The Rise and Fall of Aural Acoustic Immittance Assessment Tools

Navid Shahnaz, Ph.D.,[1,*] Hammam AlMakadma, Au.D., Ph.D.,[2,*] and Chris A. Sanford, Ph.D.[3]

ABSTRACT

Clinical assessment of middle ear function has undergone multiple transformations and developments since the first acoustic impedance measurements were made in human ears nearly a century ago. The decades following the development of the first acoustic impedance bridge by Metz in 1946 witnessed a series of technological advancements leading to the widespread use of single-frequency admittance tympanometry in the 1960s. In the 1970s, multi-frequency and multi-component tympanometry (MFT) emerged for clinical use, allowing for a better understanding of the middle ear acoustic-mechanical response at frequencies between 200 and 2,000 Hz. MFT has not gained widespread clinical adoption despite its advantages over single-frequency tympanometry. More recent technological developments enabled assessment for frequencies greater than 2,000 Hz, leading to the advent of wideband acoustic immittance measures with capabilities for comprehensive assessment of middle ear acoustic mechanics, and a great potential for use of acoustic immittance testing in various diagnostic practices. This article reviews important historical markers in the development and operation of middle ear assessment tools and analysis methods. Technical and clinical factors underlying the emer-

* *N.S. and H.A. have jointly contributed as first co-authors.*

[1]School of Audiology and Speech Sciences, University of British Columbia, Vancouver, Canada; [2]Department of Otolaryngology and Communicative Disorders, School of Medicine, University of Louisville, Louisville, Kentucky; [3]Department of Communication Sciences and Disorders, College of Health, Idaho State University, Pocatello, Idaho.

Address for correspondence: Navid Shahnaz, Ph.D., School of Audiology and Speech Sciences, Faculty of Medicine, University of British Columbia, 2177 Wesbrook Mall, Friedman Building, Vancouver, British Columbia V6T 1Z3, Canada (e-mail: nshahnaz@audiospeech.ubc.ca).

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gence and adoption of different acoustic immittance tests as a standard of clinical practice are described. In addition, we discuss the likelihood for widespread adoption of wideband acoustic immittance and wideband tympanometry in future clinical practice.

KEYWORDS: wideband acoustic immittance, wideband tympanometry, timeline, tympanometry, clinical adoption

EMERGENCE OF AURAL ACOUSTIC IMMITTANCE TESTS: TYMPANOMETRY

Today, tympanometry is a well-established immittance test tool in routine audiologic and otologic assessment. A brief historical analysis of discovery and innovation milestones in the area of middle ear function assessment reveals the recent nature of aural acoustic immittance tests, including tympanometry. A timeline of important discoveries and innovations in this area is illustrated in Fig. 1: From the first anatomical description of the middle ear cavity in the 1500s, to descriptions of the Eustachian tube and innovations for the assessment of its function in the 1700s and 1800s, to the advent of acoustic impedance testing in human ears taking place at the beginning of the 20th century. In the time period between 1932 and the early 1970s, acoustic impedance testing witnessed developments in measurement approaches, and analysis techniques, accompanied by technological advancement and the emergence of multiple clinical instruments. The first "tympanometry" equipment for clinical use emerged in the early 1960s. Fig. 2 illustrates notable examples of commercial tympanometry equipment at various stages of development, from single-frequency 226-Hz tympanometry in the early 1960s to multifrequency tympanometry in the 1980s. In this article, we review milestone events in the development of immittance testing tools that have taken place over the past century and highlight factors underlying their success and widespread adoption, or lack thereof.

The first classic monograph on the application of acoustic impedance in audiology was published in 1946 by Otto Metz.[1] Metz measured impedance in normal and pathological ears at ambient ear canal pressure using a mechanical acoustic measuring bridge. It was not until 1959 and 1960 that Terkildsen and his colleagues,[2,3] at the same university hospital as Otto Metz, developed the first electroacoustic device to measure acoustic impedance (Za) while varying static ear canal pressure in the presence of a 220-Hz probe tone. Their pioneering work in 1961 resulted in the first commercially available electroacoustic impedance bridge, the Madsen ZO70 (Fig. 2). Shortly following this development in 1962, Terkildsen coined the term "tympanometry." Interestingly, the selection of a 220-Hz probe tone was primarily due to convenience and technical considerations, e.g., to avoid nonlinear microphone response at higher frequencies.[2] Hence, the selection of a low-frequency probe tone had nothing to do with its diagnostic accuracy for detecting middle ear pathologies or dysfunction.

Early tympanometry instruments (e.g., Madsen Z070) produced impedance measurements (Z), plotted on a tympanogram with impedance expressed in arbitrary impedance units from 0 to 10. In his classic, large-scale clinical study in 1970, Jerger[4] built on the work of Lidén[5] to develop simple shape-based tympanogram categories for clinical assessment. Fig. 3 illustrates three impedance tympanogram types (A, B, and C) that were suggested by Jerger's classification system (note these are impedance, rather than admittance tympanograms). One issue was the large variability in measurements and tympanogram shapes in relation to large differences in patients' ear canal volumes, posing limitations to the accuracy of impedance tympanograms. Note that since the introduction of the Madsen Z070 system, which Jerger used in his early work, new versions of this device were introduced into the market under the trade name Madsen and then GN Otometrics, and now under the trade name Natus. The most recent product from this lineage of devices is the Madsen Zodiac.

