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Acoustic Measurement of the Ear: Its History and Future

Tatsuhiko Harada[*]

[*]*Department of Otolaryngology, International University of Health and Welfare, School of Medicine and Atami Hospital, Japan.*

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ABSTRACT

The history, current application and future direction of acoustic measurement of the ear, including acoustic impedance measurement and otoacoustic emission, are overviewed. Acoustic measurement of the ear began in the late 1930s by Metz with the clinical application of acoustic impedance measurement. Impedance changes with acoustic reflex and air pressure condition, later termed "tympanogram," were then investigated. In the late 1950s, equipments based on electroacoustic principles with an airtight probe became commercially available. Jeger introduced and spread these methods to the United State in the 1970s, establishing acoustic measurement as a clinical test. From 1978 to 1979, Kemp presented acoustic signals, which are emitted from the cochlea according to its active amplification mechanism, with various techniques termed "otoacoustic emissions (OAEs)."

Currently, these measurements are essential for evaluating the peripheral auditory system in otolaryngology clinics. Tympanometry and OAEs are used for assessing middle and inner ear functions, respectively. The acoustic reflex and medial olivocochlear (MOC) reflex are used for assessing brainstem function; however, these methods still have limitations in clinical application because of the potential risk of causing hearing loss during acoustic reflex measurement and reliability of the results in MOC reflex assessment. With the current progress in signal processing, acoustic measurement of the ear will advance to higher resolution both in terms of frequency and time course. These advances are expected to reveal more detailed dynamic characteristics of hearing functions, including the acoustic reflex and MOC reflex.

Keywords: Acoustic measurement, Tympanometry, Acoustic reflex, Otoacoustic emissions

Abbreviations: ABR: Auditory Brainstem Response; CAS: Contralateral Acoustic Stimulation; DPOAE: Distortion Product Otoacoustic Emission; MOC: Medial Olivocochlear; OAE: Otoacoustic Emission; SFOAE: Stimulus Frequency Otoacoustic Emission; SOAE: Spontaneous Otoacoustic Emission; SOC: Superior Olivary Complex; SPL: Sound Pressure Level; TEOAE: Transient Evoked Otoacoustic Emission

INTRODUCTION

As the specific organ for hearing, the ear can effectively transfer sound and vibration. From the aspect of physiological measurement, this means that sound can also be used to evaluate hearing function. Historically, acoustic measurement of the ear began shortly after the onset of the development of equipment for sound measurement. Acoustic measurement then maintained a certain status in the assessment of hearing owing to its advantages of non-invasiveness and simplicity, which are useful for repetitive assessment or application with patients who are difficult to cooperate with. This article reviews the history of the typical acoustic measurements of impedance audiometry and otoacoustic emissions (OAEs) and discusses the future of acoustic measurement of the ear.

History of impedance measurement (Table 1)

The word "impedance" was originally used by Oliver Heaviside as "the ratio of the impressed force to the current" in electronics [1]. This concept of impedance was applied to acoustics by Webster [2] as the ratio of sound pressure amplitude to volume velocity amplitude.

Corresponding author: Tatsuhiko Harada, Department of Otolaryngology, International University of Health and Welfare, School of Medicine and Atami Hospital, 13-1 Higashikaigan-cho, Atami, Shizuoka 413-0012, Japan, Tel: +81-557-819171; Fax: +81-557-836632; E-mail: t-harada@iuhw.ac.jp

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In 1928, West [3] made the first measurements of ears and published the results; however, these measurements were not intended for medical purposes. In the late 1930s, the Danish otolaryngologist Metz [4] began clinical research on acoustic impedance measurements of the ear for the purpose of diagnosing conductive hearing loss and published his results in 1946. Metz [5] also measured the acoustica reflex elicited by contralateral stimuli and identified loudness recruitment in ears with sensorineural hearing loss. After that, Thomsen [6] measured the changes in acoustic impedance in a pressure chamber for investigating tubal function and measuring middle ear pressure.

Table 1. Summary of the hisory of acoustic measurement of the ear.

