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Implementation of Wideband Acoustic Immittance in Clinical Practice: Relationships among Audiologic and Otologic Findings

Chris A. Sanford, Ph.D.,[1] Jeff E. Brockett, Ed.D.,[1] Venkatesh Aithal, M.P.H., Ph.D.,[2] and Hammam AlMakadma, Au.D., Ph.D.[3]

ABSTRACT

A number of studies have produced normative and developmental data and examples of wideband acoustic immittance (WAI) obtained in ears with pathologies and or dysfunction. However, incorporation of this tool into clinical audiology and otolaryngology practice has been slower than expected, potentially due to challenges with interpretation, integration into existing test batteries, and confidence in practical application. This article presents information aimed at helping clinicians increase their confidence in using this new tool by becoming more familiar and making connections with the ways that WAI outcomes both align with and add to standard immittance, audiometric and otologic diagnostic test outcomes. This article presents several case studies to demonstrate the use of WAI in realistic clinical settings. Each case presents a brief background, case history, audiologic/otologic findings, and initial recommendations, followed by a discussion on how the inclusion of WAI test outcomes aids in diagnostic decisions. The overall aim of this work is to identify the relationships among different diagnostic test outcomes, to demonstrate

[1]Department of Communication Sciences and Disorders, Idaho State University, Pocatello, Idaho; [2]Audiology Department, Townsville University Hospital and Hearing Research Unit for Children, University of Queensland, Queensland, Australia; [3]Department of Otolaryngology and Communicative Disorders, School of Medicine, University of Louisville, Louisville, Kentucky.

Address for correspondence: Chris A. Sanford, Ph.D., Department of Communication Sciences and Disorders, Idaho State University, Mail Stop 8116, Pocatello, ID 83209 (e-mail: chrissanford@isu.edu).

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basic WAI interpretation principles, and encourage the reader to engage with this diagnostic tool in clinical practice.

KEYWORDS: wideband acoustic immittance, absorbance, tympanometry, middle ear disorders, audiology, otolaryngology

Health care providers in audiology and otology practice settings rely on both subjective and objective diagnostic tools for the assessment of middle ear status. Procedures such as behavioral audiometry, standard and pneumatic otoscopy, and an immittance test battery are some of the useful tools used to help determine middle ear status and the presence or absence of a conductive hearing loss (CHL).[1,2] When individual test results correlate or agree with the results of other tests, this often provides confirmation of a particular disorder or dysfunction.[3] Sometimes, however, inability to obtain sufficient data or emergence of conflicting results leaves a definitive diagnosis in question. These challenges are relatively common occurrences in otolaryngology (ENT) settings where patients present with a variety of conditions, including otitis media with effusion (OME), tympanic membrane (TM) perforation, otosclerosis, excessive middle ear pressure, disarticulation of the ossicular chain, patulous Eustachian tube, tympanosclerosis, cholesteatoma, and more. Often, individual audiological or otologic test tools are prone to classification errors (e.g., false-negative or false-positive errors) and are insufficient for reaching a definitive diagnosis. For example, an otoscopic exam may reveal a healthy-appearing TM and immittance results may suggest normal middle ear function in spite of significant air–bone gaps (ABGs) as revealed by pure-tone audiometry.[4,5] Similarly, reports show that an otoscopic examination may miss ossicular chain fixation or discontinuity.[6] Other challenging scenarios in otologic diagnostic practices include etiologies that mimic each other on a number of audiological or otologic tests. For example, superior canal dehiscence is shown to mimic a number of other otologic conditions such as endolymphatic hydrops, and other etiologies of the middle ear where a true CHL is present.[7,8] As a result, clinicians do not rely on an individual test, but use a combination of tests to critically appraise the relationships among their findings to work toward accurate diagnoses.

In cases with insufficient or confounding diagnostic test results, the search for definitive diagnoses can move from routine, in-office procedures to more costly and invasive imaging studies and/or confirmation by exploratory surgeries. Wideband acoustic immittance (WAI) is a cost-efficient and noninvasive diagnostic tools that is feasible for routine evaluation in otologic and audiological settings. WAI has shown improved accuracy over conventional single-frequency tympanometry testing including ability to improve differential diagnosis.[9–13] Due to the capability of WAI technology to assess middle ear sound conduction over a wide range of frequencies, clinicians are able to discern subtle changes in middle ear acoustic-mechanical properties in ways that are not possible with traditional tympanometry tests (for more details about fundamental concepts in WAI, the reader is referred to the review by AlMakadma, Kei et al in this edition). While applicable across the age span, this test is especially beneficial in young children or difficult to test populations (see Shahnaz, Aithal & Bargen in this issue for in-depth discussion of WAI applications in pediatric populations). The scope of this work is to demonstrate the use of WAI as part of a battery of tests, and to encourage the adoption of this tool in clinical settings. For detailed discussions of technical aspects, the reader is referred to previous reports on the topic.[14,15]

