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# A Historical Perspective of Hearing Tests of Peripheral Auditory Function

Wayne O. Olsen

The intent of this brief review is to present a few highlights in the short history of hearing evaluations to differentiate conductive from sensorineural pathologies and cochlear versus retrocochlear lesions. Not all developments can be cited in a limited review. Equally interesting historical reviews in the developments of tests of central auditory function and tests for pseudohypocusis can be derived from a research of the literature but are not included here.

## CONDUCTIVE HEARING LOSS

### Air and Bone Conduction Audiometry

In 1550 Cardano described sound transmission to the ear by means of a rod held between one's teeth. A few years later, Capivocci used this mode of stimulation to help differentiate disorders of the tympanic membrane and "hearing nerve" (Feldmann, 1960/70). Feldmann (1960/70) stated that, "Historically speaking, bone conduction is of such importance . . . that one may consider this to be the time of birth of the functional diagnosis of hearing disorders" (p. 14). It wasn't until almost 300 years later that the lateralization of bone conducted tuning fork stimuli by hearing-impaired persons was described by Weber in 1834. Rinne reported his observations on comparisons of responses to tuning forks with the stem held against the skull and then with the tines held near the ear for normal hearing and hearing-impaired persons in 1855. In a review article 30 years later, Schwabach summarized comparisons of responses to tuning forks by hearing-impaired individuals relative to responses observed for normal hearing persons (Feldmann, 1960/70). Thus, in the late 1800s the origins of the basic audiologic test battery comparing responses to air-conducted and to bone-conducted stimuli for a given individual (Rinne) and against a "normal standard" (Schwabach) were described.

The first electronic audiometers were described in Germany in 1919 (Feldmann, 1960/70). Three years later Fowler and Wegel (1922a, b) described the first audiometer commercially available in the United States, the Western Electric 1A. It generated 20 octave and semi-octave frequencies between 32 and 16,384 Hz and controlled signal intensity with a logarithmic attenuator.

A similar but less expensive unit, the Western Electric 2A, followed. Its frequency range was one octave less at each end, 64 Hz through 8,192 Hz. This unit gained acceptance by many otologists at that time (Bunch, 1941). As of 1928, Western Electric 2A audiometers were routinely supplied with bone vibrators empirically calibrated across the whole range from 64 Hz through 8,192 Hz.

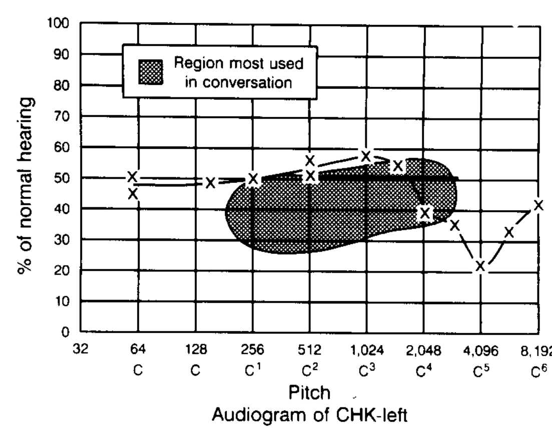


**Figure 1** Audiogram from Fowler and Wegel, 1922b, p. 110. Note aspect ratio of 20 units of "Percent of Normal Hearing" on ordinate = one octave on abscissa. Also note plot for estimate of speech spectrum on audiogram format. (With permission from the American Otological Society.)

Section of Audiology, Department of Otorhinolaryngology, Mayo Clinic, Rochester, Minnesota

Reprint requests: Wayne O. Olsen, Section of Audiology, Department of Otorhinolaryngology, Mayo Clinic, Rochester, MN 55905.