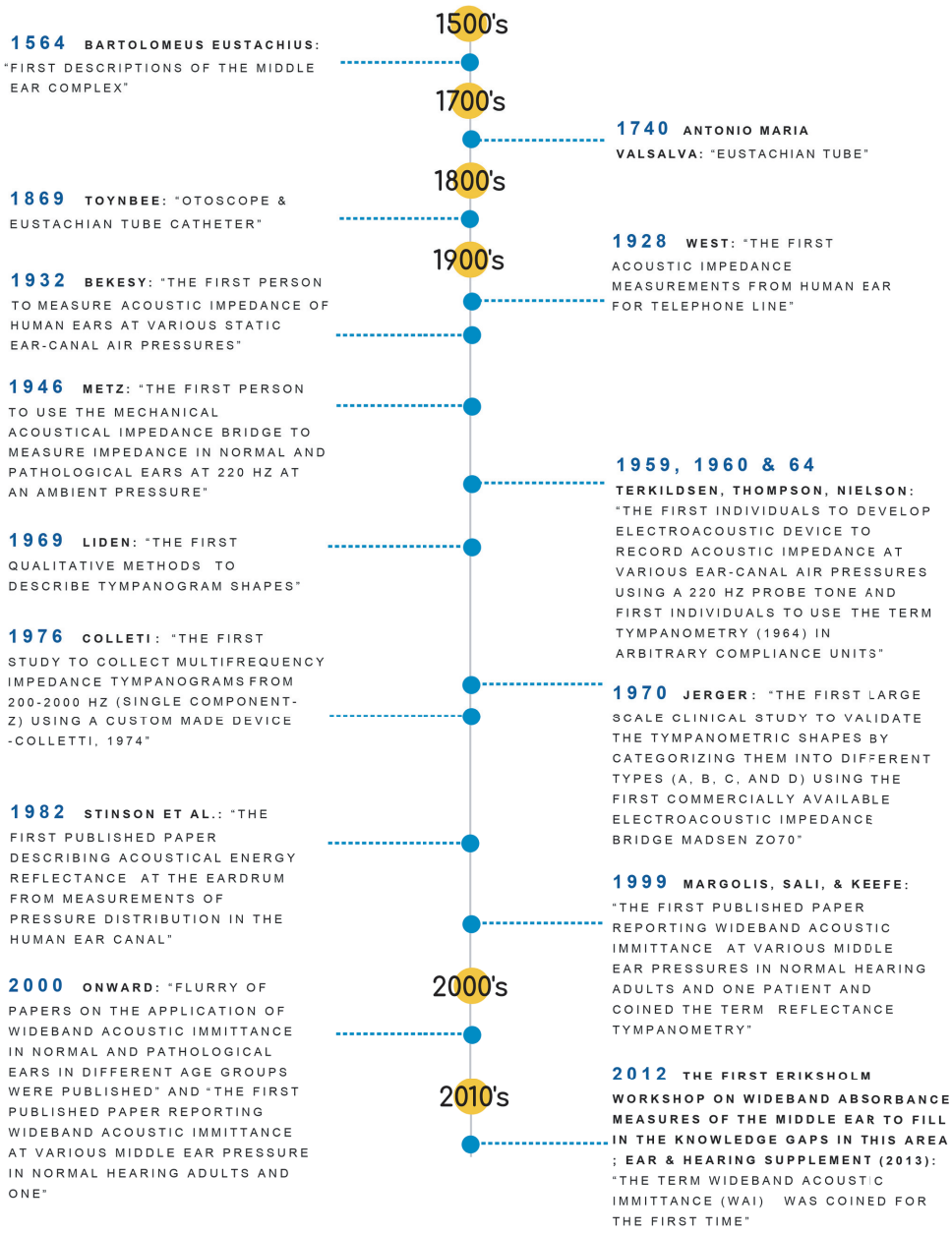

Figure 1 Historical timeline of milestone events in the development of assessment tools for the middle ear function. Acoustic impedance assessments began in the 1920s leading to the emergence of the first commercial instruments in the 1960s. The following decades witnessed the emergence of single-frequency admittance tympanometry, and multi-component, multi-frequency tympanometry. Development of wideband acoustic immittance tests began in the 1980s, followed by a series of investigations and developments leading to the first commercial equipment in the mid-2000s.

In 1971, the Grason-Stadler (GSI) Otoadmittance meter (model 1720) was the first commercially available system to measure admittance (Y) tympanograms instead of impedance tympanograms. Significant developments with the emergence of this instrument were the ability to obtain calibrated measurements in absolute physical units (mmho) rather than

Figure 2 A chronological illustration of key clinical instruments for aural acoustic immittance testing starting with the Madsen ZO70 model by Madsen Electronics in the 1960s, the 1720 Otoadmittance meter by Grason-Stadler in the 1970s, the Virtual 310 middle ear analyzer by Virtual Corporation, and Tympanometer 33 V2 by Grason-Stadler in the 1980s, the HearID by Mimosa Acoustics in the 2000s (used with permission from Mimosa Acoustics Inc.), the Titan by Interacoustics A/S in the 2010s (used with permission from Interacoustics A/S), and the TympStar Pro by Grason-Stadler in the 2020s (used with permission from Grason-Stadler).