STANDARD AUDIOLOGIC/ OTOLARYNGOLOGY TESTS

While individual tests bring strengths to a clinician's diagnostic "toolbox," clinicians will most often perform diagnostic assessments using a battery of tests. Clinicians engage in critical analysis of the various test outcomes and whether they point to a common diagnoses or if there is discord among clinical outcomes in ambiguous cases. This is consistent with the premise underlying the "cross-check principle" purposed by Jerger and Hayes[16] over 40 years ago. The cross-check principle suggests that a single test should not be used in isolation to determine a diagnosis until its outcomes are confirmed by another independent test. While a clinician's judgment is of significant value in the effective use and interpretation of a combination of tests and test outcomes, the validity of a diagnosis is limited by the accuracy of the individual test components. In this section, we review common audiological and otologic tests that are used for diagnosis of middle ear disorders. While an exhaustive review of common audiologic/otologic test performance for different diagnostic tools is beyond the scope of this article, the following presentation highlights the need for the inclusion of and comparison across independent test measures in the process of differential diagnosis.

Pure-tone audiometry is often employed in clinical cases for which a hearing loss is suspected. Air- and bone-conduction hearing thresholds provide information about the type and degree of hearing loss; the derived ABGs are the gold standard for diagnoses of CHL. The presence of significant ABGs often is associated with a disorder or dysfunction of the middle ear and its configuration across frequency may also present useful diagnostic clues about underlying etiologies. However, it should be cautioned that conductive dysfunction as indicated by ABGs can sometimes be caused by dysfunction that is not directly related to the middle ear and therefore not considered a typical CHL. For example, with superior canal dehiscence, an ABG presentation is the reflection of the shunting of energy away from the cochlea rather than a CHL due to a lesion of the middle ear.[17] In this case, ABGs alone are not very useful in differential diagnosis of superior canal dehiscence. Moreover, the use of an ABG configuration across frequency as a diagnostic tool, while useful, is not without error. A common example of this is Carhart's notch, which is defined as poorer than expected bone conduction thresholds at and around 2,000 Hz, relative to other bone conduction thresholds, as revealed with bone conduction audiometry. In the presence of significant ABGs, a Carhart's notch often points to a diagnosis of otosclerosis. However, Carhart's notch is also observed in other conductive conditions. Yasan[18] reported on the accuracy of Carhart's notch in differential diagnosis. They reviewed audiometric findings from 305 middle ear surgeries, showing that among 41 individuals with a Carhart's notch at 2 kHz, just over 50% were diagnosed with chronic otitis media with and without effusion, and only 41% had otosclerosis. Furthermore, just over 80% of patients with otosclerosis did not present with a Carhart's notch. Therefore, additional assessment tools can be helpful in guiding a clinician to the correct diagnosis.

Single-frequency tympanometry, another routine audiological assessment tool in clinical practice, provides helpful information that aids in the diagnosis of middle ear disorders. Often, a 226-Hz probe tone is used to measure admittance of the middle ear, and other tympanogram parameters including tympanometric peak pressure (TPP), tympanometric width, and an equivalent ear canal volume estimate. When assessing admittance with this low probe-tone frequency, admittance of the middle ear is predominantly a measure of the middle ear's compliance. Used together with other audiological and otologic tests, inferences on whether middle ear compliance is normal, hypo-, or hyper compliant (e.g., tympanogram types A, As, and Ad, respectively) aid in differential diagnosis of underlying pathologies. Tympanometry is also an effective tool for the detection of TM perforation and measuring Eustachian tube dysfunction (ETD) and the presence of excess pressure in the tympanic cavity. While low-frequency tympanometry is sensitive to changes in the degrees of middle ear stiffness, there is limited ability to differentiate middle ear disorders that have more complex pathophysiology than simply a change in compliance, such as pathological changes in mass. Such changes may be better captured at high-frequency probe tones. Unfortunately, tympanometry is limited in its ability to sufficiently assess the acoustic-mechanic properties of the middle ear across a broad frequency range due to instable measurements at frequencies greater than 2,000 Hz. Several studies have reported on the ineffectiveness of low-frequency tympanometry in differential diagnosis. For example, tympanometric data suggest good test sensitivity to otitis media, but poor sensitivity to otosclerosis.[19,20] Browning et al[21] reported on 226-Hz tympanometric findings in adults with confirmed diagnoses of otosclerosis and significant ABGs ranging from 18 to 54 dB and adults with normal hearing. They reported that admittance magnitude identified patients with otosclerosis with a sensitivity rate of 88% and a specificity rate of 90%.

Otoscopic examination, although subjective in nature, is another valuable assessment tool commonly used by clinicians. Investigators have reported the ability of pneumatic otoscopy to predict middle ear effusion with sensitivity and specificity values ranging from 87 to 93% and 58 to 91%, respectively.[19] However, situations with a normal-appearing TM and aerated middle ear (e.g., otosclerosis and ossicular disarticulation) reduce the effectiveness and accuracy of otoscopy. In these and other situations with contradictory findings, imaging techniques such as computed tomography (CT) or magnetic resonance imaging (MRI) are often used in otologic practice to aid in the differential diagnosis of ambiguous clinical presentations.[22] Similar to other individual test tools when used in isolation, imaging tools are also prone to diagnostic errors. For example, a systematic review conducted by Wegner et al[23] reported the sensitivity of CT imaging to otosclerosis was between 60 and 95%.