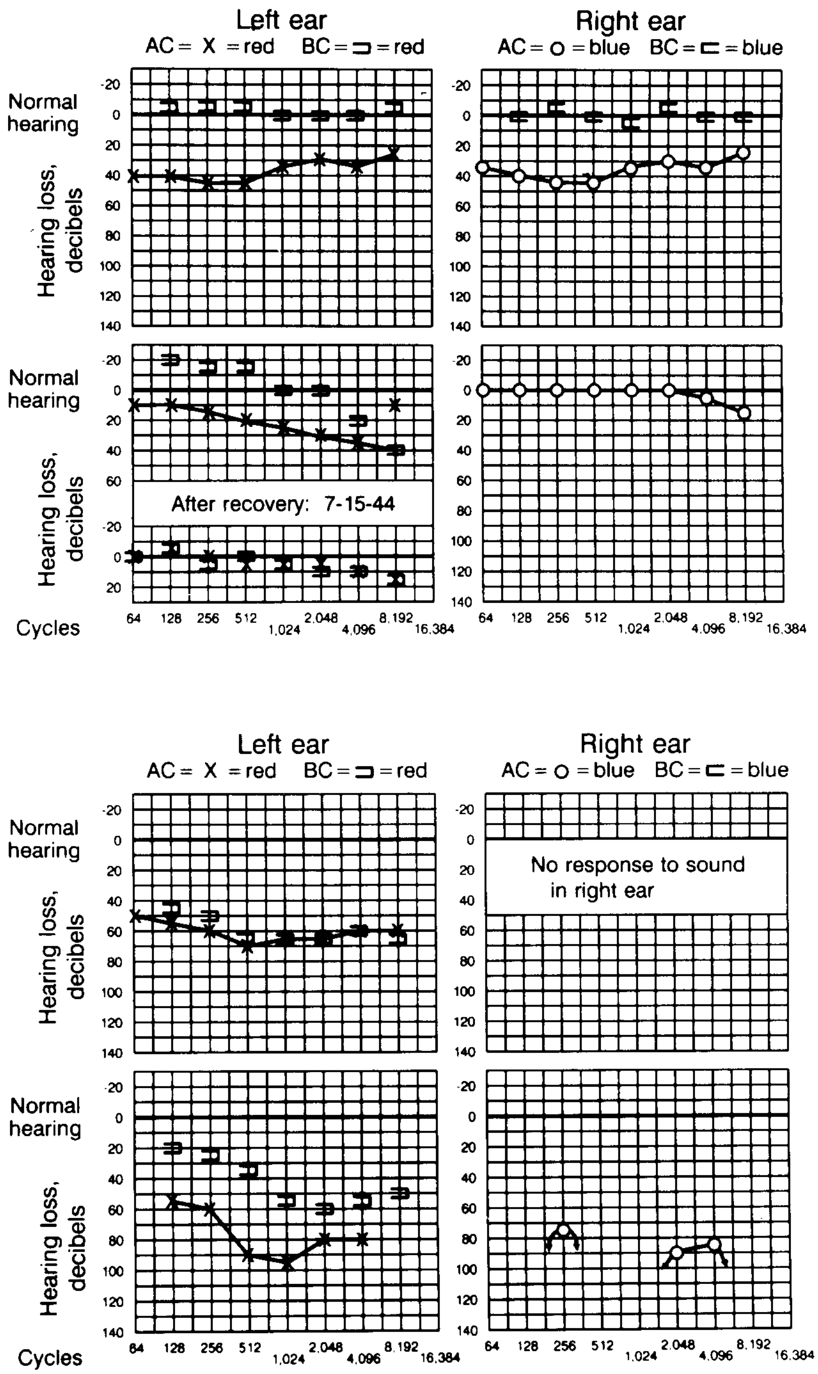


**Figure 2** Audiograms from Lierle and Reger, 1946, pp. 200, 203, 205, and 214. Top row is for a patient with otosclerosis. Second row is for patient with otitis media and after recovering from otitis media. Third row is for a patient with sensorineural hearing loss, and bottom row is for a patient with a mixed hearing loss. Note separate charts for left and right ears, air conduction thresholds from 64 through 8,192 Hz, and bone conduction thresholds from 128–8,192 Hz. Vibrotactile responses were noted for 128 and 256 Hz bone conducted stimuli in third row. (With permission from the *Laryngoscope*.)

In those same early publications, Fowler and Wegel (1922a, b) described charts they called audiograms (Fig. 1). Normal hearing sensitivity was plotted as a straight line with "percent of normal hearing" plotted on the ordinate and octave frequencies were indicated on the abscissa. Their aspect ratio of ordinate to abscissa, one octave on the abscissa equals 20 units on the ordinate, persists today as the standard format for audiograms. It is also worth noting that as early as 1922, Fowler and Wegel plotted an estimate of speech spectra on their audiogram format.

