Paparella: Volume II: Otology and Neuro-Otology

Section 2: Audiology

Chapter 5: Hearing Measurement in Children

M. Wende Yellin

Hearing is necessary to learn language and speech and to develop cognitive skills. Through hearing, the developing child learns to recognize sounds, identify objects and events, and internalize concepts. By imitating models, words and sentences are formed and ideas and feelings are expressed. Because hearing is so important for normal educational and social development, hearing loss can be devastating. The developing child must pass through critical periods of language acquisition, and even a mild hearing loss can interfere with this natural growth. Early identification and treatment are essential to minimize the handicapping effects of hearing loss.

The hearing of every child can be evaluated. Auditory behavior follows a hierarchy of development, and audiologists know appropriate procedures to follow. Flexibility is the key, and testing must be adapted to the child's response level. A child's inability to respond as expected may identify a handicapping condition; however, hearing loss can be identified in even the most uncooperative child by combining objective and behavioral measures. The purpose of this chapter is to present procedures used to evaluate hearing in children.

Neonatal Screening

In order to guarantee early identification of hearing loss, neonates can be evaluated before being discharged from the nursery. Early screening studies of every newborn found a high incidence of false-positive and false-negative results, and these tests proved to be expensive. Since the incidence of hearing loss in the special-care nursery has been estimated as 1 in 56, compared with 1 in 750 in all neonates, this population obviously needed attention, but not at the risk of missing hearing problems in well babies. The Joint Committee on Infant Hearing and Screening, made up of representatives from the Academy of Otolaryngology-Head and Neck Surgery, the American Academy of Pediatrics, the American Nurses Association, and the American Speech-Language-Hearing Association, addressed this problem in 1982 and recommended factors to identify infants at risk for hearing loss.

The Infant High Risk Register lists the following factors:

1. A family history of hearing impairment.

2. Congenital perinatal infection such as cytomegalovirus, rubella, herpes, toxoplasmosis, and syphilis.

3. Anatomic malformations of the head and neck, such as dysmorphic appearance including syndromal and nonsyndromal abnormalities, overt or submucous cleft palate, and morphologic abnormalities of the pinna.

4. Birth weight less than 1500 grams.

5. Hyperbilirubinemia at a level exceeding indications for exchange transfusion.

6. Bacterial meningitis, especially *Haemophilus influenzae.*

7. Severe asphyxia, which may include infants with APGAR scores of 0-3 who fail to institute spontaneous respiration within 10 minutes and those with hypotonia persisting to 2 hours of age.

Infants identified in one or more of these categories should be screened by or under the supervision of an audiologist, preferably by 3 months of age, and no later than 6 months of age.

Once a child is being identified as being at risk for hearing loss, hearing should be evaluated. Testing while the infant is still in the nursery ensures that the infant's progress will continue to be observed and that follow-up recommendations will be charted. Several tests have been developed for neonatal screening. Behavioral procedures include the arousal test, the Crib-O-Gram, and the Auditory Response Cradle; physiologic procedures include auditory evoked potentials.

The arousal test is carried out in a quiet area in the nursery while the baby is in a light sleep state. A high-frequency narrow-band noise signal is presented for 2 seconds at a predetermined distance from the baby's ear. Trained observers must see an arousal from sleep on at least 2 of three presentations for the baby to pass the test. The arousal test is most useful if used in conjunction with the High-Risk Register.

The Crib-O-Gram is an automated system that measures an infant's movement in response to sound. A motion-sensitive transducer, placed under the infant's crib mattress, automatically monitors crib movement for 10 to 15 seconds before and 6 seconds after the presentation of a 90-dB sound pressure level (SPL) high-frequency narrow-band noise signal. A microprocessor unit performs, scores, and interpretes 30 trials, providing a pass/refer result with screening score. Although the Crib-O-Gram had promised to be a fast, efficient screening tool, recent studies have found that its poor reliability limits its usefulness, especially in the special-care nursery.