In summary, a single diagnostic test is typically not sufficient on its own to provide the most accurate and comprehensive assessment for a given condition and any improvements in a clinician's ability to use simple, noninvasive, and objective diagnostic tests are welcome. The use of a test battery approach and implementation of the cross-check principle helps bring together data from a number of tests so they can be considered together. The inclusion of WAI, an immittance test that has significant benefits relative to traditional tympanometry, has the potential of improving the differential diagnosis of middle ear pathologies and dysfunction.[11,13,20,24]

WIDEBAND ACOUSTIC IMMITTANCE MEASURES AND CLINICAL ASSESSMENTS

This report presents WAI test findings and a variety of other diagnostic assessment data from research participants and/or clinical patients with a variety of otologic and audiometric profiles of middle-ear dysfunction. The umbrella term, WAI, covers a variety of quantities (power absorbance, power reflectance, impedance, etc.) that are derived from ear canal recordings in response to a broadband stimulus (click or chirp). An advanced calibration technique utilized for WAI tests allows for accurate recording of the acoustic response in the ear canal over a wide range of frequencies (typically expressed from 250 to 8,000 Hz).[15] WAI measurements can be obtained at ambient ear canal pressure or in the presence of dynamic pressures sweeps; each provides alternative perspectives and different diagnostic value to this broadband assessment tool.[14,25] WAI testing performed in the presence of pressure sweeps is referred to as wideband tympanometry (WBT). While different quantities of WAI have been reported in the literature (e.g., reflectance, impedance, absorbance), WAI data for the present article are displayed in terms of absorbance as a function of frequency, or wideband absorbance (WBA). The values of WBA range from 0, where minimal sound energy is absorbed by the middle ear system, to 1 where maximal sound energy is absorbed. Absorbance values can also be expressed in percentages, ranging from 0 to 100%. An example of a WBA measurement obtained at ambient ear canal pressure from an adult with normal middle function ear is illustrated in the top panel of Fig. 1. The gray shaded regions represent a normative range of absorbance. The bottom panel of Fig. 1 illustrates the outcome of a WBT test as a three-dimensional graph, with absorbance values plotted on the z-axis as a function of both frequency and ear canal pressure. Often, WBA data are extracted from a WBT test at ambient ear canal pressure (or at 0 daPa) and at TPP. A comparison of WBA at 0 daPa (WBA_0) and at TPP (WBA_{TPP}) is useful in differential diagnosis in general, or under suspicion of multiple disorders being present concurrently.[26–28]

One of the benefits of WAI is its ability to produce a range of pathology-specific patterns

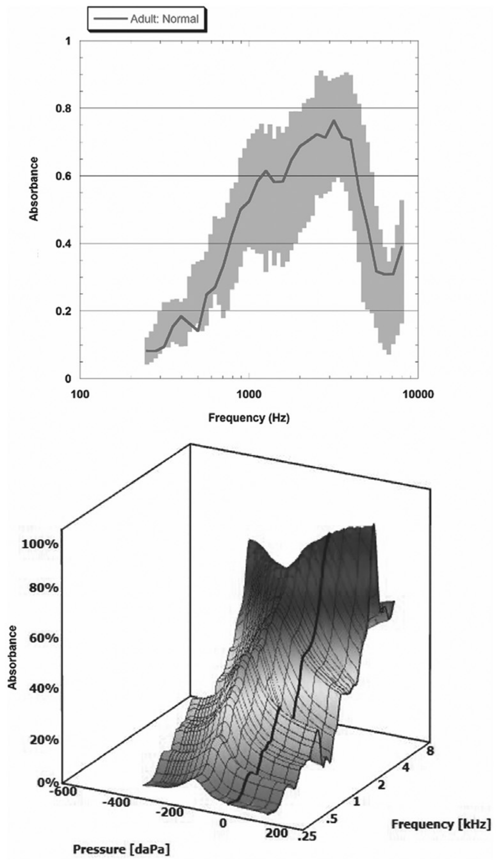

Figure 1 Examples of wideband acoustic immittance and wideband tympanogram (WBT) measurements. The top panel represents a normal WBA_0 response (solid line) obtained at ambient ear canal pressure; gray-shaded region represents a range of normal responses for adults. The lower panel is a WBT, obtained from an individual with negative TPP in the presence of a dynamic pressure sweep, with absorbance (scaling from 0 to 100%) plotted as a function of frequency and ear canal pressure.

