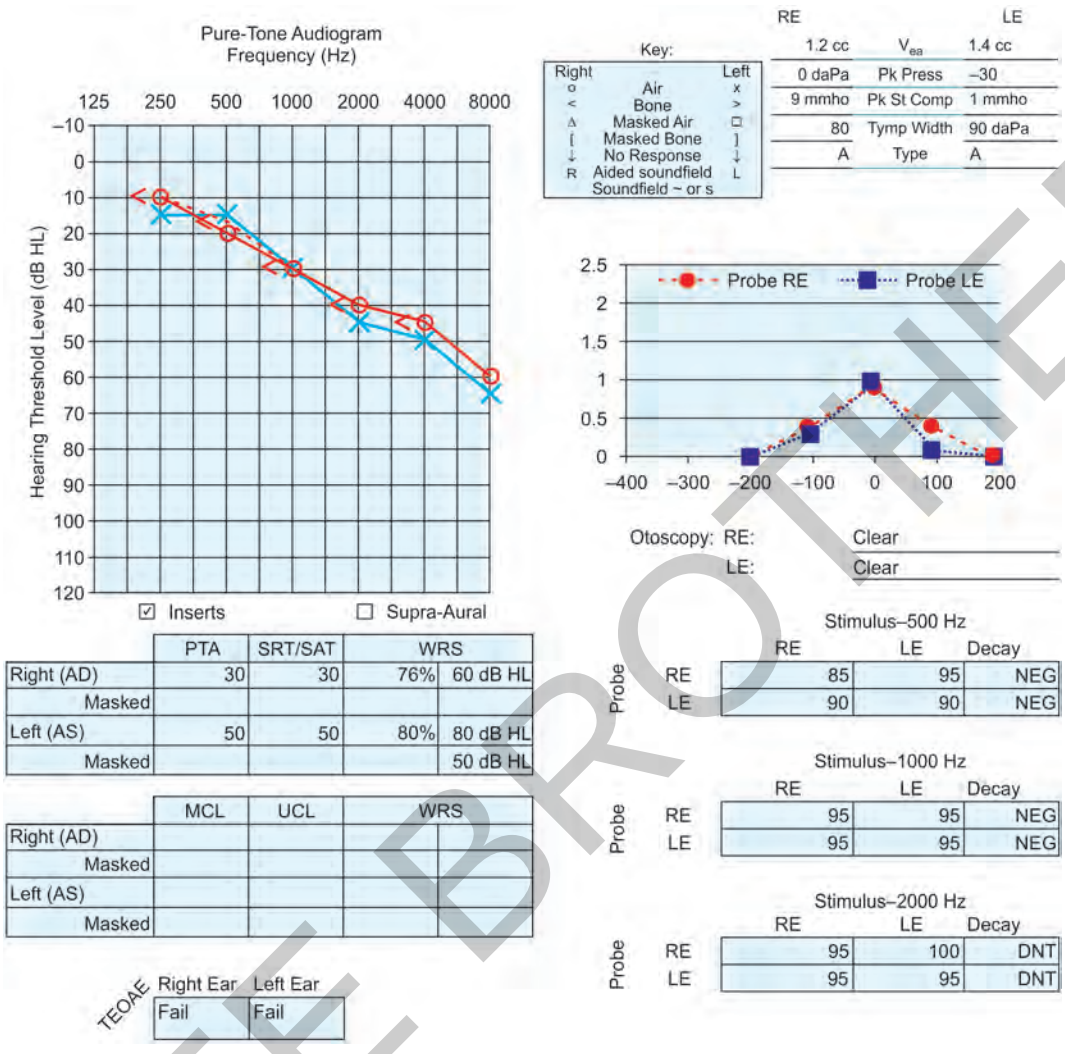
Example audiograms are provided in Figures 2.2 to 2.5 to illustrate typical results obtained for bilateral and/or unilateral losses as well as conductive (Fig. 2.4), sensorineural (Fig. 2.2), mixed type hearing loss (Fig. 2.5), and a functional hearing loss (also referred to as malingering, Fig. 2.3). Each case includes results for pure tone air and bone conduction tests as well as many of the other tests described below such as OAEs, tympanometry, word recognition, etc.

Speech Testing

The SRT is used as a reliability check for the pure tone findings. The PTA described above should be within ±6 dB of the spondee threshold.[13] The SRT is measured by presenting two syllable words, called spondee words, with equal stress on each syllable. The words can be presented using either recorded speech or monitored live voice. Standardized testing procedures must be employed. The outcome of this measure is a threshold for speech and should be in good agreement with the average of the pure-tone thresholds at 500, 1000, and 2000 Hz (PTA). There may be times when traditional SRT testing cannot be employed. Examples of this might be with non-native speakers of English, infants, or difficult to test patients. In cases such as these, a speech detection threshold (SDT) or a speech awareness threshold (SAT) would be obtained. The preferred term according to ASHA[14] is SDT because it is an accurate description of the task of exhibiting a behavioral change to spondee words or cold running speech. The SDT is often lower than the expected SRT because it requires the patient only to detect rather than recognize and correctly repeat speech stimuli.

The other speech test typically administered is used to obtain the word recognition score (WRS), using monosyllabic words. This suprathreshold test should be administered 30–40 dB above the SRT.[15] The goal of word recognition testing is to determine the best score a patient can attain. In some cases, this test may need to be administered at more than one intensity to find the level of maximum performance. This level is known as PB max (phonetically balanced) and is the highest speech recognition score that is determined using a PI function (performance intensity).

According to Gelfand,[16] speech recognition measures are used in every phase of audiology such as (1) to describe how hearing loss affects speech understanding, (2) in the differential diagnosis of auditory disorders, and (3) for determining the need for amplification and other forms of audiologic rehabilitation. Word recognition measures can also be used as part of a monitoring protocol, when needed. In patients with a sensorineural hearing loss, it is expected that the WRS will decrease as the severity of the loss increases. When dealing with a conductive loss, however, WRSs often approach the "excellent" range due to the normal bone conduction scores, when the words



	PTA	SRT/SAT	WRS	
Right (AD)	30	30	76%	60 dB HL
Masked				
Left (AS)	50	50	80%	80 dB HL
Masked				50 dB HL

	MCL	UCL	WRS
Right (AD)			
Masked			
Left (AS)			
Masked			

Stimulus–500 Hz	RE	LE	Decay
Probe RE	85	95	NEG
Probe LE	90	90	NEG

Stimulus–1000 Hz	RE	LE	Decay
Probe RE	95	95	NEG
Probe LE	95	95	NEG

Stimulus–2000 Hz	RE	LE	Decay
Probe RE	95	100	DNT
Probe LE	95	95	DNT

Fig. 2.2: Results for a 75-year-old patient. The pure tone results indicate a bilateral, symmetrical sensorineural hearing loss. Hearing thresholds are normal through 500 Hz, sloping to a mild sensorineural loss at 1000 and 2000 Hz, with a moderately severe loss at 8000 Hz. Good agreement between the PTA and SRT is noted. Immittance results indicate normal middle ear function. The patient has good word recognition scores bilaterally. TEOAE results indicate refer bilaterally. Audiologic recommendations for this patient would include hearing aids and perhaps other assistive devices. (PTA, pure-tone average; SRT, spondee recognition threshold; TEOAE. transient evoked otoacoustic emissions).

are presented at 30–40 dB above the SRT. In contrast, individuals with cochlear pathology usually have WRSs between 60% and 90% when measured at the same relative level. Scores for this group vary widely depending upon the degree and configuration of hearing loss. For patients with retrocochlear pathologies, an often observed result is WRS much poorer than expected based on the degree of hearing loss. For example, a patient with a PTA of 30 dBHL may obtain a WRS of 54% when tested at 30 or 40 dB above the PTA.