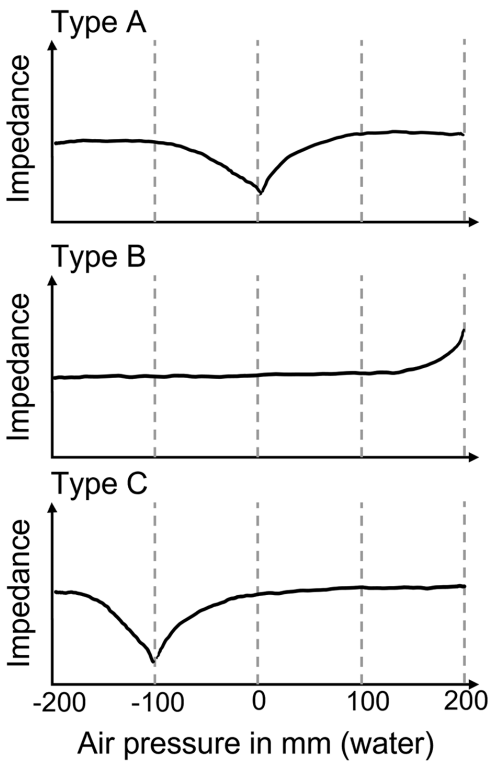

Figure 3 Impedance tympanogram classification system by Jerger.[4] From top to bottom, three shape-based impedance tympanogram types A, B, and C are shown.

arbitrary units (such as with the earlier Madsen Z070) and the ability to monitor and maintain constant sound pressure levels of the probe tone in different ear canal volumes using automatic gain control units. Because admittance at low frequencies (e.g., 220-Hz probe tone) is dominated by compliance-susceptance, a measure that is directly related to acoustic volume, 1 mmho unit was shown to be mathematically equivalent to 1 cc or 1 mL.[6] Taking advantage of this relationship, a simple calibration method in acoustic cavities of known volumes allowed for the determination of admittance units in physical terms. This continues to be the method of calibration for low-frequency admittance tympanometry to this day. An additional advantage was the ability to compensate and control for the influence of ear canal volume admittance. Recall that prior to the emergence of calibrated admittance tympanograms, differences in ear canal volume among patients (e.g., in males vs. females or children vs. adults) introduced variability in the shapes of impedance tympanograms.[7] By contrast, acoustic admittance tympanogram shapes remain constant regardless of ear canal volume but simply shift admittance values along the *y*-axis in an additive manner. This allowed for a simple subtraction of admittance values (in mmho units) at extreme static pressures, where the middle ear is essentially immobilized, to isolate ear-canal and middle-ear admittance from each other. This method also allowed for the estimation of ear-canal volume that is trapped between the probe tip and the tympanic membrane (as mmho and volume units are equivalent).[8]

Another important development in tympanometry testing was the advent of multi-component, multi-frequency tympanometry (MFT). The GSI Otoadmittance meter (1720) device had the additional capability of producing admittance subcomponents in the form of susceptance (B) and conductance (G) tympanograms in response to two probe tones, 220 and 660 Hz. The additional probe tone (660 Hz) allowed for more insight into the acoustic mechanics of the middle ear, with potential for improved diagnostics, especially for ossicular abnormalities.

These advancements paved the way for further developments in the 1980s with the release of newer computer-based devices, such as the Virtual 310 Tympanometer (Virtual Corporation, USA) and GSI 33 V2 in the 1980s (Fig. 2), which allowed for automated testing at multiple probe frequencies between 200 and 2,000 Hz. The advantage of high-frequency tympanometry in the evaluation of mass-related pathologies of the middle ear was demonstrated by Feldman.[9] Vanhuyse et al[10] described the normal patterns for susceptance (B) and conductance (G) tympanograms based on the number of peaks and troughs on these component tracings when using a 678-Hz probe tone. In comparison to 226-Hz tympanometry, analysis of the B- and G-tympanogram peak patterns at higher probe tone frequencies allowed for inferences to be made regarding changes in mass, stiffness, and, subsequently, resonance frequency.[11–13] These measures were shown to be advantageous over 226-Hz tympanometry in the diagnosis of middle ear pathologies.[14–16] For a detailed

account of developments in MFT testing, analysis techniques, and advantages over single-frequency tympanometry, the reader is referred to the report by American Speech-Language-Hearing Association (ASHA) Working Group on Aural Acoustic-Immittance Measurements of the Committee on Audiologic Evaluation (1988).[17]

Despite its diagnostic advantages, MFT testing has not gained widespread adoption as a routine assessment tool in clinics. An investigation by Emanuel et al[18] provided important insights into factors underlying the lack of widespread adoption among clinicians. They surveyed audiological immittance practices in 2012 and showed that 77% of audiologists in the United States had never used MFT tests. Among the cited reasons were equipment availability, training, and time burden. For example, additional test time was needed to obtain multiple tympanograms at different frequencies (e.g., using probe tones at 678 and 1,000 Hz). Moreover, training was required to assess and interpret patterns of responses that were more complex than traditional 226-Hz admittance tympanograms. The outcomes of this survey demonstrated the need for reducing time burden and simplifying analysis methods either by providing simpler clinical interpretation schemes or by implementing machine-automated analysis. A newer MFT instrument, the GSI TympStar Pro, allows for multi-component MFT testing over a significantly shorter time period by utilizing a broadband probe stimulus. This allows for the assessment of frequencies from 250 to 2,000 Hz in a few seconds, thereby considerably reducing the time burden compared to older equipment. The latest upgrades to the TympStar Pro have enabled the system (May 2022) to run much faster and conduct wideband tympanometry (WBT; Fig. 4).