of measurements, which conventional tympanometry cannot. As a starting point, a basic question may arise regarding the overall WBA pattern (pattern of absorbance as a function of frequency) for a normally functioning middle ear (refer to Fig. 1, top panel). The normal WBA pattern can be simply described as a band-pass filter, with mid frequency sounds (2,000–4,000 Hz) passing through more easily than the surrounding lower and higher frequencies, as shown by the prominent absorbance peak in the mid-high frequency range. In the presence of a pathological change, WBA patterns are altered; for example, absorbance values may increase or decrease at all or some frequencies, and the absorbance peak may shift to higher or lower frequencies. A qualitative assessment of abnormal WBA patterns allows for inferences about pathological changes to be made in relationship with the acoustic mechanics of the middle ear, for example, pathological changes in mass, stiffness, and frequency of resonance. Such qualitative assessment paradigms are presented in details in Withnell et al[29] and AlMakadma, Kei et al in this issue. For example, a pathology or dysfunction which introduces stiffness (e.g., negative middle ear pressure) would hypothetically result in decreased absorbance for low frequencies. Conversely, pathological increase in mass is hypothesized to decrease absorbance for the high frequencies (e.g., cholesteatoma). To familiarize the reader with some of the ways that WBA patters are influenced by different pathologies/dysfunctions, several examples based on findings from Feeney et al[30] and Sanford and Brockett[5] are illustrated in Fig. 2 including ossicular discontinuity, negative middle ear pressure, and OME. As well, an example of WBA form ears with pressure equalization (PE) tube is illustrated. While some conditions may present with, at least to some extent, similar absorbance patterns (PE tube and ossicular discontinuity), others, like OME and negative middle ear pressure, are vastly different. The ability to identify WBA patterns that correlate with different middle ear conditions demonstrates the great potential of WAI testing over current clinical immittance tests. Of course, mass and stiffness effects related to pathologies and dysfunction are not always applied in simple and unidimensional ways and can be very dynamic in nature. As noted in the case studies that follow, a simple application of the principles related to mass and stiffness effects are a good first step when assessing WBA patterns and working toward a diagnosis.

WAI CLINICAL APPLICATIONS

In the following clinical cases, a variety of WAI and WBT test findings are presented that demonstrate how patterns of WBA differ or are similar for an array of different pathologies/dysfunctions (similar to the examples in Fig. 2). For each case, changes in WBA in comparison

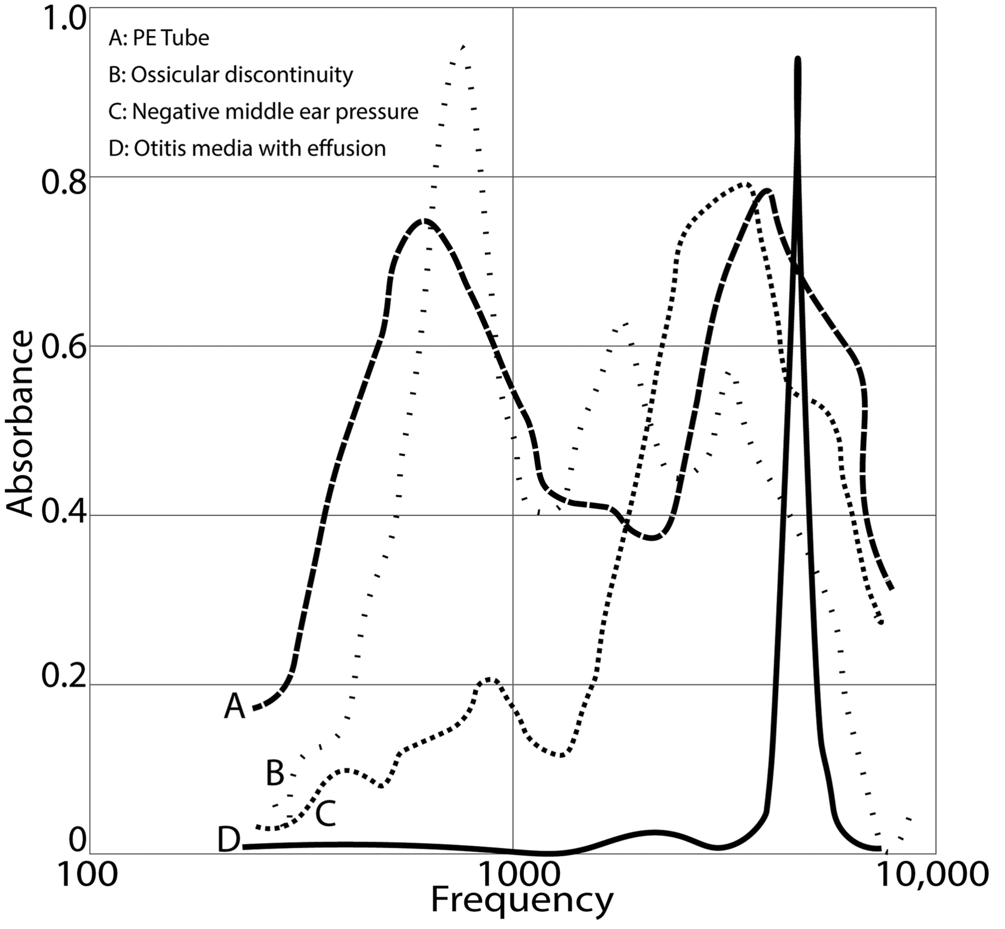

Figure 2 Representative individual wideband absorbance (WBA) examples, plotted as a function of frequency for different middle ear disorders or dysfunction: A—pressure equalization (PE) tube; B—ossicular discontinuity; C—negative middle ear pressure; D—otitis media with effusion. These examples are patterned after literature reports by Feeney et al[30] and Sanford and Brockett.[5] Disorder-specific WBA patterns demonstrate the utility of these measurements in differential diagnosis.