The Auditory Response Cradle is another automatic, microprocessor-controlled screening tool. The infant is placed in a "cradle" that monitors trunk and limb movements, head jerk, and respiratory patterns in response to an 85-dB SPL high-frequency narrow-band noise signal. Unlike the other two tests described, this procedure present the signal through ear probes coupled to the ears. No-sound "controls" are used to determine if changes are true responses to sound and not spontaneous behavior changes. Early studies with the Auditory Response Cradle are indicating greater efficiency and accuracy than screening with the Crib-O-Gram.

Behavioral measures are most successful at identifying severe-to-profound hearing loss. Many times mild or moderate hearing loss is missed because of the high-intensity noise signal, but the importance of behavioral test measures should not be ignored. The development of objective auditory measures, which is discussed later, has allowed clinicians to evaluate hearing sensitivity more confidently.

Behavioral Auditory Measures for Infants and Young Children

Although the High Risk Register and neonatal screening programs attempt to identify hearing loss before the child leaves the hospital, hearing loss may develop any time throughout the childhood, making testing a vital ongoing process. Infants born with normal hearing may suffer progressive degenerative hearing loss and must be identified. Children who contract illnesses such as meningitis, measles, and chickenpox, or who suffer from colds and accompanying middle ear infections must be tested. A child labeled slow and unresponsive should be tested as well as the child labeled hyperactive to rule out a mild or moderate hearing loss. When a parent voices concern, the child should be evaluated. a simple hearing test can relieve anxieties or bring about aggressive action to treat or minimize the effects of hearing loss.

Behavioral testing looks for an overt behavioral change linked to an auditory stimulus. When a passive procedure is used, the examiner observes the child for a response. When an operant conditioning procedure is used, the child responds and the response is reinforced. For behavioral testing to be successful, the examiner must know how a child is expected to perform. An auditory behavior index for infants has been developed that describes response levels based on the child's age.

Evaluation Procedures

Behavioral observation audiometry (BOA) provides the least information with regard to hearing sensitivity but is often the only method successful when testing an uncooperative child. This procedure is most effective with infants under 6 months of age and with children with developmental delays. An auditory signal is presented through soundfield speakers, and the child is observed. Any change in behavior, such as alerting, cessation of activity, eye widening, or facial grimacing, is accepted as a response. In some instances, a startle response to high-intensity stimuli may be the only behavioral change noted. BOA is considered a gross sensitivity measure, and responses should be considered minimum response levels. Children habituate quickly to this procedure, which limits its effectiveness as a measuring tool.

Conditioned orientation reflex (COR) audiometry and visual reinforcement audiometry (VRA) are successful with children from 6 months up to 3 years of age. Based on the orientation reflex, an audiometry stimulus is first paired with a light stimulus. The child is then conditioned to look at the light source following presentation of an auditory stimulus. COR was developed using only soundfield conditions and requiring an orienting response. VRA is less stringent, using speakers, earphones, or a bone vibrator to present the stimulus, and accepting any behavior change as a response. COR and VRA have been successful when testing hearing and hearing-impaired children and are quick, effective evaluation tools.

Play conditioning audiometry (PCA) is the most reliable procedure for obtaining thresholds in children over 2.5 years of age. After hearing a stimulus, the child is conditioned to drop a block in a bucket, place a peg in a hole, or perform some other play activity. This play activity, with accompanying verbal praise, is reinforcement that keeps the child's attention on the task. PCA is most effective when obtaining frequency-specific information and, unlike conventional testing, becomes a game. Testing can be performed in the soundfield, under earphones, or by bone conduction.

A variety of stimuli may be used for testing. BOA, COR, and VRA initially use speech stimuli because speech is interesting and maintains attention. If the child continues to cooperate once speech information is obtained, frequency-specific testing begins. Narrow-band noise or warbled tones are presented, as opposed to pure tones, to avoid standing wave problems and to maintain interest. For PCA, frequency-specific pulsed pure tones provide sensitivity information and keep the child's attention focused on the task. Masking is difficult to achieve in children under 5 years of age because it is disruptive and often difficult for the child to discriminate.

Speech Audiometry

A useful tool for the evaluation of hearing in children is speech audiometry. Speech audiometry is often omitted from the pediatric test battery because the child lacks the language skills, maturity, or intelligence to cooperate for testing. However, speech audiometry is often the most practical and successful procedure used because it is more concrete and interesting than pure tones. Speech audiometry verifies pure-tone audiometry results and determines how the child understands and uses auditory input. The tests most frequently performed are those of speech detection, speech reception, and speech understanding.