*Clinical Audiometry*, written by C. C. Bunch, was published in 1943. Many of the figures in this publication show many of the audiometric configurations he recognized even then as being associated with various etiologies of hearing losses. In 1946 Lierle and Reger reported air and bone conduction audiograms they found for patients having otosclerosis, otitis media, and "inner ear" and "mixed" lesions (Fig. 2).

Carhart's 1950 article "Clinical Application of Bone Conduction Audiometry" engendered greater acceptance of bone conduction audiometry. Carhart quantified the mechanical shift in bone conduction sensitivity associated with stapes fixation. His observations of the 5-, 10-, 15-, 5-dB depression in bone conduction thresholds at 500, 1000, 2000, and 4000 Hz respectively for patients with otosclerosis and that this alteration in bone conduction response disappeared following successful middle ear surgery not only provided a diagnostic indicator of stapes fixation, but also allowed surgeons to predict more accurately hearing sensitivity following successful middle ear surgery. These observations in the late 1940s and early 1950s led to air and bone conduction testing as routine procedures in hearing evaluations for patients with hearing losses.

### Speech Audiometry

Any conversation among two or more individuals can be considered a test of hearing for speech, but more formal tests using speech signals had their inception in the early 1800s. In 1804 Pfingsten categorized hearing loss according to three categories of speech sounds, i.e., vowels, voiced consonants, and voiceless consonants. Schmalz in 1846 classified hearing impairments on the basis of the distance at which speech was understood when spoken at "normal" and "moderate" levels. Twenty-five years later Wolf refined the approaches of Pfingsten and Schmalz in classifying speech sounds according to their frequency content and determined the distances at which the various sounds could be heard (Feldmann, 1960/70). The invention of the phonograph by Edison in 1877 was followed by the first recorded speech test materials by Lichtwitz in 1889. He developed an "acumetric scale" based on Wolf's work; intensity was controlled by speaking at a constant level, but at different distances from the sound pickup. As early as the late 1800s Lichtwitz indicated that now that recordings of speech tests could be made, equivalent tests in all languages could be developed allowing "uniform" tests in all countries (Feldmann, 1960/70).

Barany, in 1910, described a test with "phoneme substitution words" in which only one phoneme per word was changed in a given set. Thirteen years later, Lempert described a test in which only one phoneme was different in a given set, but the difference could be a vowel or initial or final consonant (Feldmann, 1960/70). Clearly Barany's and Lempert's efforts were early versions of other closed response sets developed 50 or so years later.

Campbell and Crandall described a different approach in 1910 with their articulation lists of 50 nonsense syllables. Each list had 5 consonant-vowel, 5 vowel-consonant, and 40 consonant-vowel-consonant items and was used to test telephone circuits (O'Neill and Oyer, 1966). This approach was a forerunner to Egan's development of 20 lists of monosyllables, 50 words per list, phonetically balanced to be representative of English speech (Egan, 1948). Carhart (1946) and Thurlow et al (1949) used these materials in clinical settings. The latter investigators noted that scores for patients responding to Rush-Hughes recordings of these test lists differentiated themselves into high scores for conductive hearing losses and poorer performance for those with "nerve involvement." Thus, in the late 1940s speech tests were viewed as providing differential information regarding site of auditory involvement.

### Immittance Tests

In his 1946 publication Metz credits West, Troger, Shuster, and Waetzman in the 10-year span of 1928 to 1938 with having made early measurements of the acoustic impedance of human ears. Metz' publication "The Acoustic Impedance Measured on Normal and Pathological Ears" led the way for further study and ultimately routine clinical utilization of impedance (now called immittance) measurements of the human middle ear system. Shallop (1976) credits Denmark for introduction of the first commercially available electroacoustic immittance unit in 1957. Terkildsen and Thomsen first described tympanograms for normal and pathologic ears using such a unit in 1959, and in 1960 Terkildsen and Nielsen described an "electroacoustic impedance measuring bridge for clinical use." Classifications of tympanograms were described by Liden in 1969, Jerger in 1970, and Liden et al in 1970.