to normal are assessed and interpreted using the stiffness–mass–resonance paradigm that was described in the article by AlMakadma, Kei et al in this issue. The reader is referred to Voss et al[31] and Nakajima et al[11] for detailed descriptions of WAI measurements in middle ear disorders. All cases presented in this work from clinic and research data obtained proper permissions and IRB approvals.

Case 1: Cholesteatoma

BACKGROUND

Otolaryngology/ENT specialists become very skilled at assessing middle ear status using otoscopy. A normal-appearing TM is somewhat translucent and allows the identification of landmarks in the middle ear; it also allows the visualization of abnormal middle ear conditions such as effusions and vascularization (e.g., Schwartze sign).[32] However, sometimes the TM is not translucent, which makes it difficult to evaluate middle ear status. Patients with a long history of middle ear disease, for example, will present with what ENTs refer to as "thickened" or "opaque" TMs. This lack of translucency prevents adequate assessment of the middle ear by otoscopy. This opacity can be from a long-standing disorder of the TM such as tympanosclerosis or myringosclerosis, but it could also indicate the presence of an acute disorder. In cases like these, an ENT may request additional audiological tests to aid with differential diagnosis. For example, a standard low-frequency (226 Hz) tympanometry test can provide additional data points to help with the diagnosis. But, what if the TM looked opaque and the 226-Hz tympanogram produced normal findings (e.g., type A classification). Assuming the patient is old enough for reliable data to be obtained, air- and bone-conduction audiometry can provide another layer of information. For example, large ABGs would suggest a greater middle ear dysfunction than no ABGs. The following case presents a situation where WAI testing played an important role in steering the path to diagnosis.

CASE HISTORY

An adult patient presented to an ENT practice with what she described as the sensation that her right ear was plugged for several months. The onset reportedly followed "a really bad cold" where both ears became "plugged." Her left ear cleared as the rest of her "cold" symptoms diminished but her right ear remained symptomatic.

AUDIOLOGIC/OTOLOGIC FINDINGS AND INITIAL RECOMMENDATIONS

Otoscopy revealed what the ENT described as "thickened and opaque" TMs, bilaterally. Tympanometry testing revealed type A tympanograms, bilaterally, with a slight pressure imbalance between the ears, where the right ear had a slightly negative TPP and abnormally large tympanometric width of 295 daPa (Fig. 3). Consequently, a complete audiometric evaluation was performed to aid in diagnosis. Pure-tone air- and bone-conduction thresholds were obtained (Fig. 4). Results showed a mild to moderate sensorineural hearing loss (4,000–8,000 Hz) for the left ear and a mild to severe mixed hearing loss for the right ear. The mixed nature of the hearing loss warranted a closer assessment of the conductive component. For the left, asymptomatic ear, 10 to 15 dB ABGs were present in the low frequencies (250–1,000 Hz) where hearing sensitivity was within-normal limits, with little or no ABGs in the high frequencies (2,000–4,000 Hz). In the right, symptomatic ear, there was a 15-dB low-frequency ABG at 250 Hz that essentially closed by 1,000 Hz, with additional 15 to 30 dB ABGs at 2,000 Hz and higher. The configuration of ABGs across frequencies does not provide obvious clues to a specific pathology. For example, there was not a significant "notch," or poorer bone conduction thresholds at and around 2,000 Hz, relative to other bone conduction thresholds, which is often indicative of otosclerosis (re: Carhart's notch).

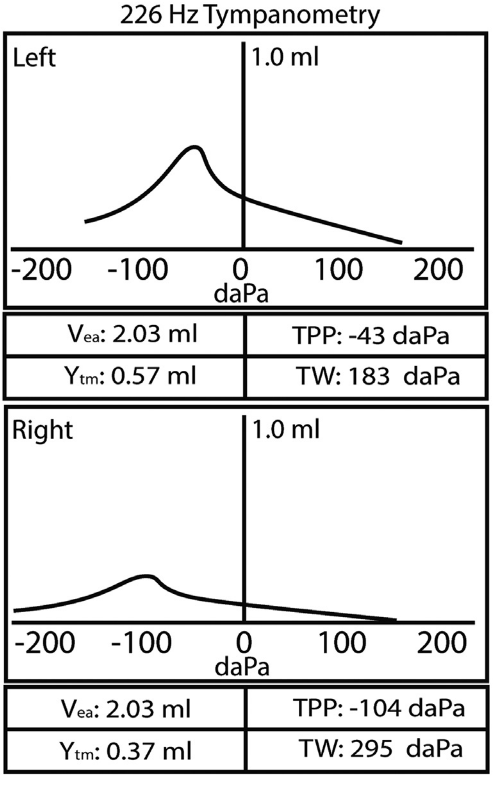

Figure 3 Conventional (226 Hz) tympanograms measured in the left ear (top panel) and right ear (bottom panel) of the individual in Case 1 (cholesteatoma). Vea, Ytm, TPP, and TW correspond to equivalent ear canal volume, peak compensated static acoustic admittance, tympanometric peak pressure and tympanometric width, respectively.