The speech detection threshold (SDT) or speech awareness threshold (SAT) is the lowest level at which speech is detected and recognized as speech. The SDT may be the only formal information obtained regarding hearing sensitivity, but it must be carefully interpreted. Speech is a broad-band signal, and when any portion of this broad band is detected, the child may respond. If the child has an irregular hearing configuration, such as in a high-frequency hearing loss, responses may indicate better overall hearing sensitivity, since only the range of best hearing is being measured. Despite this limitation, the SDT is an effective tool for conditioning a child for behavioral procedures and, if cautiously interpreted, provides some information regarding the presence of absence of hearing impairment.

The speech reception threshold (SRT) is the lowest level at which spondee words are identified 50 per cent of the time. Spondee words are two syllable words that have equal stress on both syllables (ie, hotdog, baseball). The test is quickly and easily performed by having the child repeat the word or point to an object or picture representing the word. The SRT correlates well with the pure-tone average and thus provides relevant information regarding hearing sensitivity. Although high-frequency sensitivity information continues to be limited with this procedure, the SRT provides some speech intelligibility information and is useful in confirming pure-tone audiometry results.

Speech discrimination tests measure the child's ability to understand speech. Although this information is essential in order to analyze listening skills, speech discrimination has not been fully developed or researched in children. Standards for normal function are difficult to establish because of individual development differences caused by age, speech and language levels, hearing status, and background. Speech testing must also be performed quickly to maintain attention levels so that the scores reflect the child's listening ability and not motivation level. Several tests have been developed for the pediatric population.

The PBK-50 word lists are phonetically balanced word lists geared to the kindergarten language level. In this open-set test, the child repeats the word presented. Although the procedure is efficient, the child's speech must be easily understood and attention must be maintained to complete a list of 25 or 50 words.

Several closed set procedures have been developed to address the problems of receptive language levels, speech intelligibility, and child cooperation. The discrimination by identification pictures (DIP) test is a two-choice picture identification test; whereas the word intelligibility by picture identification (WIPI) test is a four-picture forced-choice speech discrimination test. These tests require the child to point to a pictorial representation of the word presented. The auditory number test (ANT) asks the child to recognize sequences and individual numbers. The sound effects recognition test (SERT) presents familiar environmental sounds that the child must first recognize and then identify a picture representation of. Because of their limited language basis, these measures provide only gross information regarding speech understanding.

A new test developed with standardized norms for both hearing and hearing-impaired children is the pediatric speech intelligibility (PSI) test. To overcome the receptive language problem, a language screening is first performed. The appropriate PSI test format, using either monosyllabic words with a competing message or sentences with a competing message, is then selected. The child is presented the stimulus material and must choose from a closed picture set. The PSI test is a time-consuming procedure but is proving to be valuable in measuring both speech understanding and central auditory function in children.

Objective Auditory Measurement

Although early identification of hearing loss is crucial for normal cognitive development, the ability to confidently evaluate infants and difficult-to-test children has only become possible over the last 25 years. Objective test procedures have been developed that require no cooperation or active participation from the child. No longer must we wait until a child is 3 years old and is able to condition to play audiometry. No longer must we wonder if a mentally retarded child has the additional handicap of hearing loss. Objective auditory measures allow evaluation of all children whenever desired.

Auditory Evoked Potentials

The development of the electroencephalograph (EEG) offered new hope for physiologic hearing assessment. After years of research, auditory evoked potentials (AEPs) have become clinically useful measuring tools. AEPs are neuroelectric events that can originate from the cochlea, auditory nerve, or neuronal populations within the auditory central nervous system. The latency of the response determines which area of the pathway is being evaluated. AEPs not only measure hearing sensitivity but also the integrity of the central auditory pathway. Although much is yet to be learned from these potentials, AEPs are presently providing clinically useful information regarding hearing.

AEP testing depends on signal-averaging computers. AEPs are small-amplitude, time-locked responses. By the summation process possible with signal-averaging computers, the auditory potential can be measured while other electrical noise from the EEG, electrocardiograph (ECG), muscle potentials, and even electrical wall outlets is averaged out. Stimulus and recording parameters are adjusted to obtain optimal responses at specified latencies. AEPs include electrocochleography, auditory brain-stem response audiometry, middle latency responses, and long latency potentials.