In addition to the traditional word lists used to obtain speech scores, there are other tests that can accomplish the same goal. When testing a child or a patient who is unable to verbally respond, tests such as the Word Intelligibility by Picture Identification—WIPI,[17] Northwestern University Children's Perception of Speech—NU-CHIPS,[18] or Pediatric Speech Intelligibility Test—PSI may be utilized.[19] These tests require the patient to point to a picture in a closed set that corresponds to the word they heard the audiologist speak. Tests also exist to assess how well a patient can hear in noise. In these tests, a target stimulus (word or sentence) is presented in the presence of background noise. Examples of these tests are the BKB-SIN, the Quick-SIN and the Revised Speech Perception in Noise Test.[20]

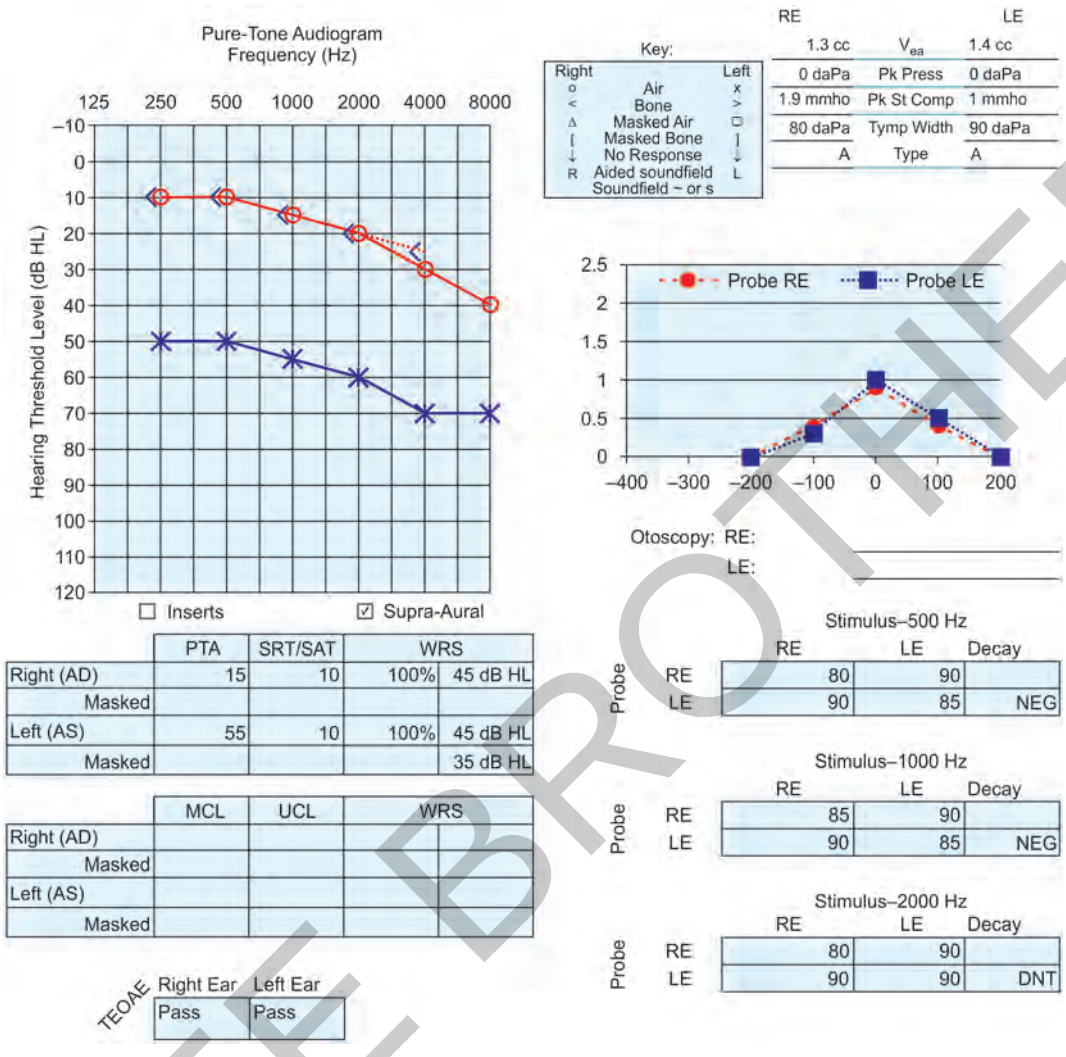


Fig. 2.3: These are results for a 15-year-old male who reported a sudden hearing loss in his left ear following an automobile accident. Test results were inconsistent. Right ear thresholds indicate normal hearing from 250 to 2000 Hz with a mild high frequency loss. Left ear results indicate a moderate hearing loss from 250 to 1000 Hz, sloping to moderately-severe from 2000 to 8000 Hz. Left ear thresholds reveal a shadow curve because interaural attenuation has been exceeded; therefore, crossover cannot be ruled out. The poor PTA–SRT agreement, normal tympanogram and acoustic reflexes, as well as "pass" OAE results for the left ear suggest that this patient is malingering. Recommendations for this patient would include a complete audiologic re-evaluation in 3–6 months. (PTA, pure-tone average; SRT, spondee recognition threshold; OAE, otoacoustic emission).

Immittance

An integral part of a complete audiologic evaluation is the inclusion of the immittance test battery. Immittance protocols are used to evaluate middle ear status and the function of the ipsilateral and contralateral reflex patterns.

Otoscopy should be performed prior to immittance to rule out any complications or pre-existing conditions that may contraindicate the use of this battery. Some examples of conditions that may preclude the use of tympanometry include a draining ear or cerumen that occludes the ear canal. The series of tests administered includes tympanometry, determination of the ipsilateral and contralateral reflex thresholds, and observation of reflex decay (if any).

In order for the tests to be performed, a pneumatic seal between the probe assembly and the patient's outer ear must be obtained. Failure to obtain a seal prevents completion of the test.

Tympanometry is the first portion of the immittance battery. Once the seal is obtained, a probe tone is presented