Despite the ability to make inferences about the middle ear acoustic-mechanical properties using MFT compared to single-frequency tympanometry, such inferences are fundamentally

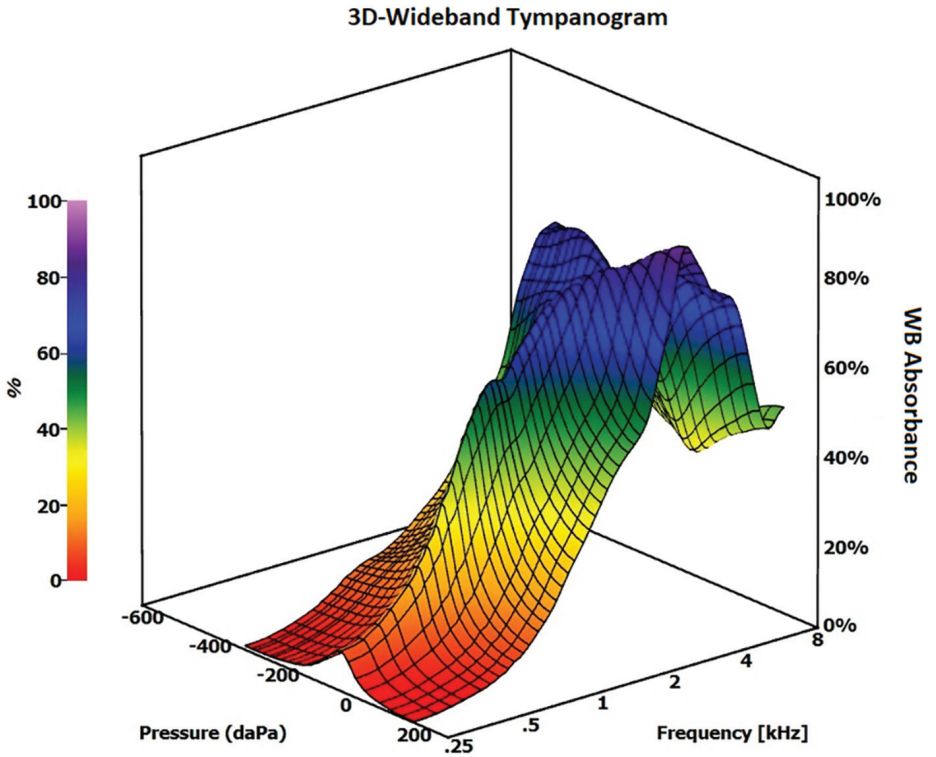

Figure 4 An example of wideband tympanometry outcomes showing a three-dimensional wideband absorbance tympanogram with power absorbance plotted on the z-axis, and frequency and static pressure plotted on the x- and y-axis, respectively.

limited by the inability to obtain accurate measurements at frequencies greater than 2,000 Hz. A complete assessment of middle-ear function requires the ability to obtain acoustic measurements over a wider range of frequencies. Concurrent with technical developments in probe calibration, the emergence of a new type of immittance testing has enabled a more comprehensive assessment of the middle-ear function, called wideband acoustic immittance.

WIDEBAND ACOUSTIC IMMITTANCE

Stinson et al[19] reported the first wideband ear canal recordings in the early 1980s. Subsequent advances in probe "calibration" techniques were described[20,21] (also referred to as determination of the Thévenin-equivalent of the probe[22]) that enabled accurate measurements of acoustic impedance at frequencies above 2,000 Hz. In these early reports, it was common to use wideband power reflectance as the measure of choice (compared to admittance in tympanometry), defined as the proportion of acoustic power reflected at the surface of TM relative to the incident power provided by an ear canal speaker. The use of the term "wideband acoustic immittance" has been recommended more recently (Consensus Statement: Eriksholm Workshop on Wideband Absorbance Measures of the Middle Ear[23]) as an umbrella term that encompasses a host of measures (e.g., pressure/power reflectance, pressure/power absorbance, impedance, admittance). See AlMakadma, Kei et al in this edition for a more detailed description of those measures.

In 1999, a seminal report by Margolis et al[24] demonstrated that, unlike MFT, wideband reflectance progressed in an orderly fashion as frequency increased from 250 through 11,300 Hz. Since then, WAI has increasingly overtaken tympanometry as the subject of study and development by hearing scientists and clinical/translational researchers. Additionally, because WAI utilizes a different calibration method than tympanometry, pressurization of the ear canal is no longer a prerequisite for WAI testing, and measurements are possible at ambient and static ear canal pressures. Early WAI studies investigating maturation-related changes in the outer/middle ear took advantage of this ability to record measurements at ambient pressure to avoid pressure-induced effects on the newborn's immature ear canal walls,[21,25] which were shown to collapse or swell in the presence of negative or positive static pressure, respectively.[26] The following two decades witnessed a flurry of investigative reports on the applications of wideband acoustic immittance measurements in assessing newborn, children, and adult middle-ear function.[21,27–36]

In 2006, Mimosa Acoustics Inc. (USA) released the first commercially available system, called HearID, that could perform WAI tests using the company's module called Middle Ear Power Analysis (MEPA). An illustration of the HearID instrument is shown in Fig. 2. This system allowed for the assessment of middle ear function across a wide range of frequencies at ambient ear canal pressure, comparable to the frequency range commonly used in audiometric assessments. Accessibility to this system facilitated further investigations and clinical research in the area of WAI testing.