WAI TESTING AND OUTCOMES

WAI was added to the diagnostic workup and revealed both differences and similarities in WBA patters between ears (Fig. 5). As described earlier (e.g., in Fig. 2), researchers have published data related to specific middle ear pathologies and the WBA patterns they reveal; this particular patient's WBA pattern did not seem to match any of the more common absorbance patterns. The absorbance pattern in the left ear (Fig. 5, top panel) presents with a normal/typical response through about 3,000 Hz with decreased

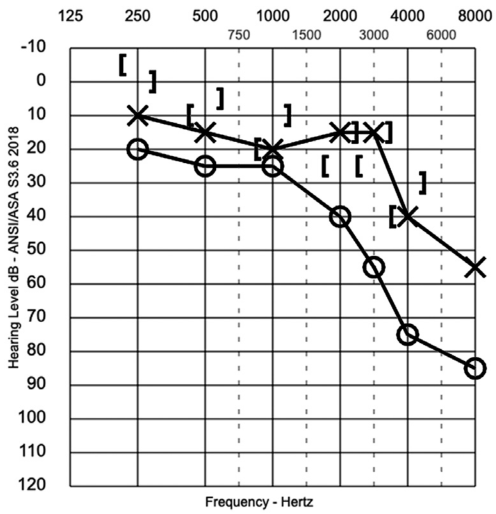

Figure 4 Pure tone air- and bone-conduction audiometric thresholds plotted as a function of frequency from the patient discussed in Case 1 (cholesteatoma). Threshold levels are plotted along the y-axis using conventional audiometric symbols. Results show a mild to moderate sensorineural hearing loss for the left ear and a mild to severe mixed hearing loss for the right ear.

absorbance in the high frequencies. The WAI pattern for the right ear (Fig. 5, bottom panel) is normal for frequencies up to about 750 Hz, and then shows decreased absorbance in the mid to high frequencies; this seems to correlate with the presence of 30 to 35 dB ABGs in the mid and high frequencies, as seen in the audiogram in Fig. 4. The absorbance patterns for this patient seem to suggest that the pathology has the attributes of increased mass (since the mid- to high-frequency absorbance values are significantly decreased). This is opposite of what is typically observed with many stiffness-dominated middle ear pathologies such as early stages of otosclerosis, OME, and negative middle ear pressure, where low frequencies will not pass through the middle ear system efficiently, possibly resulting in a low-frequency CHL. Increase in the mass of middle ear, as in this case, will generally not allow high frequencies to be transmitted efficiently, resulting in reduced absorbance and potentially hearing loss across the high frequencies. As discussed earlier, an understanding of the basic principles of the effects of mass and stiffness on frequency is a good starting point, with variations in effects, including those that influence WAI patterns, for different pathologies.

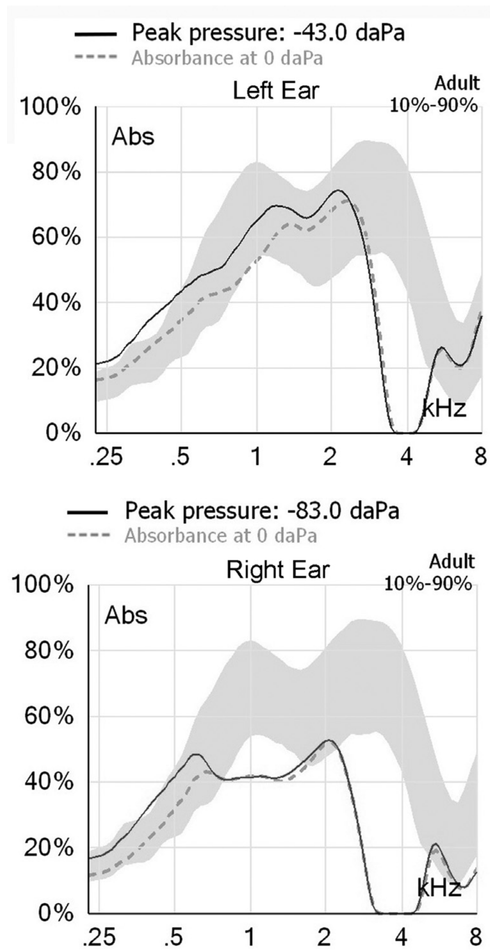

Figure 5 WBT measurements from the individual represented in Case 1 (cholesteatoma) illustrated in the top panel for the left ear, and bottom panel for the right ear. The solid lines represent WBA_{TPP}, the dashed lines represent WBA_0, and the shaded regions in the background represent the normative 10th to 90th percentiles, plotted across frequency. Measurements from the right ear, with a diagnosis of cholesteatoma, show significantly reduced absorbance in mid-high frequencies for the right ear, with no notable differences between WBA_{TPP} and WBA_0.