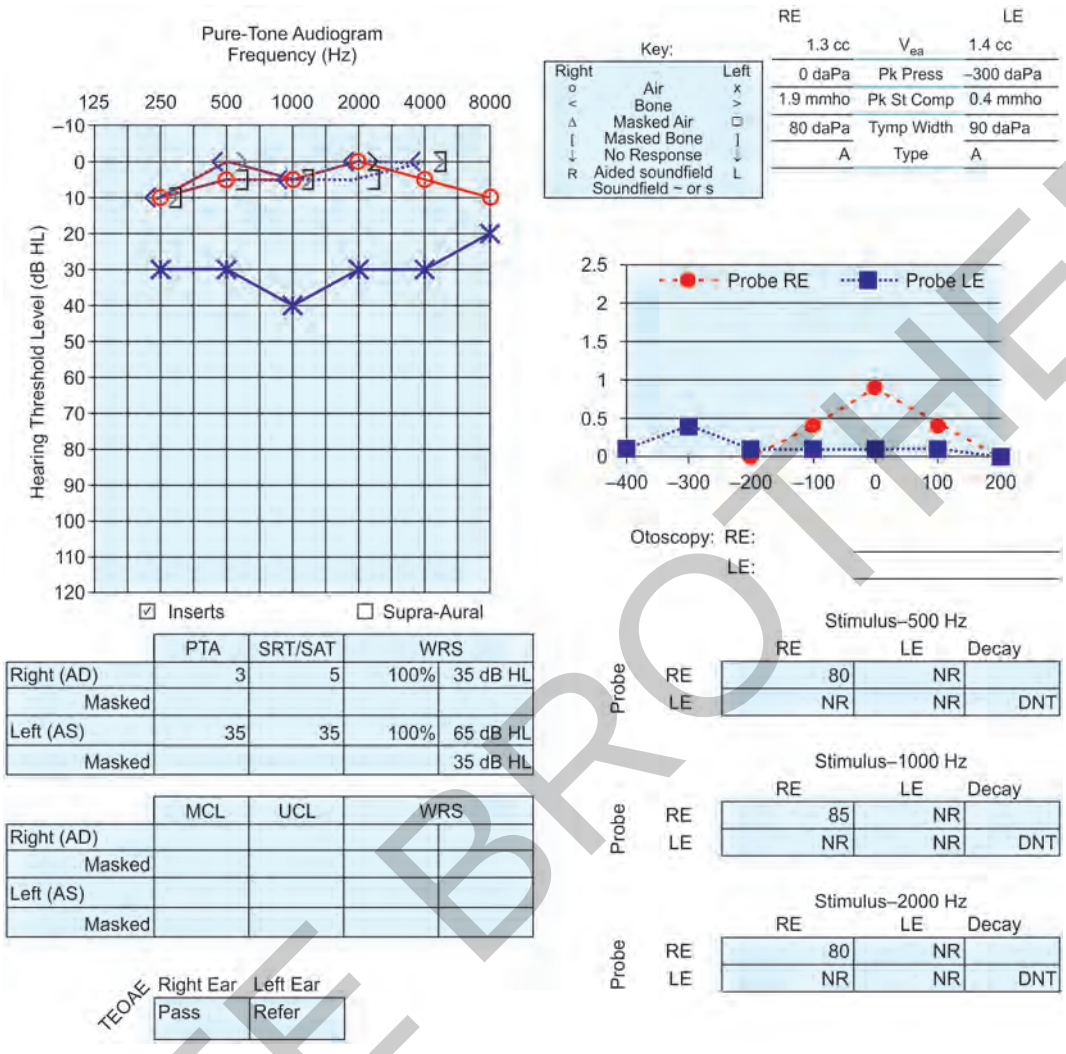


Fig. 2.4: Audiometric results for a 6-years-old with a history of chronic, recurrent otitis media. Pure tone thresholds in the right ear are within normal limits by air and bone conduction. Left ear thresholds indicate a mild flat conductive loss from 250 to 4000 Hz, gently rising to normal hearing at 8000 Hz. Note the excellent word recognition scores in the left ear, which are expected with a purely conductive loss. The air-bone gaps present from 250 to 4000 Hz in the left ear are also indicative of a conductive component. Tympanometry reveals negative pressure and reduced compliance in that ear. This patient "referred" on OAE results left ear, and "passed" right ear. Recommendations for this patient would include referral to an otolaryngologist. (OAE, otoacoustic emission).

to the patient's outer ear and the pressure in the canal is varied to determine the point of maximum compliance of the middle ear system. The probe tone used for individuals over 6 months of age is 226 Hz, while a 1000 Hz probe tone is used for patients who are newborn to 6 months old. More information regarding the use of tympanometry in the pediatric population can be found in several pediatric audiology textbooks.[21]

Tympanograms are interpreted on several parameters: (1) ear canal volume, (2) equivalent peak pressure, and (3) static admittance. In more recent years, tympanometric width has been added to the parameters that are used in the assessment of middle ear function. Table 2.1 summarizes the normative data for these tympanometric parameters described by ASHA.[22]

Interpretation of tympanometric width (or gradient) was introduced in 1968 by Brooks. It is a measure of the sharpness of the peak of the tympanogram. The gradient can be measured by bisecting the distance from the peak to the positive end of the tympanogram. Tympanometric width is reported in dekapascals (daPa). According to ASHA,[22] the normal range is 60–150 daPa for children

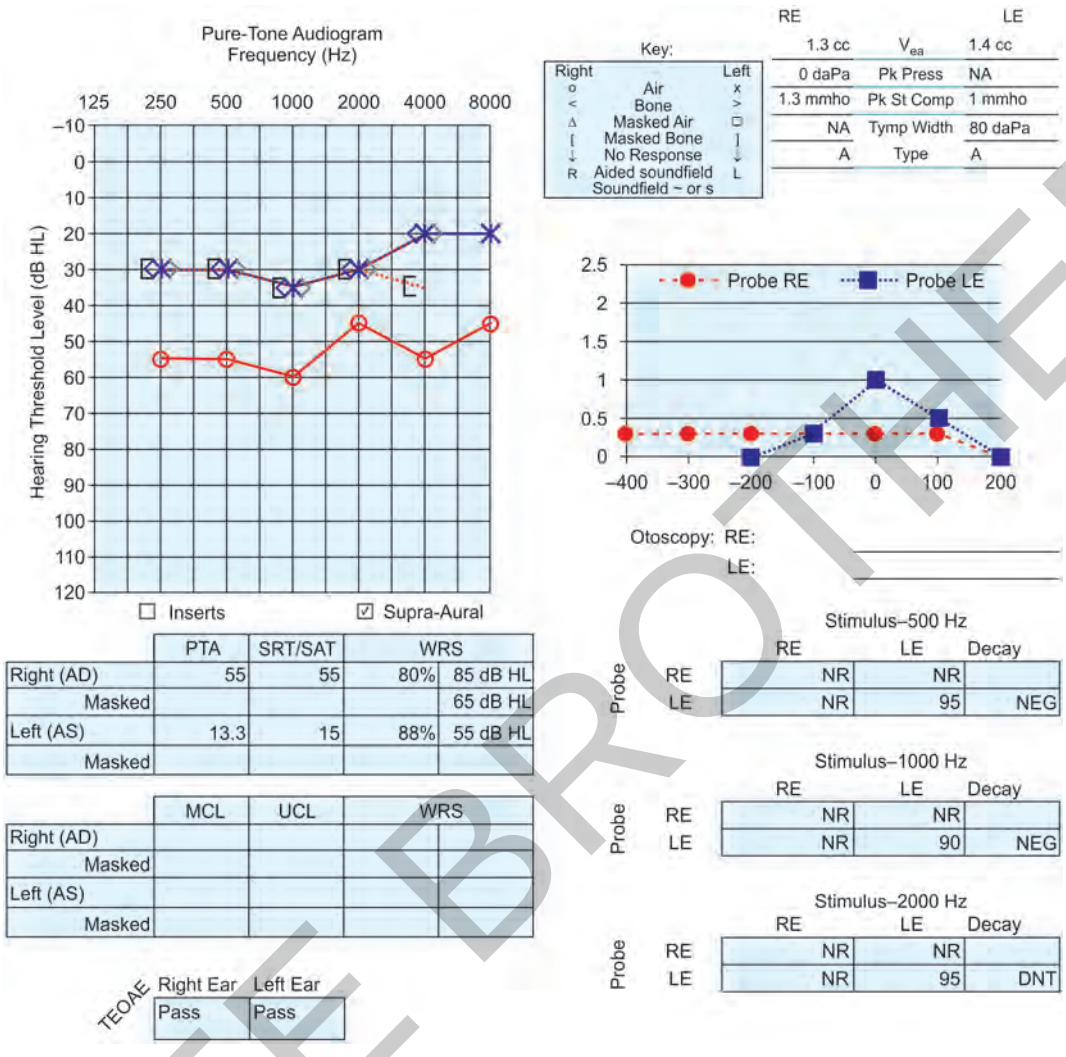


Fig. 2.5: These results are for a 55-year-old patient with a history of a mild sensorineural hearing loss. He came to the clinic complaining of stuffiness and pressure in the right ear. Left ear thresholds reveal a mild sensorineural loss from 250 to 2000 Hz, rising to normal hearing at 4000 Hz. Right ear thresholds reveal a moderate mixed loss at 250 and 500 Hz, sloping to a moderate loss at and above 1000 Hz. The air-bone gaps present from 250 to 4000 Hz, and the bone conduction thresholds >25 dBHL indicate a conductive component in that ear. Tympanometry reveals a flat configuration in the right ear, and a normal result in the left ear. TEOAE responses were "refer", bilaterally. Recommendations for this patient should include referral to an otolaryngologist, and annual audiologic evaluations.

and 50–100 daPa for adults. Abnormal tympanometric width should be considered an indication of middle ear dysfunction.[23]

In 1970, Jerger introduced a classification system for tympanograms using a 226 Hz probe tone that is still in use today. Based on this system, tympanograms are characterized as either type A, A_d, A_s, C, or B.[24]

During tympanometry, the external ear canal pressure is changed from atmospheric pressure (0 daPa) to 200 daPa above the ambient pressure and down to 200–600 daPa below the ambient pressure. As would be expected, maximum compliance will be obtained when the pressure on each side of the tympanic membrane is the same. So, in order to evaluate middle ear status in a clinical population, the pressure in the outer ear is adjusted to find the point of maximum compliance. In some cases, there is no point of maximum compliance (Jerger type B). This is commonly seen in patients whose ears have middle ear effusion or have patent ventilating tubes in the tympanic membrane.

In cases where the pressure in the external canal has to be a negative value to achieve maximum compliance, the tympanic membrane has been shown to be retracted into the middle ear space (Jerger type C).