Year	Events
1928	West made the first measurements on ears and published the results
Late 1930s	Metz started clinical researches of acoustic impedance measurement of the ear
Late 1950s	Terkildsen and Scott-Nielsen developed an impedance measurement system based on electroacoustic principles
1964	Terkildsen presented "tympanometry" as currently applied manor
1970s	Jerger introduced acoustic impedance measurement into the United State
	Classification of tympanometric patterns and abnormality of acoustic reflex were established
1978-1979	Kemp presented OAEs

Classification of OAEs: SOAE, TEOAE, DPOAE, SFOAE

In the late 1950s, Terkildsen and Nielsen [7] developed an impedance measurement system based on electroacoustic principles. Its operation was rather simple, and commercially available equipment was introduced based on this development. This equipment was airtight, thus facilitating the measurement of acoustic impedance changes. Terkildsen and Nielsen [8] termed this method "tympanometry" with a fixed frequency technique. A 220- or 226-Hz probe tone was used in tympanometry for several reasons: the available transducers are nonlinear at higher frequencies, and not the even harmonic of the typical power line frequency in Europe (50 Hz); the phase angle is relatively constant at low frequencies with tympanometry; the acoustic reflex is not typically elicited with a low frequency stimulus; and the 226-Hz probe tone is specified for aural acoustic impedance and admittance measurements [9].

In the 1970s, Jerger [10] introduced and established the acoustic impedance measurement as a clinical test in the United States. In addition, he modified the classification of the tympanometric patterns, the concept of which was first introduced by Liden [11]. He also formally classified the patterns of abnormal acoustic reflex based on the results of four combinations of stimulus and measurement sides, revealing its efficacy in identifying the location of lesions in the reflex arc [12] **(Table 2)**. Prior to that, acoustic reflex had already been used as a diagnostic test for retrocochlear lesions by Anderson et al. [13] and the newer version of the measurement bridge, which could elicit the ipsilateral reflex, became available and was used by Greisen and Rasmussen [14].

Table 2. Diagnosis from 4 patterns of acoustic reflex recordings.

Recording	**Left**	**Left**	**Right**	**Right**
Stimulation	**Left**	**Right**	**Left**	**Right**
(Left side disease)				
Left mild middle ear disorder	×	×	○	○
Left facial nerve disorder				
Left hearing loss due to cochlea or VIIIth nerve	×	○	×	○
Left severe middle ear disorder	×	×	×	○
Intra-axial brainstem disorder (eccentric to left side)				
Other Brainstem disorders	○	×	×	○
	○	○	×	○

Reversed patterns to those of left side disease

Beginnings of OAEs

From 1978 to 1979, Kemp presented novel acoustic measurement methods of the ear [15,16]. He detected acoustic signals, which are emitted from the cochlea according to its active amplification mechanism, by using a variety of techniques. About 30 years before Kemp's discovery, the British physicist Gold [17,18] reviewed theories and data related to the ear and predicted that the cochlea should have an active mechanism that counteracts the damping that arises from the viscosity of the liquid to result in the sensitivity and precision of the normal cochlea. Kemp's discovery on OAEs provided evidence for the existence of a nonlinear source of vibration in the cochlea and the potential for traveling-wave amplification. After that, Brownell et al. [19] identified the power source of outer hair cell motility. Although creating a mathematical model comprising cochlear function that included the amplification mechanism is challenging, the concept that the cochlea has an amplification mechanism became widely accepted.

The signals that Kemp discovered were termed "OAEs" and are classified into four types **(Table 3)**: spontaneous (SOAEs), transient evoked (TEOAEs), distortion product (DPOAEs), and stimulus frequency OAEs (SFOAEs). SOAEs are low-level tones in the ear canal without any external stimuli and can be detected in approximately 40%-80% of normal hearing ears [20,21]. Multiple SOAEs are often detected from the same ear. On average, four different frequencies of SOAEs can be recorded [21,22]. SOAEs are considered to reflect the activity of the cochlear active mechanism [23]. TEOAEs are transient sounds with extremely short durations (clicks or tone bursts). Usually, a stimulus of 80 dB peaks equivalent SPL or approximately 45 dB above the perceptual threshold is used, and the response sound can be recorded within 20 ms of the stimulus [24]. TEOAEs originate in the cochlea due to the amplification and reflection of traveling waves emerging on the basilar membrane with evoked sounds in the cochlea [24,25]. DPOAEs are recorded distortions to two different frequency pure tone stimuli. In general, the frequency of the relatively lower frequency stimulus is termed "f1," whereas that of the relatively higher frequency stimulus is termed "f2." Frequencies of distortions can be displayed as mf1 ± f2 (where m and n are integers) and distortion of the 2f1 − f2 component is typically predominant in all of the distortion components. The level of this 2f1 − f2 component (termed "DPOAE level") changes with the level and frequency ratio of the stimulus tones. The DPOAE level is largest when the ratio of f2/f1 is approximately 1.22 [26,27] and 50-60 dB below the stimulus levels [28]. Therefore, a 60-70 dB SPL is typically used for the stimulus tone levels, and the level of the lower tone is slightly larger (usually 10 dB) than that of the higher tone so that the overlap of traveling waves on the basilar membrane of the cochlear elicited by the stimulus tones is maximal. DPOAEs are generated with nonlinear vibration at the overlap of the traveling waves on the basilar membrane near the characteristic place of f2 due to active amplification mechanisms [24,25].