Electrocochleography (ECoG)

ECoG is a measurement of the potentials generated by the inner ear and auditory nerve. ECoG is characterized by the summating potential (SP)(a cochlear receptor potential reflecting hair cell transduction) and the whole nerve action potential (AP) of the auditory nerve. The large-amplitude response is observed within the first 5 mseconds following stimulus presentation, with absolute latency of the SP and AP dependent on stimulus intensity.

The primary advantage of the ECoG is its ability to measure auditory sensitivity within 20 decibels of the patient's perceptual threshold; however, ECoG has not gained widespread clinical acceptance. To measure the SP and AP, electrode placement must be close to the round window. To achieve this recording montage and obtain an optimum response a transtympanic approach is necessary. This invasive procedure has limited the use of electrocochleography, but new recording techniques using ear canal electrodes hold promise for making ECoG a clinically feasible procedure.

Auditory Brain-Stem Response Audiometry

Auditory brain-stem response (ABR) audiometry is the most popular evoked potential technique used clinically for the measurement of hearing sensitivity. The procedure is noninvasive, easy to record, and requires no patient cooperation. Air conduction and bone conduction sensitivity as well as brain stem integrity can be measured for each ear with easy replication. Because of avid studies of the ABR, effective protocols and accurate norms have been established.

ABR audiometry does have some limitations. Although sensitivity thresholds can be derived, ABR audiometry provides no information regarding how the input is being processed. ABR audiometry measures sensitivity in the 1000-4000 Hz frequency region of the cochlea; thus, low-frequency sensitivity is ignored. To pick up these small-amplitude responses, the patient must be still. Children often must be given a mild sedative, such as chloral hydrate, before testing. Finally, the ABR depends on the neural integrity of the child. For example, no response may be present when evaluating a hydrocephalic child, although hearing sensitivity may be within normal limits.

The ABR is elicited within the first 10 mseconds following stimulus presentation and is characterized by a series of five waves. The source wave I is the auditory nerve; wave II is the cochlear nucleus; wave III is the superior olivary complex; wave IV is the lateral lemniscus; and wave V is the inferior colliculus. In normal adults, wave I appears approximately 2 mseconds following stimulus onset; each subsequent wave appears approximately 1 msecond apart. For infants under 8 months of age, the intervals are prolonged because of the infant's immature central nervous system. The overall latency of the ABR stabilizes and reaches its mature response at approximately 18 months of age. Testing children below this age requires a knowledge of infant norms and careful interpretation.

Optimum ABRs are elicited using a click stimulus. At high intensities, the five wave pattern is easily identified. As intensity is decreased, early waves begin to deteriorate and latency increases. Wave V remains the most robust, so threshold testing follows the wave V response until no repeatable response is detected. A graph of the latency of wave V at a specified intensity, called the latency-intensity (L-I) function, plots the threshold of hearing sensitivity. ABR recordings and the L-I function for a normal-hearing 10-month-old infant are shown.

A thorough knowledge of auditory brain-stem evoked potentials, normative data, and response patterns is necessary for accurate interpretation of the ABR. As mentioned above, wave V latency is followed until no response is observed. Perceptual sensitivity threshold in the 1000-4000 Hz sensitivity region is predicted to be within 20 dB less than the ABR threshold.

Different patterns of the L-I function provide useful information. If the L-I pattern of responses follows the normal curve but at delayed latencies, a conductive hearing loss is suspected. If the L-I pattern has a steep increase in latency as intensity is decreased, a high-frequency sensorineural hearing loss is suspected. If no response is observed to air conduction stimuli, bone conduction measures must be performed to rule out maximum conductive or mixed losses.

Although ABR audiometry is considered effective for measuring hearing sensitivity and for early detection of hearing loss and confirmation of hearing impairment in infants and difficult-to-test children, the results must be interpreted cautiously, realizing that this information gives only a general prediction for a high-frequency region and that this test cannot replace the behavioral information obtained from subjective measures.