Table 2.1: Normative data for use in interpretation of tympanograms*

Type	*Ear canal volume (ECV) in cc*	*Tympanometric peak pressure (daPa)†*	*Admittance (mmho)*
A	0.6–1.5 (adults) 0.4–1.0 (children)	+100 to −100 daPa	0.3–1.4 mmho (adults) 0.2–0.9 mmho (children)
A_d	0.6–1.5 (adults) 0.4–1.0 (children)	+100 to −100 daPa	>1.4 mmho
A_s	0.6–1.5 (adults) 0.4–1.0 (children)	+100 to −100 daPa	<0.3 mmho (adults) <0.2 mmho (children)
C	0.6–1.5 (adults) 0.4–1.0 (children)	>−100 daPa	0.3–1.4 mmho (adults) 0.2–0.9 mmho (children)
B	Varies based on pathology: PE tubes, perforations, etc. = larger ECV	No peak recorded	Essentially flat

*Values in this table are taken from ASHA.[22]

†It should be noted that there is no clear cutoff in terms of peak pressure which definitely indicates the presence of middle ear effusion. The norms listed above should be considered in conjunction with case history, otoscopy, and audiometric findings.

For patients who have normal middle ear pressure (i.e. the point of maximum compliance is at ambient pressure) (Jerger type A), there can be changes in mobility of the middle ear system. The mobility may be reduced (Jerger type A_s) or greater than normal (Jerger type A_d). These tympanogram types may be seen in patients with stapes fixation or ossicular discontinuity, respectively.

It should be noted that these Jerger classifications that were established in the 1970s are still in use but are not adequate to completely describe middle ear function. Further, the use of these classifications is limited to findings obtained with a 226 Hz probe tone in adults. Because the typical middle ear system is stiffness dominated, the use of this probe frequency does not allow an analysis of the effects of changes in mass on the middle ear system.

In order to further assess the effects of changes in middle ear stiffness and the possible effects of changes in mass components on the middle ear, multifrequency, multicomponent tympanometric protocols have been developed. The details of this type of tympanometry are beyond the scope of this chapter but interested readers should consult Wiley and Fowler.[25]

An area of middle ear assessment that is beginning to be used clinically is wideband reflectance. This is a procedure that does not require a pneumatic seal or adjustment of pressure in the outer ear canal to evaluate the middle ear system. In the future, wideband reflectance may prove to be a more flexible tool than tympanometry. This technique relies on measurement of amount of energy that is transferred through the middle ear system and so gives information about the input impedance of the middle ear. Using this technique, we get an estimate of the magnitude of reflectance as a function of frequency. The reflectance is a ratio of the reflected sound to the input sound. A low reflectance value indicates that most of the sound power in the incident wave is delivered to the middle ear system. In contrast, a high reflectance value indicates that most of the sound power is reflected back into the ear canal. For more information regarding this tool, *see* Keefe and Feeney.[26]

Figures 2.6 to 2.10 provide examples of the most commonly observed tympanograms elicited in response to a 226 Hz probe tone.

Acoustic Reflexes

Measurements of acoustic reflexes are useful in the evaluation of middle ear function, auditory nerve function, brainstem function, and facial nerve function. It is important to note that the acoustic reflex threshold is an indirect measure of the integrity of the reflex pathway. In order to measure an acoustic reflex, the stapedius muscle must contract. Contraction of the muscle creates a change in middle ear compliance that can be observed. The acoustic reflex is a bilateral event. Observation of a compliance change in the same ear as the reflex activating stimulus (RAS) is referred to as an ipsilateral reflex. In contrast, an observation of a change in compliance in the ear opposite the RAS is referred to as a contralateral reflex. The lowest stimulus level that produces a change in acoustic admittance is the acoustic reflex threshold. Studies document normal thresholds of 70–100 dB SPL for tonal stimuli ranging from 500 to 2000 Hz. Reflex thresholds that are >100 dB SPL are considered elevated. Elevated or absent acoustic

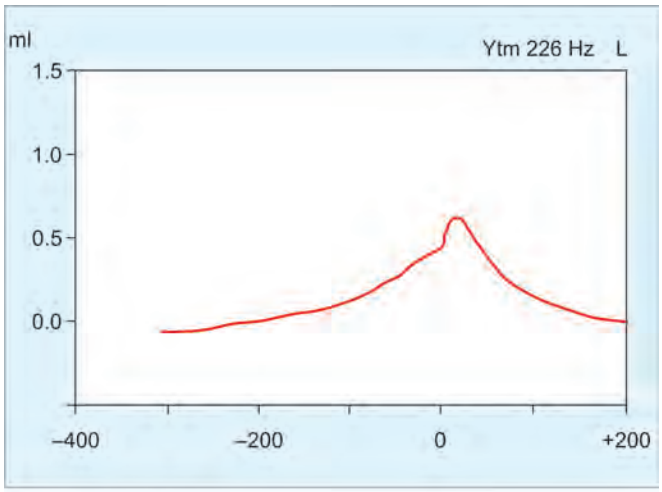


Fig. 2.6: Example of a normal, type A tympanogram. This is typically seen in individuals with normal hearing or sensorineural hearing loss. Note the peak at 0 daPa.

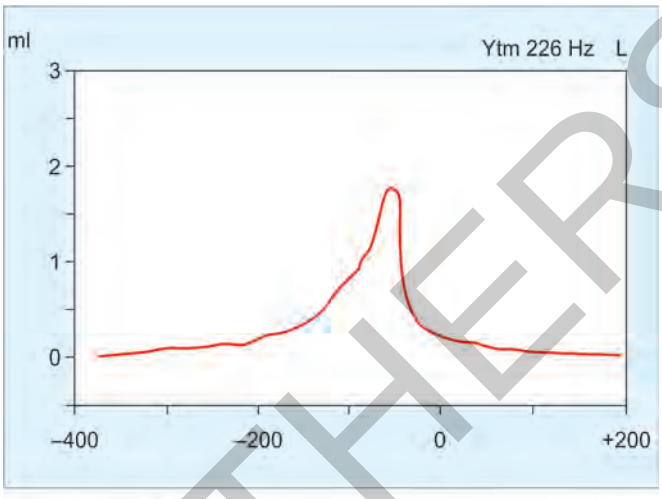


Fig. 2.7: Example of a hypermobile tympanic membrane, a type A_d tympanogram. This is typically seen in individuals with an ossicular discontinuity or a flaccid tympanic membrane. Note the peak at 0 daPa.

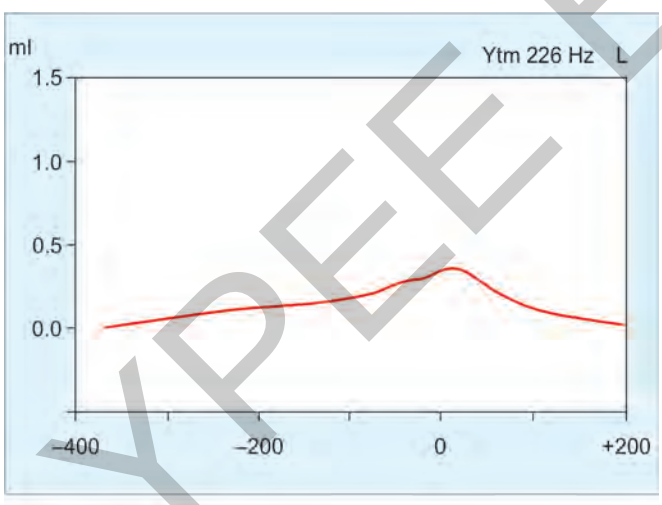


Fig. 2.8: Example of a hypomobile tympanic membrane, a type A_s tympanogram. This is typically seen in individuals with an otosclerosis. Note the peak at 0 daPa.