A more recent development in WAI testing was the incorporation of capabilities to pressurize the ear canal, not as a technical requirement (e.g., in tympanometry) but as an additional test variable. Several studies demonstrated that wideband measurements obtained at various ear canal pressures might increase the sensitivity of WAI to middle-ear disorders.[24,37] This method of WAI testing while varying static ear-canal pressure has been referred to as WBT.[38] The Titan device, which was released in 2014 by Interacoustics, Inc. (Assens, Denmark; Fig. 2), was the second FDA-approved WAI instrument in the market and the first commercially available system with WBT capabilities. Fig. 4 illustrates a WBT measurement that is represented three-dimensionally (3D) with power absorbance (equivalent to 1-power reflectance) plotted on the vertical axis (z-axis), and with static ear-canal pressure and frequency plotted on the two orthogonal horizontal axes (y- and x-axis, respectively). The additional pressure variable allows for the analysis of the acoustic mechanics of the sound conduction pathway not only across frequencies but also in terms of pressure effects.

A typical application of WBT testing is to obtain wideband measurements (e.g., wideband absorbance [WBA]), at tympanometric peak pressure (TPP). The diagnostic value of such procedures may be understood in reference to known principles from conventional single-frequency tympanometry (i.e., TPP is the pressure point at which the ear canal static pressure and pressure in the middle ear cavity are approximately equal). In cases where negative middle ear pressure contributes excess stiffness to the middle ear, tympanometric pressurization at TPP counterbalances the effect of negative middle-ear pressure, resulting in optimal admittance of the middle ear. One of the advantages of WBT is the ability to compare WBA at both ambient pressure and at TPP. Earlier work demonstrated the value of this type of comparison. For example, Margolis et al[24] reported a case where tympanometric pressurization was introduced to counterbalance the effect of the negative middle-ear pressure on WBA that was present in the ambient conditions. Rather than obtaining near-normal WBA patterns at TPP, abnormal patterns persisted, leading to the suspicion of an additional disorder concurrent with negative middle-ear pressure. In a more typical case, where negative middle-ear pressure is the sole condition underlying an abnormal [ambient] WBA response, measurements obtained at TPP would restore WBA patterns to a more normal state (see AlMakadma, Kei et al for a detailed description of this application). In this *SIH* edition, several clinical/research cases provide a variety of examples of this type of WBT application in diagnostic settings (e.g., Shahnaz, Sree, and Bargen; Sanford, Brockett, and Aithal).

FUTURE OF WAI AS A CLINICAL TEST: PROMISES AND CHALLENGES

Theoretical advantages of WAI include the ability to provide unprecedented amounts of information and insight into the acoustic-mechanical properties of the middle ear. The wide frequency range of assessment currently possible with commercial WAI systems spans the spectrum of speech, allowing for a more realistic representation of sound conduction compared to older tympanometry tests. With WBT testing, an additional dimension of measurements opens the door for even more insight into how the middle-ear acoustic-mechanical response interacts with tympanometric pressure. To realize these advantages to their fullest potential, WAI continues to be the subject of promising developments and investigations by clinical and translational researchers. However, the large amount of information provided by WAI also presents some challenges on how such data are to be analyzed both quantitatively and qualitatively. In 2013, a group of experts conferred at the Eriksholm Workshop on Wideband Absorbance Measures of the Middle Ear and published a consensus statement in which research needs were identified to build on promising clinical findings and to guide future development efforts.[23] Briefly summarized, opportunities for research and further developments included the following: (1) the need for a larger database of clinical measurements to aid in establishing norms, group variance, and better quantification of test accuracy; (2) development of methods for artifact mitigation and improved intra-subject (test–retest) variability; (3) further development of WAI measures that take advantage of timing information (e.g., pressure reflectance, reflectance phase).[23] The following is a brief account of more recent clinical research efforts that address some of these needs and future directions.

For testing in newborns and infants, WAI testing was shown to be useful in the detection of temporary conductive hearing loss that is prevalent in neonates. Detection of temporary obstruction of the sound conduction pathway due to transient outer and/or middle ear substances at the time of birth (e.g., vernix and residual mesenchymal tissue) is useful for discerning the cause for failure on newborn hearing screening tests.[39] Normal WBA measurements in newborns have been characterized, and efforts to further describe and interpret abnormal measurements are underway.[40–43] In addition, researchers are also developing methods to mitigate artifact in measurements that are specific to this population; for example, controlling for acoustic leakage due to poor probe tip fitting into newborns small ear canals.[42,44] Moreover,

manufacturers are optimizing hardware equipment to enable combined hearing screening testing (e.g., TEOAE) and WAI testing using simplified apparatuses for screening settings. For example, Mimosa Acoustics Inc. developed a handheld device, OtoStat 2.0, that displays both OAE and WAI measurements. With continued refinement and improvement, clinicians will be able to use OAE screening outcomes along with WAI outcomes to determine whether infants fail a screening because of a temporary conductive hearing loss or due to a congenital sensorineural hearing loss. This has the potential to reduce unnecessary follow-up testing and to expedite the referral of infants at risk of congenital hearing loss for diagnostic evaluation.