Middle Latency Response

The middle latency response (MLR) is electrical activity elicited 10 to 50 mseconds following stimulus presentation. This response is characterized by an initial positive peak (Po) at 11 to 13 mseconds, a negative peak (Na) at 16 to 25 mseconds, and a prominent positive peak (Pa) at 25 to 35 mseconds, followed by a negative peak (Nb) at 35 to 45 mseconds. The area generating the MLR has not been determined, but it is speculated that myogenic, thalamic, and/or temporal lobe structures are responsible.

Early studies of adults found that the MLR is a good predictor of hearing sensitivity. Since tone pips proved to be effective stimuli, frequency-specific information could be obtained, and researchers began applying the test to infants and children. However, testing on children proved to be difficult, as results could not be replicated. Parameter variations and the state of the patient made interpretation difficult. These variations were not observed in ABR testing.

Further research now shows that stimulus rate seriously limits the clinical use of the MLR for threshold testing of children. At rates higher than 8 per second, no MLR is observed. Many averages, at rates as low as 1 per second, are necessary to elicit a response. The 40-Hz steady-state evoked response (SSEP), a good predictor of frequency-specific thresholds in adults, is now believed to be successive ABRs when measured in infants.

Like the ABR, the MLR follows a course of maturation. Studies indicate that a mature response may not stabilize until a child is 10 or 11 years of age. Until the development of the MLR is understood, this potential is of limited value.

Long Latency Potentials

The long latency potential (LLP) response is elicited 50 to 1000 mseconds after stimulus onset. This response is characterized by N1 at 100 mseconds, P2 at 200 mseconds, P3 at 300 mseconds, and Nc at 300 to 1000 mseconds. N1 and P2 are elicited by external stimuli while the patient is in a passive condition; P3 and Nc are elicited by an internal cognitive process, with the patient participating. When testing infants, a "novel" stimulus presented among normal stimuli attracts the attention to elicit a response.

The late potentials are not clinically useful for evaluating infants at this time, as findings have been inconsistent. Morphologic differences are found when using speech as opposed to tone stimuli, and responses are affected by electrode placement. As with the MLR, these differences are probably due to maturational factors. The LLP response is not stabilized and mature until at least adolescence. Until a maturational course has been established, these potential are of limited clinical value.

Acoustic Immittance Audiometry

Acoustic immittance audiometry is a measurement of the integrity and function of the peripheral auditory mechanism. The term immittance is a derived term, representing the combined measurement of acoustic impedance and acoustic admittance. Acoustic impedance measures opposition to energy flow, while acoustic admittance measures ease of energy flow through the middle ear system. Acoustic immittance measurement is used to differentiate middle ear disease, predict cochlear impairment, and identify nerve VIII disorder.

Acoustic immittance is performed on an electroacoustic immittance meter. A probe with three holes is coupled to the external auditory canal, forming an air-tight seal. One hole emits a 220-Hz probe tone; the second hole acts as an outlet for an air pressure manometer; and the third leads to a pick-up microphone that compares sound pressure level (SPL) in the external meatus with a reference SPL. As air pressure is varied, the pick-up microphone measures acoustic energy being reflected off the tympanic membrane. If the middle ear system is stiff, acoustic energy is reflected off of the tympanic membrane; if the middle ear system is compliant, acoustic energy is absorbed by the tympanic membrane.

Three procedures make up the acoustic immittance battery: tympanometry, static compliance, and the acoustic reflex threshold test.

Tympanometry measures the mobility of the tympanic membrane as air pressure in the external auditory canal is varied from positive pressure to normal to negative pressure. The tympanic membrane is most compliant when air pressure is equal on both sides.

Five types of tympanogram have been identified:

1. Type A tympanogram occurs when the point of maximum compliance is at normal atmospheric pressure. Type A characterizes normal mobility of the middle ear system.

2. Type B tympanogram occurs when no compliance change is seen as air pressure is varied. This flat pattern is consistent with impacted cerumen, otitis media, and some congenital middle ear malformations.

3. Type C tympanogram occurs when the compliance peak is reached at a negative pressure point of -200 decapascal or worse. This negative pressure state is usually indicative of a resolving or forming middle ear effusion.