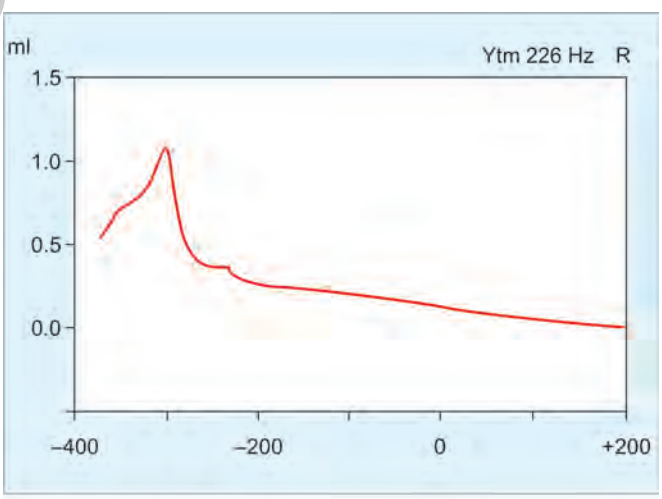


Fig. 2.9: Example of a middle ear with negative peak pressure, a type C tympanogram. This is typically seen in individuals with a retracted tympanic membrane. Note the peak at –300 daPa.

reflex thresholds in an individual with normal hearing or a sensorineural hearing loss may be indicative of a retrocochlear lesion and require further investigation. Acoustic reflex thresholds <70 dB SPL are consistent with cochlear hearing loss. If a patient exhibits a type B tympanogram, and/or has significant other middle ear pathology, acoustic reflexes will most likely be absent. Figures 2.11A and B provide examples of acoustic reflex thresholds measured at 500 and 1000 Hz.

A decrease in the strength of the stapedius contraction during continuous stimulation is referred to as acoustic reflex decay.[27] Acoustic reflex decay is usually tested contralaterally at 500 and 1000 Hz. Reflex decay testing involves the presentation of a tone at 10 dB above the contralateral acoustic reflex threshold. The tone is presented for 10 seconds. If, during that time, the response decreases by 50% or more, decay is considered to be positive. Abnormal, or positive, reflex decay is often a sign of possible retrocochlear pathology. This finding should be considered together with the rest of the test battery and analyzed in conjunction with other results.

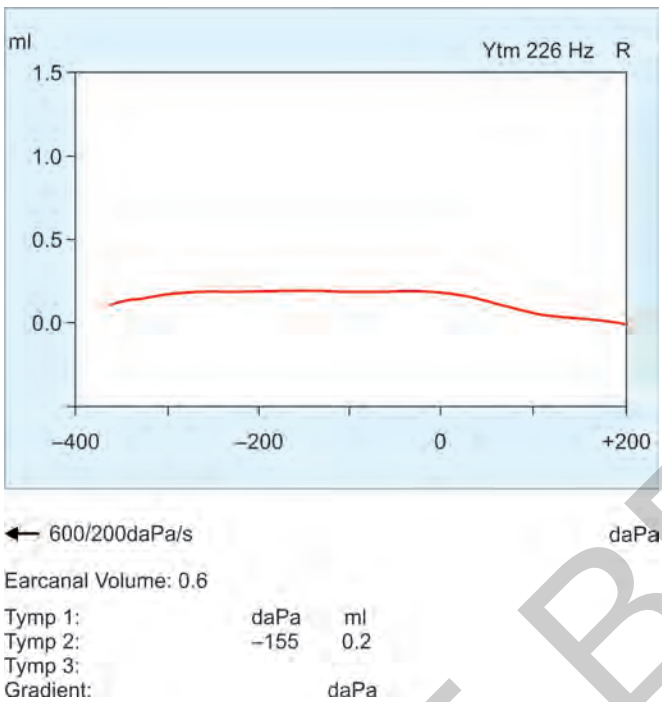
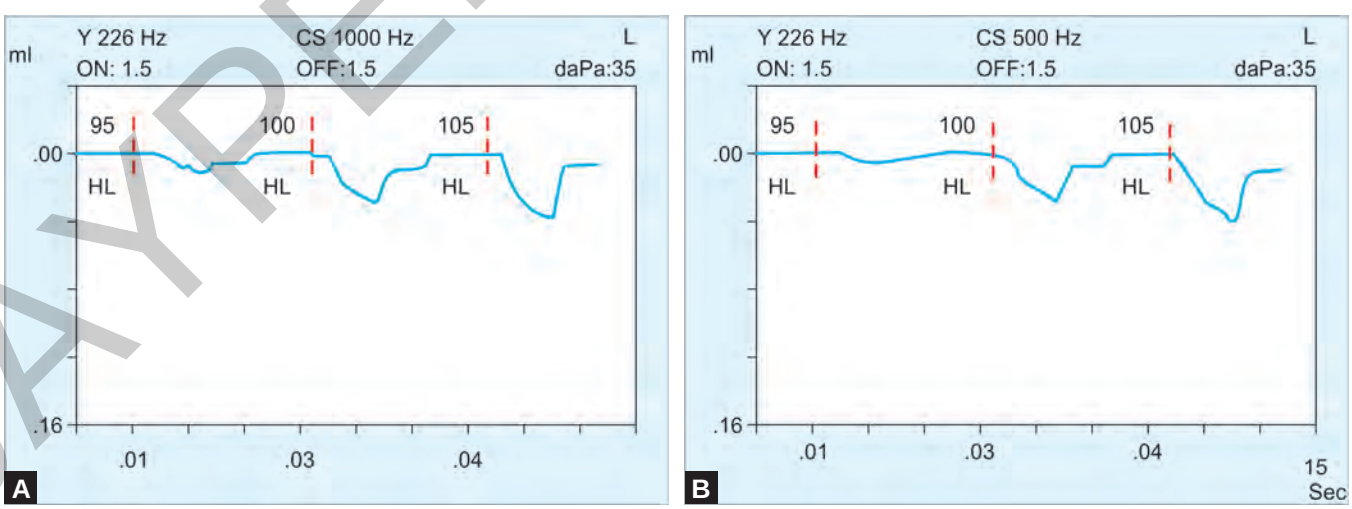


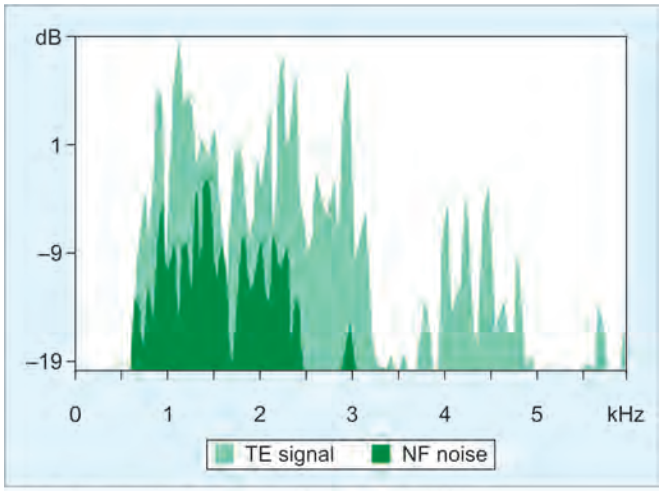
Fig. 2.10: Example of a tympanic membrane with little or no mobility, a type B tympanogram. This is typically seen in individuals with a fluid filled middle ear or impacted cerumen. Note the absence of a peak in the tympanogram.

Otoacoustic Emissions

Robust OAEs are indicative of healthy outer hair cell function. These emissions are typically observed in response to an evoking stimulus. Clinically, OAEs are used to measure small changes in hearing status that may not be detectable by traditional audiometry. This is an excellent tool for monitoring cochlear status in patients with noise-induced hearing loss or exposed to any ototoxic medications or radiation. OAE testing is objective and does not require a behavioral response from a patient. Thus, it is also used to rule out functional hearing loss. The test is noninvasive, easy to administer, and provides rapid results; therefore, OAEs are often used as part of a newborn hearing screening process.



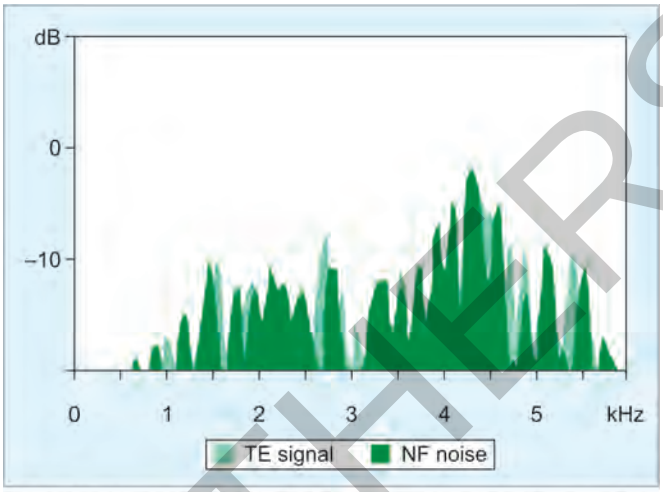
Figs. 2.11A and B: Contralateral acoustic reflex thresholds measured at 500 and 1000 Hz in the patient's left ear. According to these results the reflex threshold at both 500 and 1000 Hz is at 100 dBHL.