DIAGNOSIS AND DISCUSSION

The possibility of the presence of increased mass raised concern and radiographic imaging of the temporal bones using CT without contrast was ordered. Radiologic reports for the right ear indicated that fluid or inflammatory debris was present in the hypotympanum and there did not appear to be any ossicular erosions. Additionally, the epitympanum was well aerated and there were some fluid-opacified mastoid air cells at the mastoid tip but otherwise all other temporal bone structures appeared normal. Given the audiometric and tympanometric findings along with the abnormal CT findings showing partial opacification of the meso- and hypotympanum, an exploratory tympanotomy for the right ear was performed. During this procedure, an atypical presentation of middle ear cholesteatoma was found that invaded a significant portion of the central TM and the long process of the malleus. Acquired cholesteatomas can form from a retraction pocket (primary), or from a perforation (secondary).[33] In this case, the cholesteatoma formed somewhat centrally and intruded the meso and hypotympanum. However, because of the thickened and opaque TM, the origin of the cholesteatoma was not visible by otoscopy. The added mass to the central portion of the TM and to the manubrium of the malleus seemed to match well with the high-frequency ABGs and the WBA pattern with poor absorbance above 750 Hz. Having access to WAI testing with the ability to measure WBA across an expanded frequency range was valuable to the diagnostic process. Examining both conventional audiometric and immittance data, along with the WBA patterns, provided a synergistic effect to the evaluation of middle ear conditions for this patient.

Case 2: Ossicular Fixation

BACKGROUND

Sudden sensorineural hearing loss (SSNHL) is a fairly common finding in an ear, nose, and throat (ENT) specialist clinic. Sudden-onset CHL loss that is not explained by trauma, or another disease process, however, is not quite as common. The case that follows is an example where WAI was added to the diagnostic workup and the results helped the ENT reassess the case history that ultimately resulted in the correct diagnosis.

CASE HISTORY

A female patient in her early 30s presented with what she reported as a sudden hearing loss in her right ear. At the time of the visit, the patient was approximately 6 months pregnant with her first child.

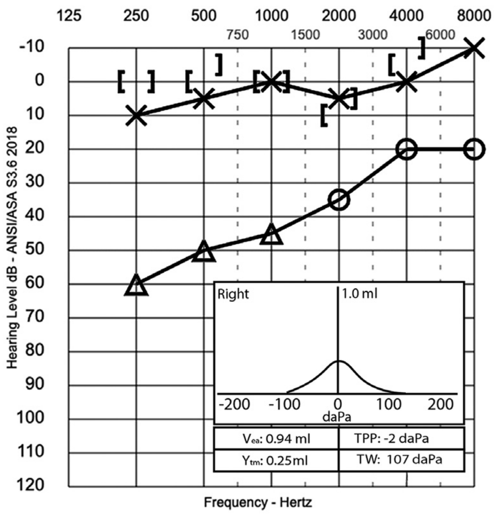

Figure 6 Pure tone air- and bone-conduction audiometric thresholds plotted as a function of frequency from the patient discussed in Case 2 (ossicular fixation). Threshold levels are plotted along the y-axis using conventional audiometric symbols. The audiogram reveals thresholds within normal limits for the left ear, with a moderate, rising CHL for the right ear. On the bottom-right corner of the audiogram, conventional (226 Hz) tympanogram outcomes for the right ear are plotted inside the black-outlined box (left ear tympanogram outcomes not shown). Tympanogram abbreviations are the same as in Fig. 3.

AUDIOLOGIC/OTOLOGIC FINDINGS AND INITIAL RECOMMENDATIONS

The ENT performed a complete otologic examination which was unremarkable. Comprehensive audiometry was performed and showed normal findings for the left ear, and a moderate, rising, CHL for the right ear (Fig. 6). Standard low-frequency (226 Hz) tympanometry (see inset on Fig. 6) revealed a normally shaped type As tympanogram with low admittance (0.25 mL). While the type As tympanogram suggested a pathology that increases stiffness, it did not point to a specific pathology. Moreover, tympanometry findings did not completely explain the severity of the conductive loss, nor did it help explain the sudden nature of the loss onset. Radiographic imaging of the temporal bones was ordered in the form CT without contrast. The radiology report was normal and did not indicate the presence of fluid, ossicular discontinuity, or any sort of space-occupying lesion. Due to the patient's pregnancy, it was decided that watchful waiting was the most appropriate strategy until after she delivered her baby. She returned approximately 4 months after having her baby and audiometry and tympanometry were repeated, with no significant changes noted in either ear.