Also, in his 1946 publication, Metz noted that his measurement apparatus detected contractions of the stapedius muscle in response to intense stimulation to the opposite ear. In addition, he reported that conductive hearing losses eliminated such acoustic reflex responses on the affected side. Klockhoff, in 1961, using an electroacoustic immittance unit, confirmed Metz' observations, stating that even a slight middle ear involvement abolished measurements of stapedius muscle activity in the involved ear.

## COCHLEAR VERSUS VIIIth NERVE HEARING LOSS

### Word Recognition

Subsequent to Fowler's description of the recruitment phenomenon in 1937, investigators endeavored to relate word recognition scores and a variety of other test results to measurements of recruitment. (Fowler's recruitment test and other such tests are described in later sections). With regard to speech tests, Dix et al (1948) observed that, for two patients with Meniere's disease and recruitment, word recognition scores improved as a function of stimulus intensity up to a point, but then declined at higher intensity levels. Scores for two patients with eighth nerve lesions and no recruitment, on the other hand, continued to improve at successively higher intensities. Eby and Williams (1951) made similar observations for larger samples of Meniere's disease and eighth nerve tumor patients.

Liden (1954) was first to note unusually poor word recognition scores for patients with eighth nerve tumors. Schuknecht and Woellner supported Liden's observations in 1955.

Whereas Dix et al (1948) and Eby and Williams (1951) reported continued improvement in word recognition scores at successively higher presentation levels for eighth nerve tumor patients, Jerger and Jerger (1971) found a marked decrease in performance at high intensities (110 dB SPL). The reduction in scores was less marked at the same intensity levels for patients with cochlear hearing losses. From these observations they derived a "rollover ratio" based on scores obtained from presentation of monosyllabic word lists at successively higher levels. The rollover ratio is calculated by subtracting the poorest score (PB min) observed for presentation levels above the level at which the best score was attained from that best score (PB max) and dividing that difference by PB max.

Rollover ratio = PB max − PB min/PB max

Jerger and Jerger found that a rollover ratio of 0.45 or greater was obtained for patients with eighth nerve lesions, whereas those having cochlear pathologies yielded smaller values. Identical or similar rollover ratios for other test materials have differentiated between most cochlear and retrocochlear lesions in the studies of Dirks et al (1977), Bess et al (1979), and Meyer and Mishler (1985).

### Loudness Balance

In 1924 Pohlman and Kranz observed that even though one of their subjects had diminished hearing sensitivity in relatively narrow frequency regions, tones at suprathreshold levels across the normal and impaired frequency regions were perceived as "normal" in loudness. Fowler (1928) noted that higher sensation levels of tones were necessary in the normal ear to match the loudness of a tone at a lower sensation level in the impaired ear of some patients with unilateral hearing losses. In 1936 Fowler described the alternate binaural loudness balance (ABLB) test to judge loudness of tones alternating between the two ears. In 1936 Reger also described the monaural bifrequency loudness balance (MBFLB) test for judgments of loudness for two different tones alternating with one another at one ear. The term "recruitment" was used by Fowler in 1937 to describe the loudness phenomenon observed by Pohlman and Kranz (1924) and Fowler (1928). Also in 1937 Fowler reported ABLB results showing recruitment for a number of patients, including one patient with an eighth nerve tumor. The 1948 publication by Dix et al heightened interest in recruitment and ABLB testing. They reported findings of recruitment for all 30 of the Meniere's disease patients in their sample, no recruitment for 14 of 20 eighth nerve tumor patients, and "incomplete" recruitment for the other six.

### Metz Test-Acoustic Reflex

An article by Metz in 1952 reported that ears demonstrating recruitment on the ABLB test also could be shown to elicit acoustic reflex responses when the affected ear was stimulated with tones at about the same intensities needed to cause acoustic reflexes in normal ears. Importantly, Metz also discussed two eighth nerve tumor patients who revealed absence of recruitment according to the ABLB test and no acoustic reflexes in response to intense acoustic stimulation of the impaired ear.

### Difference Limens for Intensity

Using his newly devised audiometer with which subjects measured and recorded their threshold sensitivity for continuous tones, Bekesy (1947a, b) observed very narrow excursions in the tracings when patients with cochlear hearing losses traced their thresholds. Like small excursions were not obtained for persons with conductive hearing losses (Fig. 3). Bekesy attributed the reduced excursions to recruitment and a demonstration of enhanced difference limens (DLI) for intensity at threshold levels. These observations resulted in considerable interest in measurements of DLI for hearing-impaired patients.