Left: 23-Apr-13: Stab: 99% : TE test: 13D23T01. TE

Frq(kHz)	Repor(%)	TE(dB)	NF(dB)	TE-NF(dB)	Result
1.0	94	15.1	0.7	14.4	–
1.5	73	12.2	4.1	8.1	–
2.0	91	15.5	1.5	14.0	–
3.0	99	11.4	–6.3	17.7	–
4.0	96	5.0	–11.0	16.0	–
1.2-3.4	83	18.2	6.3	11.9	–

Fig. 2.12: Transient emissions recorded from 1000 to 4000 Hz. Note that the reproducibility percentage is higher than 70% at all frequencies and the TE-NF (transient emission-noise floor) ratio is of sufficient amount (10 dB for adults, 15–20 dB for children, at all frequencies.[30] This TEOAE test would be considered a "pass" overall.



Right: 03-May-13: Stab: 100% : TE screen: 70% at 3/4 freq. for Pass: 13E03T00. TE

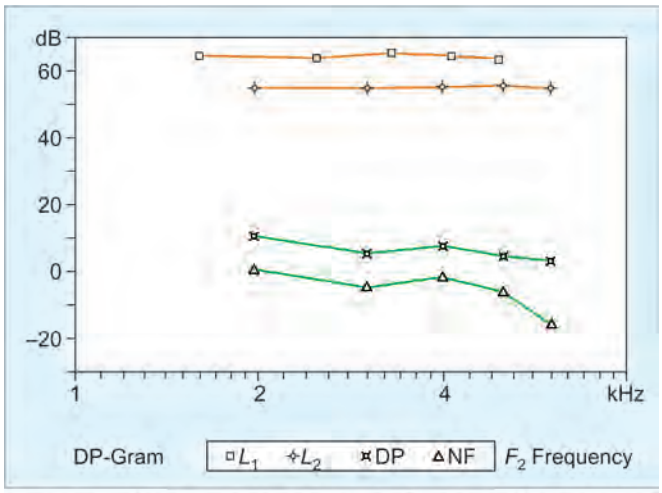
Frq(kHz)	Repor(%)	TE(dB)	NF(dB)	TE-NF(dB)	Result
1.0	0	–9.0	–7.7	–1.3	–
1.5	0	–4.8	–4.5	–0.3	Refer
2.0	0	–4.1	–1.5	–2.6	Refer
3.0	2	–0.8	–1.2	0.4	Refer
4.0	2	6.7	6.6	0.1	Refer
1.2-3.5	0	1.9	2.6	–0.7	–

Fig. 2.13: Transient emissions tested from 1000 to 4000 Hz. Note the reproducibility percentage is between 0% and 2% at all frequencies and that the TE-NF ratio is poor at all frequencies. This TEOAE test would be considered an overall "refer".

Testing is done by placing a probe assembly in the external auditory meatus to both present a stimulus and record a response. The indirect evaluation of the cochlea obtained by using OAE protocols helps to separate the effects of changes in cochlear and neural function. Common clinical practice utilizes distortion product otoacoustic emission (DPOAE) and/or transient evoked otoacoustic emission (TEOAE) protocols. The presence of these emissions indicates that hearing sensitivity is no poorer than 30 dBHL. Interpreting OAE results is an important portion of an audiometric evaluation, especially for ruling out auditory neuropathy and functional hearing loss. Auditory neuropathy is a result of the lack of synchrony in the auditory nerve. It should be noted that there will be times when an emission may be present, but cannot be recorded as a result of middle or outer ear pathology.

TEOAEs are recorded in the range of 250–4000 Hz for children[28] and from 500 to 6000 Hz for adults[29] at a stimulus level of approximately 80 dB SPL. TEOAE results may be confounded by the presence of background noise and are not utilized as often as DPOAEs due to this phenomenon. These emissions are recorded between stimulus presentations; therefore, TEOAEs evaluate the outer hair cell status in a resting state. Figures 2.12 and 2.13 provide examples of TEOAE measures. Test results shown in Figure 2.12 reveal a robust response indicating normal outer hair cell functioning. In contrast, results shown in Figure 2.13 suggest abnormal outer hair cell function.

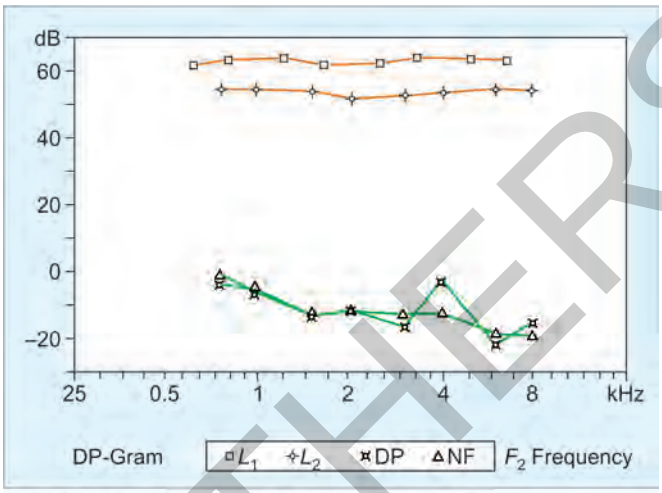
DPOAEs are elicited by presenting two primary simultaneous pure tones that are fairly close in frequency; the emission is usually observed at one of the distortion products that is created. The most prominent distortion product is the cubic distortion product that occurs at $2F_1 - F_2$. Examples of DPOAEs are shown in Figures 2.14 and 2.15. In a clinical setting, the primary tones used to elicit the OAEs are typically in a frequency ratio of 1.1 to 1.3; and the levels may be equal or may be separated by 10 dB. For example, the first row of frequencies and levels shown in Figure 2.14 below are F_1 = 4922 Hz and F_2 = 6000 Hz (F_1:F_2 ratio = 1.2) and the levels are separated by 9.9 dB (L_1 = 63.8 dB and L_2 = 54.9 dB). The cubic distortion product should be observed at 3884 Hz. This test measures responses from narrow regions of the cochlea when the outer hair cells are active. DPOAEs are most reliable when recorded in the frequency range from 750 to 16,000 Hz.



Left: 10-Nov-11: Pass: 2-6 kHz Screen, 3/5 for Pass: 11K10D01.OAE

L_1(dB)	L_2(dB)	F_1(Hz)	F_2(Hz)	GM(Hz)	DP(dB)	NF(dB)	DP-NF(dB)	Result
63.8	54.9	4922	6000	5434	4.9	–16.2	19.1	Pass
64.9	55.6	4125	5016	4549	4.4	–6.4	10.8	Pass
65.7	55.4	3281	3984	3616	7.5	–1.6	9.1	Pass
64.3	55.2	2484	3000	2730	5.1	–4.8	9.9	Pass
64.8	55.1	1594	1969	1771	10.4	0.6	9.8	Pass

Fig. 2.14: Distortion product emissions recorded from 2000 to 6000 Hz. Note the L_1 and L_2 values are 65 and 55 dB, respectively. The output shown above also reports the geometric mean (GM) of F_1 and F_2, which is a value in between the F_1 and F_2. Note the DP-NF ratio is well above 6 dB at all frequencies and the DP itself is above –6 dB. This patient would be considered to have "passed" the test.