In ENT and audiology clinics, WAI testing has shown great promise in the area of differential diagnosis. Preliminary studies in animal models and in human ears have shown that different middle ear pathologies are often associated with unique WBA measurement patterns making them distinguishable from each other.[31,36,45,46] These findings highlight the potential of WAI as a noninvasive tool for presurgical diagnosis of middle ear disorders. Researchers are developing methods to refine WBA measurements, mitigate sources of variability, and gather larger data sets to better describe measurements from different middle ear pathologies.[47–49] These efforts are instrumental for the determination and characterization of etiology-specific features in WBA measurements to be used diagnostically. In the future, trained clinicians will be able to examine WAI outcomes and qualitatively determine whether WBA has features that indicate specific pathologies (e.g., otitis media vs. otosclerosis vs. cholesteatoma). Researchers are also working on quantitative and automated methods for the analysis of WAI outcomes in diagnostic practice. For example, preliminary efforts show promising outcomes for the utility of artificial intelligence algorithms to process the broad range of information provided by WAI and identify the most informative diagnostic features in measurements.[50–52] In addition to presurgical diagnosis, there are efforts to also examine the use of WAI in postsurgical assessment of outcomes, and restoration of function.[48,53–55]

Another area of active development is the use of WAI technology to evaluate middle ear muscle reflexes (MEMR). In traditional MEMR testing using tympanometry, change in the admittance is measured in response to an eliciting stimulus (a single frequency pure tone, or a broadband tone) that is presented in the same ear, or in the opposite ear. By comparison, the emerging "wideband MEMR" test measures changes in WAI quantities (e.g., power reflectance or power absorbance) to determine threshold reflex levels according to specific criteria. Methods for wideband MEMR have been described since the late 1990s. Schairer et al[56] provided a brief review of early developments in this area. Wideband MEMR testing has great promise over traditional MEMR tests for its ability to obtain MEMR thresholds at lower stimulus levels, and the ability to assess its presence/absence at greater levels of hearing loss.[57] In addition, there is emerging evidence for the clinical benefit of assessing the reflex growth function using wideband MEMR responses, where the strength of MEMR is measured between threshold and maximum elicitor intensity levels. For example, recent reports have demonstrated the use of MEMR growth functions in monitoring ototoxicity.[58] In addition to these promising clinical applications, the use of wideband MEMR has recently garnered the attention of hearing scientists and researchers who are interested in the investigation of hearing deficits that are not captured by the audiogram (e.g., subclinical noise-induced hearing loss, and cochlear synaptopathy).[59–61] Ongoing developments in wideband MEMR testing include refinements of methods and testing paradigms, response quantification, and analysis, including automated/adaptive testing paradigms.[62] For a detailed account of recent wideband MEMR developments and clinical applications, the reader is referred to Feeney et al in this edition. As clinical databases are expanded, and norms are established for different applications, wideband MEMR testing capabilities are likely to be included in commercially available WAI products.

The above-listed efforts demonstrate that WAI is an active area of development and are positive indicators that WAI is increasingly a candidate for incorporation into routine

audiological assessments for a variety of clinical applications. Nevertheless, technological advancement alone is not a guarantee of success. Acceptance from clinicians will be a determining factor on whether WAI technology will receive widespread adoption. Referring back to the report by Emanuel et al[18] on the lack of widespread adoption of MFT technology, discussed in an earlier section, provides insights into factors that may play a role in the successful clinical adoption of WAI (e.g., financial burden, training, and clinician burden). These factors deserve due attention from manufacturers of WAI equipment and clinical and translational researchers alike. Nevertheless, the following are encouraging indicators for the success of WAI technology: (1) It is anticipated that as evidence for the clinical value of WAI continues to grow, the test may receive its own diagnostic code for reimbursement of services to offset the cost of initial investment in purchasing the technology. Statements on clinical practices and guidelines are beginning to include references to WAI testing (e.g., Joint Committee on Infant Hearing, 2019).[63] (2) The implementation of WAI testing in clinics is unlikely to result in considerable use of clinic appointment time. Often WAI data are collected within similar timeframes as, or along with, traditional tympanometry testing. (3) Training of clinicians on use and interpretation of WAI is another important consideration. Future efforts in these regards will include both simplified paradigms for interpretation of WAI measurements in clinical settings, and efforts to develop resources and training materials. It is anticipated that the conceptual shift from tympanometry to WAI measures will not be a difficult one for practicing clinicians; nevertheless, some specialized training is needed for transitioning clinicians and curriculum modification for clinicians in training.

Further developments in methods of analysis and interpretation for various clinical applications will undoubtedly inform emerging training resources for clinicians. This special edition of *Seminars in Hearing* serves as a resource for audiologists on how WAI can be used in the clinic today alongside standard audiological tools. Several articles present simplified methods for conceptualizing wideband immittance measures and several clinical case studies for the use of WAI for different populations.

CONFLICT OF INTEREST
None declared.