In 1949 Luscher and Zwislocki described their DLI test using abrupt changes in intensity of continuous pure tones delivered at 40-dB sensation level. Normal hearing subjects detected changes of 10 to 16 percent; patients having sensorineural hearing losses of 30 dB or greater heard intensity changes of 8 percent or smaller. In a subsequent article Luscher (1951) reported normal DLIs for two patients with cerebellopontine angle tumors.

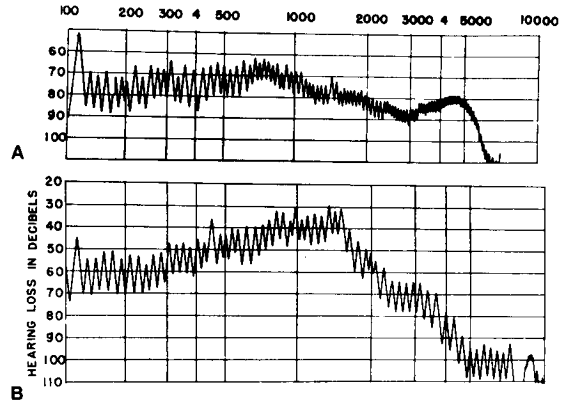


**Figure 3** Bekesy tracings from Bekesy 1947b, p. 769 for a patient with a sensorineural hearing loss (2A) and for a patient with a conductive hearing loss (2B). Reduction in excursion width at high frequencies in 2A interpreted as an indication of smaller DLIs for sensorineural hearing loss. (With permission from the *Laryngoscope*.)

A different clinical procedure for measurement of DLIs was described by Denes and Naunton at about the same time, 1950. Two presentations of the same tone at different intensities were presented. The task of the listener was to judge whether the second stimulus was louder or softer than the first. Just noticeable differences in intensity were determined for at least two sensation levels. Presence or absence of recruitment were judged on the basis of the size relationship of the DLIs at the two sensation levels. However, publications by Lund-Iverson (1952) and Hirsh et al (1954) strongly questioned any relationship between recruitment and difference limens for intensity. Lund-Iverson found considerable variability in DLIs across groups and that the mean difference limens were about the same for the groups without and with recruitment. Hirsh et al (1954) made similar observations. They also pointed out the inconsistency of loudness experience and difference limens in that loudness growth is more rapid for low frequency signals than for midfrequency tones, but DLIs are larger for low frequencies than for midfrequency stimuli.

Jerger's work (1952, 1953) led to description of the Short-Increment Sensitivity Index (SISI) by Jerger et al in 1959. Their procedures assessed the percentage of 1-dB increments heard when superimposed on a 20-dB sensation level tone. Importantly, they stated that the interest was not in this test procedure as an indirect test of recruitment but whether or not sensitivity to small changes in intensity was related to site of lesion within the auditory system. In 1961 Jerger reported that 20 Meniere's disease patients detected most of the 1-dB increments superimposed on a continuous tone at 20-dB sensation level, but 11 patients with eighth nerve tumors heard few if any of the 1-dB intensity changes at like sensation levels. In 1963, Thompson recommended that the SISI test be presented at a high intensity level, 75 dB HL (about 85 dB HL for current HL reference levels).

### Tone Decay

Gradenigo, in 1893, examined the "exhaustibility" of the auditory nerve using his "telephone audimeter." In one approach he established threshold, then stimulated the ear at the maximum output of the audiometer for one minute, then quickly returned to the previously established threshold level. Normal ears continued to hear the tone, but for those with "great exhaustibility" the tone was lost for several seconds or entirely. Another method he described consisted of sustaining a continuous tone at threshold levels, increasing its level only when perception of the continuous tone was lost. Some listeners perceived the tone for a considerable period at a single "threshold" level whereas, for others, it was necessary to increase the level from time to time to maintain perception of the tone. Gradenigo associated the "exhaustibility" he observed with cases of "neuritis."