Left: 26-Apr-13: 750-8000 HzTest: 13D26D01.OAE

L_1(dB)	L_2(dB)	F_1(Hz)	F_2(Hz)	GM(Hz)	DP(dB)	NF(dB)	DP-NF(dB)
64.1	55.0	6516	7969	7206	–15.0	–18.9	3.9
64.6	55.5	4922	6000	5434	–21.6	–18.2	–3.4
64.7	54.4	3281	3984	3616	–2.2	–12.1	9.9
63.2	53.3	2484	3000	2730	–16.4	–12.3	–4.1
62.7	52.6	1641	2016	1818	–11.5	–11.4	–0.1
64.6	54.5	1219	1500	1352	–14.1	–12.5	–1.6
63.9	55.2	797	984	886	–5.1	–6.4	1.3
62.4	55.0	609	750	676	–3.9	–1.0	–2.9

Fig. 2.15: Distortion product emissions tested from 750 to 8000 Hz. Note the L_1 and L_2 values are 65 and 55 dBHL, respectively. Note the DP-NF ratio is below 6 dB at all except for one frequency and that the DP itself is not above 6 dB at all frequencies. This patient would be considered a "refer" response.

A determination of a "pass" versus "refer" depends on the protocol employed by each clinical setting and/or recording instrument. For TEOAEs many audiologists will accept a reproducibility rate of anywhere from 50% to 70% for an emission to be considered present, in addition to the ratio of emission over noise floor. The program employed for recording TEOAEs generates a wave reproducibility value that is expressed as a percentage. The closer this reproducibility value is to the preset determining value, the stronger the emission. For DPOAEs, they must be measured at least 6 dB above the noise floor and the DP itself must not be <-6 dB.

Auditory Brainstem Responses

Physiologic testing of the auditory portion of the brainstem is referred to by many different acronyms. These include BSER (brainstem evoked response), AEP (auditory evoked potential), BAER (brainstem auditory evoked response), ABAER (automated brainstem auditory evoked response), or the most commonly used acronym, ABR (auditory brainstem response). Although there is considerable variability among individuals, it is generally expected that the ABR will be seen in the first eight milliseconds following the auditory stimulus.

An ABR records the electrical response to an auditory stimulus in the brainstem using electrodes. This is accomplished using equipment to present the stimuli and amplifiers and signal averaging equipment to amplify and record the response. A normal ABR response is characterized by five distinct peaks in the waveform. These peaks are marked using Roman numerals and are thought to be generated from the lower portion of the brainstem. Traditionally, waves I, III, and V offer the most clinical utility. Evoked potential protocols that are used to record responses from higher up the brainstem and cortex are also available, and are referred to as middle latency response (MLR) and late auditory evoked potentials (cortical ERPs); these are not typically used in the clinical setting.

Evoked potential testing may be used as part of a neuro-otologic evaluation or in threshold estimation for difficult to test patients. Often times, newborn hearing screening programs use an automated ABR protocol called ABAER. Typically, click stimuli are used for evaluation of

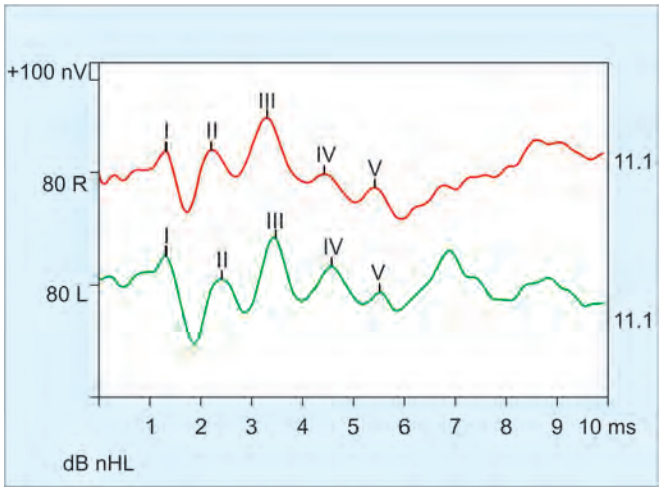


Fig. 2.16: Neurologic ABR for a 26-year-old male known to have normal audiometric thresholds. Testing completed using click stimuli with two channel electrode array with low forehead as ground. The intensity level was 80 dB, which is suprathreshold to obtain accurate recording with a rate of 11.1 clicks per second. Note that waves I–V are marked for the right ear (80R) and the left ear (80L). This is a normal neurologic ABR based on the absolute latencies, interpeak latencies, and interaural latencies.

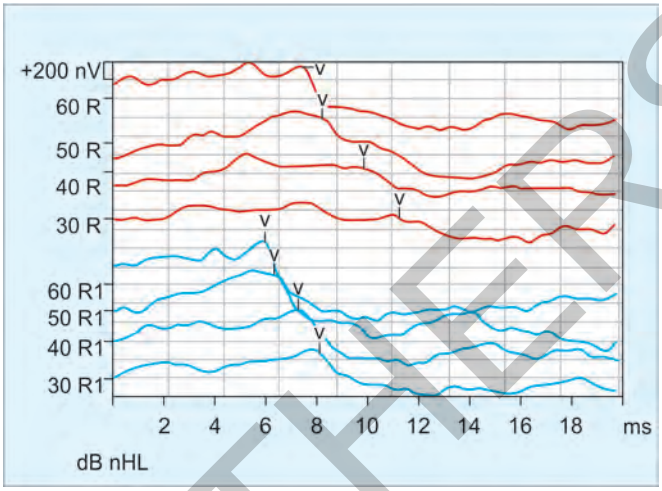


Fig. 2.17: Results for a 23-year-old female known to have normal audiometric thresholds bilaterally. ABR obtained using tone burst stimuli (top 4 waves) and using CE-Chirp (Interacoustics EP25) stimuli (bottom 4 waves) with 1 channel electrode array using nontest ear as ground. Note that threshold search for both stimuli begins at 60 dBHL and continues in 10 dB decrements to 30 dBHL to determine threshold. Presence of wave V is marked, indicating hearing is present at that frequency and intensity. Note that as recording intensity decreases and approaches the threshold of the patient, the latency of wave V increases and the amplitude of wave V decreases.

neurologic integrity as shown in Figure 2.16. In contrast, toneburst stimuli from 500 to 4000 Hz are used for threshold evaluation. An example of toneburst responses is provided in Figure 2.17. If a conductive loss is suspected, bone conduction ABR threshold testing is available.

The evaluation of individual ABR tracings includes assessment of the morphology of the waveform as well as the peak latencies, the interpeak latencies and interaural intervals. Otoneurologic evaluation using ABR is done at suprathreshold levels and is designed to evaluate the integrity of the auditory nerve and/or cochlear status. For threshold evaluation, in difficult to test populations, the presence of wave V is used to estimate thresholds. The ABR response is influenced by the degree of hearing impairment of the subject. For example, if a patient has a moderate sensorineural hearing loss, their wave V will disappear at a higher intensity tone burst level when compared to a subject with normal hearing or a mild hearing loss. In order for hearing impairment to be estimated, the ABR recordings done in nHL need to be converted to an eHL (equivalent). The eHL value varies with the type of ABR system and the normative data obtained by each clinical site. In addition, depending on which equipment is being used, the evoked response may be affected by degree of patient arousal.

Electrocochleography

Electrocochleography (ECochG) is a physiologic examination of the relationship between the summating potential (SP) and the action potential (AP) of the eighth nerve. Clinically, it is useful for diagnosis and monitoring of patients with suspected Meniere's disease. The ECochG is most likely to be clinically significant when the patient is exhibiting active symptoms of Meniere's disease. A common ECochG analysis approach is calculation of SP and AP amplitude (in microvolts) from a common baseline, and then computation of an SP/AP amplitude ratio.[31] Normative data indicate a mean SP/AP amplitude ratio to be 0.26 μV using a tympanic membrane electrode site,[32] 0.24 μV using an ear canal electrode site[33] and 0.16 μV using a transtympanic electrode site.[34] The SP/AP ratio can be recorded using a transtympanic electrode or a far-field array. The far-field recording technique is used more commonly as it is less invasive; however, it should be noted that due to the distance between the electrode and the generation site of interest, responses may be difficult to interpret. Far-field recordings typically place an electrode against the skin of the ear canal or the surface of the tympanic membrane.