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REFERENCES

1. Metz O The acoustic impedance measured on normal and pathological ears. Acta Oto-Lar; 1946
2. Terkildsen K, Nielsen SS. An electroacoustic impedance measuring bridge for clinical use. Arch Otolaryngol 1960;72(03):339–346
3. Terkildsein K, Thomsen KA. The influence of pressure variations on the impedance of the human ear drum. A method for objective determination of the middle-ear pressure. J Laryngol Otol 1959;73 (07):409–418
4. Jerger J. Clinical experience with impedance audiometry. Arch Otolaryngol 1970;92(04):311–324
5. Lidén G. The scope and application of current audiometric tests. J Laryngol Otol 1969;83(06): 507–520
6. Lilly D, Shanks J. Acoustic immittance of an enclosed volume of air. In: Popelka Ged.. Hearing Assessment with the Acoustic Reflex. Grune & Stratton; 1981:145–160
7. Shanks JE, Lilly DJ. An evaluation of tympanometric estimates of ear canal volume. J Speech Hear Res 1981;24(04):557–566
8. Van Camp KJ, Margolis RH, Wilson RH, Creten WL, Shanks JE. Principles of tympanometry. ASHA Monogr 1986;(24):1–88
9. Feldman AS. Tympanometry: application and interpretation. Ann Otol Rhinol Laryngol 1976;85 (2, Suppl 25, Pt 2):202–208
10. Vanhuyse V, Creten W, Van Camp K. On the W-notching of tympanograms. Scand Audiol 1975;4 (01):45–50
11. Shanks JE. Tympanometry. Ear Hear 1984;5(05): 268–280
12. Margolis RH, Goycoolea HG. Multifrequency tympanometry in normal adults. Ear Hear 1993; 14(06):408–413
13. Shahnaz N. Multi-frequency tympanometry and evidence-based practice. Perspectives on Hearing and Hearing Disorders: Research and Diagnostics 2007;11(01):2–12

14. Hunter LL, Margolis RH. Multifrequency tympanometry: current clinical application. Am J Audiol 1992;1(03):33–43
15. Margolis RH, Schachern PL, Fulton S. Multifrequency tympanometry and histopathology in chinchillas with experimentally produced middle ear pathologies. Acta Otolaryngol 1998;118(02): 216–225
16. Shahnaz N, Polka L. Standard and multifrequency tympanometry in normal and otosclerotic ears. Ear Hear 1997;18(04):326–341
17. ASHA Working Group on Aural Acoustic-Immittance Measurements Committee on Audiologic Evaluation. Tympanometry. J Speech Hear Disord 1988;53(04):354–377
18. Emanuel DC, Henson OE, Knapp RR. Survey of audiological immittance practices. Am J Audiol 2012;21(01):60–75
19. Stinson MR, Shaw EA, Lawton BW. Estimation of acoustical energy reflectance at the eardrum from measurements of pressure distribution in the human ear canal. J Acoust Soc Am 1982;72(03): 766–773
20. Allen JB. Measurement of eardrum acoustic impedance. In: Peripheral Auditory Mechanisms. Springer; 1986:44–51
21. Keefe DH, Bulen JC, Arehart KH, Burns EM. Ear-canal impedance and reflection coefficient in human infants and adults. J Acoust Soc Am 1993; 94(05):2617–2638
22. Voss SE, Stenfelt S, Neely ST, Rosowski JJ. Factors that introduce intrasubject variability into ear-canal absorbance measurements. Ear Hear 2013;34(701): 60S–64S
23. Feeney MP, Hunter LL, Kei Jet al. Consensus statement: Eriksholm workshop on wideband absorbance measures of the middle ear. Ear Hear 2013;34(Suppl 1):78S–79S
24. Margolis RH, Saly GL, Keefe DH. Wideband reflectance tympanometry in normal adults. J Acoust Soc Am 1999;106(01):265–280
25. Keefe DH, Levi E. Maturation of the middle and external ears: acoustic power-based responses and reflectance tympanometry. Ear Hear 1996;17(05): 361–373
26. Holte L, Margolis RH, Cavanaugh RM Jr. Developmental changes in multifrequency tympanograms. Audiology 1991;30(01):1–24
27. Ellison JC, Gorga M, Cohn E, Fitzpatrick D, Sanford CA, Keefe DH. Wideband acoustic transfer functions predict middle-ear effusion. Laryngoscope 2012;122(04):887–894
28. Feeney MP, Grant IL, Marryott LP. Wideband energy reflectance measurements in adults with middle-ear disorders. J Speech Lang Hear Res 2003;46(04):901–911
29. Feeney MP, Sanford CA. Age effects in the human middle ear: wideband acoustical measures. J Acoust Soc Am 2004;116(06):3546–3558
30. Hunter LL, Tubaugh L, Jackson A, Propes S. Wideband middle ear power measurement in infants and children. J Am Acad Audiol 2008;19 (04):309–324
31. Nakajima HH, Pisano DV, Roosli Cet al. Comparison of ear-canal reflectance and umbo velocity in patients with conductive hearing loss: a preliminary study. Ear Hear 2012;33(01):35–43
32. Prieve BA, Vander Werff KR, Preston JL, Georgantas L. Identification of conductive hearing loss in young infants using tympanometry and wideband reflectance. Ear Hear 2013;34(02):168–178
33. Rosowski JJ, Mehta RP, Merchant SN. Diagnostic utility of laser-Doppler vibrometry in conductive hearing loss with normal tympanic membrane. Otol Neurotol 2003;24(02):165–175
34. Voss SE, Allen JB. Measurement of acoustic impedance and reflectance in the human ear canal. J Acoust Soc Am 1994;95(01):372–384
35. Voss SE, Horton NJ, Woodbury RR, Sheffield KN. Sources of variability in reflectance measurements on normal cadaver ears. Ear Hear 2008;29 (04):651–665
36. Voss SE, Merchant GR, Horton NJ. Effects of middle-ear disorders on power reflectance measured in cadaveric ear canals. Ear Hear 2012;33 (02):195–208
37. Keefe DH, Simmons JL. Energy transmittance predicts conductive hearing loss in older children and adults. J Acoust Soc Am 2003;114(6, Pt 1):3217–3238
38. Sanford CA, Hunter LL, Feeney MP, Nakajima HH. Wideband acoustic immittance: tympanometric measures. Ear Hear 2013;34(Suppl 1):65S–71S
39. Doyle KJ, Rodgers P, Fujikawa S, Newman E. External and middle ear effects on infant hearing screening test results. Otolaryngol Head Neck Surg 2000;122(04):477–481
40. Hunter LL, Feeney MP, Lapsley Miller JA, Jeng PS, Bohning S. Wideband reflectance in newborns: normative regions and relationship to hearing-screening results. Ear Hear 2010;31 (05):599–610
41. Merchant GR, Horton NJ, Voss SE. Normative reflectance and transmittance measurements on healthy newborn and 1-month-old infants. Ear Hear 2010;31(06):746–754
42. Voss SE, Herrmann BS, Horton NJ, Amadei EA, Kujawa SG. Reflectance measures from infant ears with normal hearing and transient conductive hearing loss. Submitted for publication. Ear Hear 2016;37(05):560–571