Reger and Kos published an early report of excess adaptation for a patient having an eighth nerve tumor in 1952. They observed 25- to 30-dB threshold shifts for a patient tracing his threshold for a continuous tone with a Bekesy audiometer. Even more dramatic shifts in Bekesy threshold tracings were reported for an eighth nerve tumor patient by Lierle and Reger in 1955. Jerger et al (1958) noted like marked shifts in threshold tracings for continuous tones but not for interrupted tones for a patient with an eighth nerve tumor. Less dramatic threshold shifts for continuous tones were noted for patients with cochlear loss in the three publications cited above. In 1960 Jerger published his classification of Bekesy tracings based on separation of threshold tracings for pulsed and continuous tones.

In the midst of this interest in measuring adaptation for a continuous tone with a Bekesy audiometer, Carhart described a threshold tone decay test similar to the second method described by Gradenigo using a conventional pure tone audiometer. Carhart's procedure required perception of the tone for a full minute at a single level before the test was terminated. With this method Yantis (1959) observed tone decay of 40 to 50 dB for a patient with noise-induced hearing loss and one with Meniere's disease, but adaptation beyond the output limits of the audiometer for three patients having eighth nerve tumors.

Based on observations such as those outlined above, a pure tone test battery was developed in the 1960s to help differentiate retrocochlear from cochlear involvements. It consisted of two suprathreshold tests, loudness balance and Short Increment Sensitivity Index, and two threshold tests, Bekesy audiometry and threshold tone decay.

### Acoustic Reflex Decay

Anderson et al added acoustic reflex decay to the test battery in 1969. They observed that acoustic reflex responses were maintained at full or nearly full amplitude for 10 seconds for sustained stimulation at 10 dB above the previously established acoustic reflex thresholds for 500 and for 1000 Hz in normal and cochlear hearing loss ears. However, when ears having eighth nerve lesions were stimulated in that manner, the amplitude of the acoustic reflex response diminished to one-half amplitude or less within 5 seconds. Since that and subsequent reports supporting the sensitivity of acoustic reflex and reflex decay to retrocochlear lesions, this test methodology has supplanted previously used suprathreshold tests and tests of adaptation for raising suspicion of eighth nerve pathologies.

### Auditory Brainstem Response (ABR)

Davis' 1939 publications demonstrated that electrical neural activity in response to sound stimuli could be measured from the scalp of awake humans. Almost 30 years later Sohmer and Feinmesser (1967) reported measurements of auditory evoked responses from the eighth nerve and brain stem using surface electrodes. Jewett and Williston (1971) clearly demonstrated that auditory evoked potentials arising from the eighth nerve and brain stem could be measured. They assigned Roman numerals to the seven waves observed during the first 10 msec following presentations of click stimuli and suggested that Waves I through VI were observed with sufficient reliability to warrant establishment of clinical and experimental norms.

In 1977 Selters and Brackmann reported their analysis of ABR results for 46 eighth nerve tumor patients and 54 patients not having cerebellopontine angle tumors. Applying criteria for latencies of Wave V, differences between latencies of Wave V at the two ears, and absence of repeatable waveforms, they obtained abnormal ABR results for all but three of the eighth nerve tumor patients and only six of the other patients. Their findings of the excellent sensitivity and specificity of ABR testing in identifying cochlear and retrocochlear lesions have been confirmed many times since then and criteria for interpretation of ABR waveforms have been expanded.

## COMMENT

Over the years, a variety of auditory test procedures have been developed to help rule out or raise suspicion of eighth nerve lesions. During that time period radiographic techniques for detecting mass lesions have improved substantially so that smaller and less symptomatic tumors of or near the eighth nerve have been identified and subsequently removed. Auditory manifestations of these smaller lesions often are very subtle too. Hearing tests that seemed sensitive to relatively gross eighth nerve involvements found a few years ago are not capable of raising suspicion of eighth nerve pathology for small and more subtle lesions, but new auditory procedures have been developed that are sensitive to subtle auditory manifestations of eighth nerve pathology. It is encouraging that developments in audiology have "kept pace" with the times. In order to continue to keep pace, audiologists must maintain their cognizance of developments in their own and other disciplines, thereby continuing to expand their knowledge and skills as required for application of new and developing technology, and to meet the demand for better understanding of hearing and hearing disorders.

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