Video Nystagmography

Video nystagmography (VNG) is used by audiologists to assess the peripheral and central vestibular systems. As with all assessments, a case history is a crucial part of assessing a dizzy patient. Testing is conducted using infrared goggles connected to a computer system to record eye movement and to deliver visual stimuli. In addition, a caloric irrigator is necessary for the peripheral system to be evaluated. There are three main components of a VNG test battery: ocular motor, positional/positioning, and caloric testing. Results are analyzed based on presence and degree of nystagmus, if any, and subjective dizziness experienced by the patient. The VNG is an integral test to evaluate dizziness because it relies on objectively recording eye movements. The test results can provide information about inner ear function that may be missed by imaging and electrophysiologic testing. During all portions of the VNG, horizontal and vertical eye movements are measured.

The ocular motor portion of the test battery includes assessing saccadic, pursuit, and optokinetic movements of the eye as well as the ability to gaze-hold in different directions. The presence of nystagmus may indicate a possible ocular disorder, peripheral vestibular disorder or a central vestibular issue that may be contributing to the patient's complaint of dizziness. Positional testing allows the audiologist to evaluate the posterior, anterior and horizontal semicircular canals by having the patient manipulate their head and body into various positions. The positional portion of the evaluation is analyzed for the presence and degree of nystagmus within the different positions, with and without fixation. The presence of nystagmus, as well as any consistent pattern, can provide the audiologist with information about how the central or peripheral vestibular system is functioning.

Caloric testing is the final portion of a complete VNG test battery. Prior to beginning testing, an otoscopic examination should be completed to be sure that the tympanic membrane is intact and there is no obstruction in the ear canal. An irrigator with air or water is used to present the stimulus to the ear canal. By changing the temperature of the stimulus in the external auditory canal, the endolymph within the semicircular canals is affected. Once the endolymph begins to move, the vestibulo-ocular reflex is elicited producing nystagmus. Typical caloric procedures employ the bithermal and bilateral method. This requires that cool air (or cool water) and warm air (or warm water) be presented to each ear in separate trials. It is important to remember that test protocols may vary by clinic and audiologist.

Further information on vestibular anatomy and physiology and assessment can be found in additional chapters of this text.

THE FUTURE OF AUDIOLOGY

Audiology at its heart is a problem-solving profession. As members of the hearing healthcare team we are faced with the need to properly assess the communication challenges that our patients face and to determine intervention strategies that will maximize their ability to function in society.

There are many techniques that can be used to assess sensory functions related to hearing and balance and evaluate impairments of the ear and related functions. There are also intervention strategies (described elsewhere in this text) to facilitate the removal of barriers to participation. In particular, the use of products for communication (e.g. hearing aids and other assistive devices) may mitigate, at least in part, the effects of the changes in sensory function and auditory impairment that may limit participation in meaningful life activities.[35]

Audiology, like other disciplines, never seems to stand still. Assessments of hearing, balance and communication function are all essential elements of audiologic practice. The rapid increases in available technology have rendered many of the behavioral tests used prior to the 1980s (e.g. Short Increment Sensitivity Index and Alternate Binaural Loudness Balance) as antiquated and of little use. In their place, electrophysiologic tests of (1) the middle ear system (multi-frequency acoustic immittance test battery, wideband power reflectance), (2) the outer hair cells of the inner ear (OAE), (3) the inner ear and the lower brainstem (acoustic reflexes, OAE, masking level difference, and ABR), and (4) the rest of the auditory pathway [MLRs, event-related potentials (ERPs)]. MLRs and ERPs are a sophisticated evaluation of the brain's response to acoustic signals and multimodal signals (visual and auditory interactions) in ecologically valid conditions. To date, MLR and ERP assessments of an individual's brain response have been limited to research laboratories. Given the equipment required for these measurements this is unlikely to change in the near future. Nonetheless, there is a consistent pressure to assess our patients where they live.

Thus, we are challenged to examine each patient's sensory function, ear and vestibular impairment, and restrictions on communication in realistic environments and with tasks that are representative of the demands made on them. Adequate assessment and intervention requires the special expertise of audiologists, but must be done in a way in which the patient is at the center of the team; expertise

from a number of professionals (e.g. otolaryngologists, optometrists, social workers, and speech-language pathologists) is brought to bear in order to reduce the effects of the changes in sensory function and impairment on the individual's communication and day-to-day activities.

Exciting changes are in the future regarding assessment and intervention of auditory function. Through the use of simulations, patients can be tested in situations that are more representative of their everyday life than those situations found in the typical audiometric test booth (i.e. listening to pure tones and monosyllabic words in quiet). For example, virtual tests have been developed to evaluate localization ability and speech understanding in realistic environments containing both reverberation and background noise.[36,37]

There have also been a multitude of assessment tools in which the tasks are made more demanding by the introduction of noise so that the perceptual system is taxed in a way that more closely approximates everyday listening experiences. These tools are making their way into the clinical arena and will improve the ability of audiologists to assess function and impairment. In order to provide more appropriate intervention we need to do more ecologically valid assessment of communication function. In the future, we will likely find ourselves assessing not only the sensitivity and function of the auditory and vestibular systems but also doing multimodal assessments and examining the brain's response to experiences that are closely related to everyday experiences.

Another area of growth that has significant effects on our patients is the impact of the ever-increasing knowledge of genetics that is being held by clinicians of all perspectives. For example, understanding the role of the inheritance of the *POU4F3* gene in progressive hearing loss in humans changes the way that intervention is planned. This knowledge also increases the need to address possible limitations in participation by all members of the family—those affected and those unaffected by the mutation. Knowledge about the impact of mutations in the *GJB2* gene can influence decisions made by a clinician or a team of clinicians with regard to the use of a cochlear implant over conventional amplification. An understanding of the role of mitochondrial 12S rRNA mutations in nonsyndromic hearing loss and aminoglycoside sensitivity will allow prediction of individuals who are at risk for ototoxicity and will improve the outcomes of individuals who may undergo such therapy.

As our profession changes with advances in technology to facilitate assessment and intervention, we will remain rooted in one of the most important clinical tasks—listening to our patients as they describe their symptoms and the barriers that they face that limit their participation and activity in their everyday lives. There is an exciting future ahead for audiologists, particularly with the move toward interprofessional care of our patients.

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Anil K Lalwani MD is Professor and Vice Chair for Research, Director of Division of Otology, Neurotology and Skull Base Surgery, and Director of Columbia Cochlear Implant Program in the Department of Otolaryngology—Head and Neck Surgery at Columbia University College of Physicians and Surgeons. He also serves as Medical Director of Perioperative Services at New York Presbyterian—Columbia University Medical Center and recently served as President of the American Neurotology Society. He previously served as Chairman of Otolaryngology at New York University School of Medicine.

Dr Lalwani earned his MD from the University of Michigan Medical School in 1985 and subsequently completed his internship in General and Thoracic Surgery at Duke University Medical Center and his residency in Otolaryngology—Head and Neck Surgery at University of California San Francisco (UCSF). Following subspecialty training in Neurotology and Skull Base Surgery, he served as Senior staff Fellow at the National Institute on Deafness and Other Communication Disorders, National Institute of Health. In 1994, he joined the faculty at UCSF as an assistant professor and rose to the rank of Professor in 2002. In April 2003, Dr Lalwani was recruited to New York University School of Medicine to serve as Mendik Foundation Professor and Chairman of the Department of Otolaryngology—a position he held until December 2009.

Dr Lalwani's basic research has focused on two key areas: identifying genes that are critical for hearing through the use of molecular genetic and molecular biologic methods, and developing and investigating gene transfer technology for the treatment of hearing disorders. His clinical interests in otology include cochlear implantation, chronic ear disease, facial nerve disorders, cerebellopontine angle tumors (e.g. acoustic neuromas), and skull base surgery.

Dr Lalwani is considered one of the leading experts on hearing loss in children and adults. He is the author of more than 180 peer-reviewed articles, and numerous book chapters. He serves on the editorial board of numerous leading otolaryngology journals; he is the Section Editor of Triological Society Best Practice—a popular feature published in *Laryngoscope*. He has published numerous books including the textbook defining the subspecialty of Pediatric Otology and Neurotology. The 3rd edition of his highly successful second book, Current Diagnosis and Treatment in Otolaryngology—Head and Neck Surgery has been translated into Spanish, Turkish and Portuguese. The 3rd edition of Recent Advances in Otolaryngology—Head and Neck Surgery was just published.

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