43. Vander Werff KR, Prieve BA, Georgantas LM. Test-retest reliability of wideband reflectance measures in infants under screening and diagnostic test conditions. Ear Hear 2007;28(05):669–681
44. AlMakadma HA, Prieve BA. Refining measurements of power absorbance in newborns: probe fit and intrasubject variability. Ear Hear 2021;42(03): 531–546
45. Feeney MP, Grant IL, Mills DM. Wideband energy reflectance measurements of ossicular chain discontinuity and repair in human temporal bone. Ear Hear 2009;30(04):391–400
46. Nakajima HH, Rosowski JJ, Shahnaz N, Voss SE. Assessment of ear disorders using power reflectance. Ear Hear 2013;34(701, Suppl 1):48S–53S
47. Merchant GR, Al-Salim S, Tempero RM, Fitzpatrick D, Neely ST. Improving the differential diagnosis of otitis media with effusion using wideband acoustic immittance. Ear Hear 2021;42(05): 1183–1194
48. Feeney MP, Keefe DH, Hunter LL, Fitzpatrick DF, Putterman DB, Garinis AC. Effects of otosclerosis on middle ear function assessed with wideband absorbance and absorbed power. Ear Hear 2021;42(03):547–557
49. Eberhard KE, Ravicz ME, Merchant GRet al. Preserving wideband tympanometry information with artifact mitigation. Ear Hear 2022;43(02): 563–576
50. Grais EM, Wang X, Wang Jet al. Analysing wideband absorbance immittance in normal and ears with otitis media with effusion using machine learning. Sci Rep 2021;11(01):10643
51. Eberhard KE, Chari DA, Nakajima HH, Klokker M, Cayé-Thomasen P, Lee DJ. Current trends, controversies, and future directions in the evaluation and management of superior canal dehiscence syndrome. Front Neurol 2021;12:638574
52. Masud SF. Diagnosis of Mechanical Ear Pathologies Using Structure-Based Modeling and Machine Learning Techniques. Harvard University; 2020
53. Niemczyk E, Lachowska M, Tataj E, Kurczak K, Niemczyk K. Wideband acoustic immittance - absorbance measurements in ears after stapes surgery. Auris Nasus Larynx 2020;47(06):909–923
54. Shahnaz N, Longridge N, Bell D. Wideband energy reflectance patterns in preoperative and post-operative otosclerotic ears. Int J Audiol 2009;48(05):240–247
55. Eberhard KE, Masud SF, Knudson IMet al. Mechanics of total drum replacement tympanoplasty studied with wideband acoustic immittance. Otolaryngol Head Neck Surg 2022;166(04):738–745
56. Schairer KS, Feeney MP, Sanford CA. Acoustic reflex measurement. Ear Hear 2013;34(Suppl 1):43S–47S
57. Feeney MP, Keefe DH, Hunter LLet al. Normative wideband reflectance, equivalent admittance at the tympanic membrane, and acoustic stapedius reflex threshold in adults. Ear Hear 2017;38(03): e142–e160
58. Blankenship CM, Hunter LL, Feeney MPet al. Functional impacts of aminoglycoside treatment on speech perception and extended high-frequency hearing loss in a pediatric cystic fibrosis cohort. Am J Audiol 2021;30(3S):834–853
59. Kamerer AM, Kopun JG, Fultz SE, Neely ST, Rasetshwane DM. Reliability of measures intended to assess threshold-independent hearing disorders. Ear Hear 2019;40(06):1267–1279
60. Shehorn J, Strelcyk O, Zahorik P. Associations between speech recognition at high levels, the middle ear muscle reflex and noise exposure in individuals with normal audiograms. Hear Res 2020;392:107982
61. Wojtczak M, Beim JA, Oxenham AJ. Weak middle-ear-muscle reflex in humans with noise-induced tinnitus and normal hearing may reflect cochlear synaptopathy. eNeuro 2017;4(06): ENEURO.0363-17.2017
62. Schairer KS, Putterman DB, Keefe DHet al. Automated adaptive wideband acoustic reflex threshold estimation in normal-hearing adults. Ear Hear 2022;43(02):370–378
63. Joint Committee on Infant Hearing. Year 2019 Position Statement: principles and guidelines for early hearing detection and intervention programs. J Early Hear Detect Interv 2019;4(02):1–44