4. Type A_s tympanogram occurs when maximum compliance is reached at normal air pressures, but the middle ear system is stiff. This condition is consistent with fixation of the ossicular chain or a scarred tympanic membrane.

5. Type A_d tympanogram occurs when maximum compliance is reached at normal air pressures, but the middle ear system is highly mobile. This condition is consistent with

discontinuity of the ossicular chain or a monomeric tympanic membrane.

Static compliance measures equivalent volumes with the tympanic membrane under two specific conditions. The C1 reading, taken with +200 decapascal pressure, gives the volume of the external auditory canal by measuring acoustic energy being reflected off of a stiff tympanic membrane. The C2 reading, measured at the point of maximum compliance, gives the equivalent volume of the whole system. Subtraction of C1 from C2 gives the compliance of the middle ear space. In general, a small static compliance value is consistent with middle ear fluid, while a large reading is consistent with discontinuity. An abnormally large C1 reading indicates a perforation of the tympanic membrane. Static compliance varies as a function of sex and age, and as a single measure, is the least important part of the acoustic immittance battery.

The *acoustic reflex threshold test* measures the lowest intensity at which the stapedius muscle contracts. When a stimulus of sufficient intensity (70-100 dB HL) is presented, the stapedius muscle contracts. This contraction causes an immittance change that can be measured. Contraction occurs bilaterally, and measurements are made when the sound is presented to the probe ear as well as when sound is presented to the ear contralateral to the probe ear.

The presence or absence of acoustic reflexes provides much diagnostic information. When acoustic reflexes are present at appropriate stimulus levels, normal middle ear function is assumed. When acoustic reflexes are elevated or absent, middle ear disorder, sensorineural hearing loss, nerve VII disorder, or nerve VIII disorder should be suspected. Information from all acoustic immittance measures and often from other audiometric tests must be considered before interpreting the pattern.

Acoustic immittance is an excellent tool in pediatric evaluation. The procedure may take less than a minute to perform and provides information regarding middle ear status and hearing sensitivity. The main limitation of the test is that the subject must remain quiet and still in order that the examiner can read the meter movements. Also, results must be cautiously interpreted for children under 7 months of age, whose canal walls are flexible and partially formed. The flexibility observed may actually represent external canal compliance and not vibration of the middle ear system. Despite these limitations, acoustic immittance is a valuable facet of a thorough hearing evaluation.

Heart Rate Response Audiometry

Change in heart rate in response to auditory stimuli has been well documented in both infants and adults. The measurement of this change to determine auditory sensitivity is a developing area which has not achieved clinical acceptance. Although it holds potential for widespread use, more research is needed.

Heart rate response audiometry is performed using a cardiotachometer. When the heart beats, an electrical potential is generated that is conducted to the skin by body fluids. By placing electrodes on the skin, the waveform produced by this potential can be recorded and adjusted by the cardiotachometer. Heart rate is measured by counting the time interval between each wave pattern. Heart rate response audiometry looks for a change in heart rate that habituates over time in response to an auditory signal.

Many factors limit the widespread use of this procedure. First, "raw" cardiac activity must be amplified to measure a response, and problems arise in differentiating this activity from other physiologic background noise. Second, resting heart rate varies both between subjects and within a single subject, and therefore procedures must be established to differentiate normal variability from variability produced in response to a stimulus. Third, researchers disagree on whether the response habituates over repeated presentations. If one assumes that the response does habituate, it cannot be averaged over time. Fourth, the latency of the response varies from subject to subject, making the establishment of protocols and norms difficult. Finally, it is not known if more accurate results are obtained by measuring heart rate or by measuring the interval between heart beats.

Despite these limitations, heart rate response audiometry is potentially an effective tool for the measurement of hearing sensitivity. Early studies on infants and children show much promise, even for those neurologically impaired. As more research is carried out and more information is obtained, this technique is likely to evolve into a clinically acceptable evaluation tool.

Summary

Testing procedures have been developed for children of all ages and developmental levels. The audiologist must first asses the child's capabilities; then testing can begin. With the advent of objective procedures, no hearing-impaired child should be overlooked, and questionable results can be confirmed. Early identification of hearing loss is possible and necessary to insure the educational and social growth of every child.