Table 3. Recorded within 20 ms from the stimuli.

Distortion Product Otoacoustic Emission (DPOAE)
Pure tone stimuli of two different frequency (f1 and f2, f1<f2)
Calculate 2f1-f2 level of recorded sound
Stimulus Frequency Otoacoustic Emission (SFOAE)
(Suppression method)
Measuring sound pressure levels of probe pure tone with and without suppressor tone and level of the probe tone without suppressor tone is subtracted with that with suppressor tone
(Compression method)
Comparing the sound level in the ear canal of high and low level sound stimuli and calculate the residual of the measured sound level

By contrast, SFOAEs are evoked sounds with a single pure tone and are considered to be generated by the same mechanism as that of TEOAEs [25]; however, this is challenging to detect. The main methods of SFOAE measurement are suppression and compression [29-31]. The former method measures the sound pressure levels of probe pure tones twice, with and without the suppressor tone, which is a frequency nearby the probe tone frequency that is larger than the probe tone level. The measured level of the probe tone without the suppressor tone is then subtracted from that with the suppressor tone. The residual is the level of the SFOAE. The latter method depends on fact that the growth of the SFOAE level is saturated as the stimulus level increases and the resulting sound level measured does not linearly grow with an increase in the stimulus level. The level can be calculated by comparing the sound level in the ear canal for high- and low-level sound stimuli, and then calculating the residual of the measured sound level of the lower level stimulus by subtracting the expected sound level from the higher level stimulus.

Because OAEs can be detected in normal hearing ears but not in ears with middle ear and cochlear dysfunction, the clinical application of OAEs was immediately realized after their discovery. Neonatal hearing screening was one the first clinical applications of OAEs [32]. However, OAEs not widely used as auditory brainstem response (ABR) [33] because of their susceptibility to environmental noise and vernix caseous. Currently, OAEs are mainly used to diagnose sensorineural hearing loss and confirm cochlear damage or an initial hearing test in patients who have difficulty cooperating with behavioral audiometry. The routine measurement of OAEs in patients with sensorineural hearing loss resulted in the discovery of a new disease category termed auditory neuropathy, in which normal OAEs are detected but the responses are degraded in ABR and behavioral audiometry due to auditory nerve dysfunction [34,35].

Current application of acoustic measurement for peripheral auditory systems

As described above, tympanometry, acoustic reflex and OAE measurement (mainly DPOAE measurement) are essential tests in otolaryngology clinics. For patients with hearing loss, tympanometry and OAEs combined with otoscopy and pure tone audiometry can distinguish the damaged part of the auditory pathway. Conductive hearing loss without an external ear canal and eardrum can be distinguished using tympanometry because of the ossicular chain or air pressure in the middle ear cavity. OAEs can also be used to distinguish sensorineural hearing loss into cochlear and retrocochlear hearing loss. OAEs and the acoustic reflex are also used for objective hearing assessment when the candidate cannot or will not cooperate with usual types of audiometry. The acoustic reflex is also used for distinguishing the damaged region in facial palsy.

Although these acoustic measurement tests are simple and convenient, they still have limitations for clinical application. One limitation is that the peripheral part of the target area should be acoustically normal. Therefore, assessment using acoustic measurements is challenging when a subject has a middle ear disease, thus highlighting the importance of checking for other centrally located lesions. The second limitation is how to interpret the results for clinical diagnosis. Acoustic measurements are highly affected by individual body structure. Thus, normative ranges have not been established for most acoustic measurement tests and examiners or physicians must carefully apply their own judgments.

Current application of acoustic measurement for retrocochlear function

After Anderson et al. [13] first reported that the acoustic reflex measurement was used for the differential diagnosis of retrocochlear lesions; the acoustic reflex threshold was also used to differentiate cochlear, VIIIth nerve, and brainstem disorders. The comparison of uncrossed and crossed reflex thresholds is helpful for differentiating VIIIth nerve and brainstem disorders. Reflex decay has also been reported to be a sensitive measure of the VIIIth nerve disorder [36,37] and brainstem lesions [38,39]. Reflex amplitudes have been reported to be depressed in patients with VIIIth nerve tumors [36,40] and brainstem disorders [12,41]. Acoustic reflex onset latency and rise time have also been used as diagnostic tools for the differentiation of cochlear and retrocochlear disorders, but the existence of an onset latency delay in patients with VIIIth nerve disorder is controversial [42-44].

Acoustic reflex is useful for the diagnosis of retrocochlear lesions; however, it is not widely used at present because of the introduction of ABR and magnetic resonance imaging in the 1980s. Compared with these techniques, the acoustic reflex measurement is cost-effective and convenient, but it has lower accuracy as a diagnostic tool. The threshold level of acoustic reflex depends on the accuracy of the measuring instruments and the acoustic reflex amplitude itself demonstrates intersubject variability. Reflex decay measurements can reduce variation caused by instruments and subjects; however, the need to consider temporary or permanent auditory changes remains [45,46].

The discovery of OAEs results in the presence of another technique for assessing retrocochlear function with the MOC reflex. Olivocochlear bundles originate in both sides of the superior olivary complex (SOC), project into the cochlea through the vestibular nerve, and terminate in the organ of Corti, which was first described by Rasmussen [47]. The nerve fibers are classified into crossed and uncrossed types based on the side of the SOC and into medial and lateral types based on the location of the cell bodies in the SOC [48,49] **(Figure 1)**. MOC efferents originate in the medial superior olivary nuclei and terminate on the outer hair cells, whereas lateral olivocochlear efferents originate in the lateral superior olivary nuclei and terminate on the dendrites of type I auditory nerve afferent fibers. Electrophysiological recordings of single fibers of olivocochlear bundles in cat demonstrated responses to sound stimulation in both sides of the ear. Galambos [50] first attempted electrical stimulation of MOC fibers at the floor of the fourth ventricle in animal models and observed reduction of the compound action potential. With this approach, the amplitude of mechanical vibration of basilar membranes of low-to-moderate intensity and frequencies nearby the characteristic frequency to sounds reduced [51,52], indicating that MOC has an inhibitory effect on outer hair cells.

Based on these findings, the effects of contralateral acoustic stimulation (CAS) of OAEs in humans were vigorously investigated after the discovery of OAEs. Collet et al. [53] reviewed the influence of contralateral auditory stimulation on OAEs as follows: (1) alteration (mainly a decrease) of OAE amplitude; (2) alteration of response spectrum (upward shift frequency of SOAEs); (3) alteration of phase; (4) effect dependent on the intensity of contralateral stimulation; (5) effect inversely dependent on the intensity of ipsilateral stimulation; and (6) frequency specificity of the suppressive effect. They also reported that the involvement of the MOC bundle is highly probable; however, the possibility of acoustic reflex cannot be excluded. Collet et al. [53] also reported that the effect of CAS on evoked OAEs disappeared after vestibular neurectomy, in which MOC is ablated, and that the magnitude of suppression is greater for broadband than narrowband CAS [54]. The roles of the MOC reflex are considered to protect hair cells from acoustic trauma and improve hearing in noise, which is termed the "anti-masking effect." Although both these functions have been verified in animal experiments [55], the relation between the strength of MOC reflex assessed with OAEs, the rate of noise-related hearing loss, and the function of hearing in noisy conditions remain unclear in human studies [56-58].

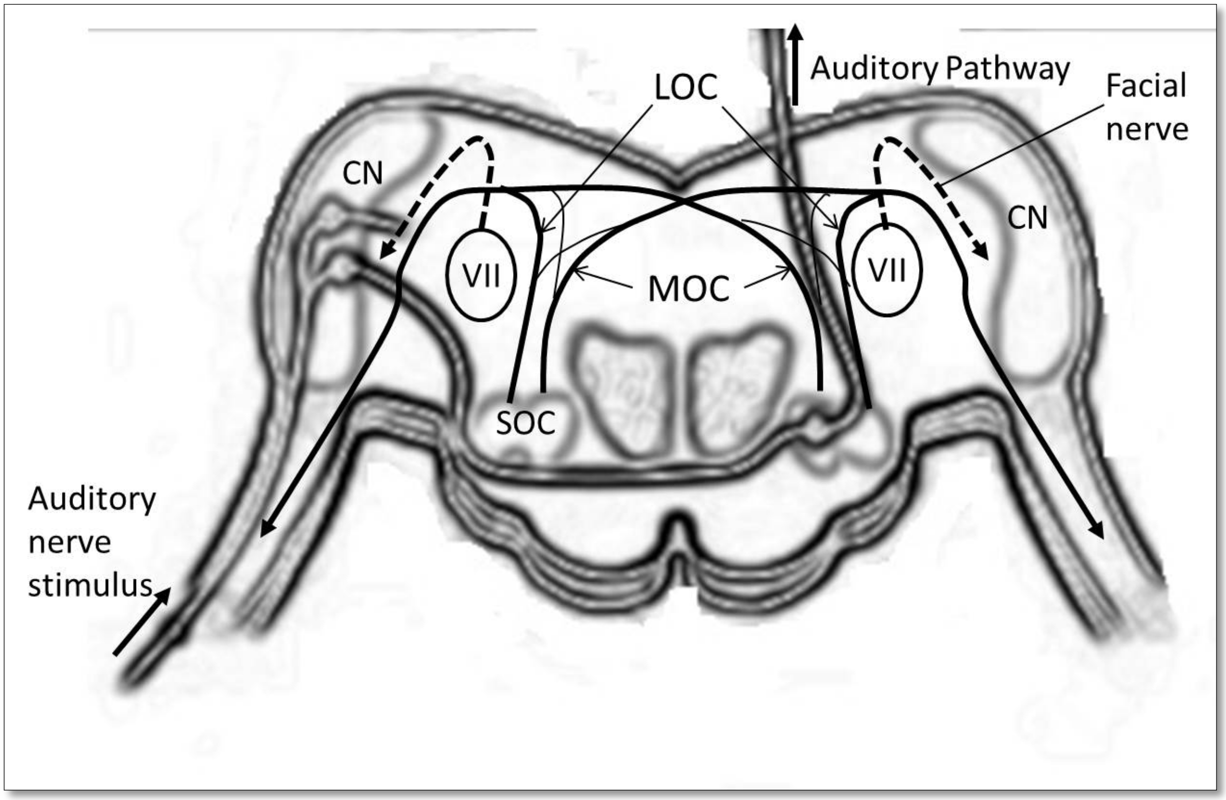

Figure 1. Schematic view of MOC (medial olivocochlear bundle) and LOC (medial olivocochlear bundle) with auditory pathway at the brainstem. MOC and LOC originate in both sides of the SOC (superior olivary complex), project into the cochlea through the vestibular nerve. MOC is mainly composed of crossed fibers (originate in contralateral SOC) and LOC is mainly composed of uncrossed fibers (originate in ipsilateral SOC). CN is cochlear nucleus. VII is facial motor nucleus, which is located cranial to CN and SOC.

RECENT ADVANCES AND FUTURE PERSPECTIVES

Given the recent progress of digital signal processing, acoustic measurement has also progressed. One important advance is that wide-band measurement is now commercially available [59,60]. This measurement method, which is termed wide-band reflectance or absorbance measurement, uses a chirp sound (short tone bursts with rapid frequency changes) of a broad frequency band and measures the sound level in the ear canal. This method is expected to facilitate more detailed or reliable measurements of the middle ear. Moreover, the applications of tympanometry have also started [61].

The other area of advancement is time course analysis. Currently, of the clinical acoustic measurement tests, acoustic reflex is the only test that uses time course analysis. However, time course analysis has also been applied in other acoustic measurements to detect the dynamic functions of hearing. Whitehead et al. [62] presented a unique method for visualizing the onset of DPOAE using eight different patterns of stimuli with different phases. Kim et al. [63] also measured the time course of DPOAE to detect the MOC reflex using the Hilbert transform. Guinan et al. [64] assessed MOC reflex using the time course of SFOAEs, which has the advantage of using a single-frequency probe tone. Acoustic reflex measurement is a primer of time course measurement, but also occurs in advance. Feeney and Keefe [65] reported sequential measurement of wide-band reflectance with contralateral sound stimuli for the assessment of acoustic reflex; however, their measurement remains intermittent and not continuous.

Acoustic measurement of the ear will advance to higher resolution in terms of both frequency and time course with progress in signal processing. Such development is expected to reveal more detailed dynamic characteristics of hearing functions, such as the acoustic reflex and MOC reflex. This will result in additional information pertaining to sound processing in the brainstem, which is a limitation of neuroimaging and evoked potentials, and can help reveal the pathophysiology of unresolved hearing difficulties.

CONCLUSION

The development of measurement tools resulted in the establishment and progression of acoustic measurements. The measurable functions have been extended from those of the middle ear to those of the inner ear and brain stem. Simultaneously, measurable frequencies have also widely expanded. Time course measurement of wide frequency areas is the next challenge and will help reveal the dynamic characteristics of hearing functions.

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