At the time of the first visit, the patient presented with a unilateral conductive component, abnormal low-frequency tympanometry, and subtle evidence of Carhart's notch (see Fig. 6); each piece of evidence provided some support for a diagnosis of otosclerosis. However, the sudden onset did not fit well in the diagnostic picture. Otosclerosis typically evolves over time and moves through a progression of otospongiosis (softening and destruction of the bone) to otosclerosis (dense, sclerotic bone developing on the bone).[34] This process takes time, and it is unlikely that a patient would have had this develop "overnight."

WAI TESTING AND OUTCOMES

Because WAI can provide data regarding middle ear status over a wide range of frequencies, a variety of WBA patterns can emerge. A WBT test was conducted for this patient, and WBA_{TPP} was extracted at TPP (−2 daPa) and presented in Fig. 7 (darker shaded line); the lighter shaded line is an "otosclerosis example" tracing provided for comparison in the

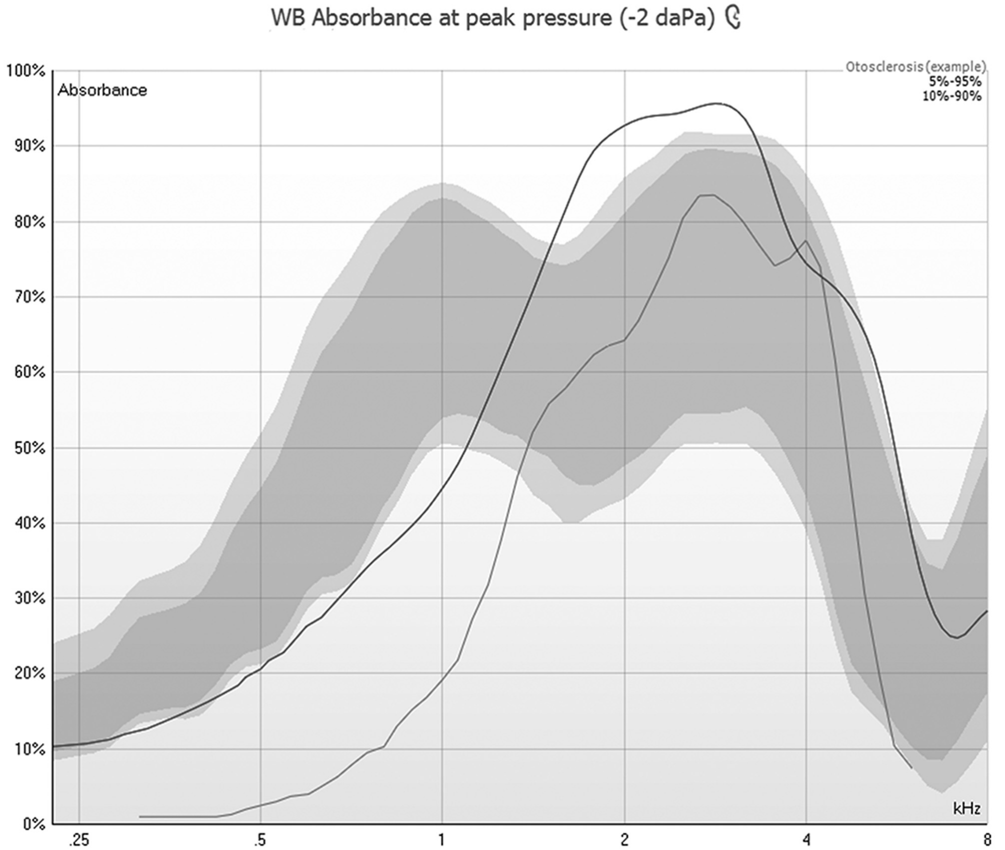

Figure 7 WBT absorbance findings from the individual in Case 2 (ossicular fixation). Solid lines represent absorbance percent values plotted on the y-axis, and frequency values in kHz are represented on the x-axis. WBA_{TPP} was extracted (TPP = −2 daPa) and presented for this patient (darker shaded line). The lighter shaded line is reference "otosclerosis example" tracing provided by the Interacoustics Titan system. Lighter and darker shaded regions in the background represent the normative 5th to 95th percentiles and 10th to 90th percentiles, respectively. The response from the patient showed a pattern of significantly reduced absorbance for approximately 250 to 1,200 Hz, with normal-appearing absorbance from approximately 1,200 to 5,000 Hz, then absorbance becoming slightly reduced again at approximately 6,000 Hz.

Interacoustics Titan system. The WAI response from the patient showed a pattern of significantly reduced absorbance for approximately 250 to 1,200 Hz, with normal-appearing absorbance from approximately 1,200 to 5,000 Hz, then absorbance becoming slightly reduced again at approximately 6,000 Hz, further confirming a stiffening of the middle ear system (i.e., stiffness reduces the low frequencies and shifts resonance to a higher frequency). While the deviation of absorbance below normal limits was not as large relative to the example of WBA for otosclerosis, the pattern of WBA for the patient showed some similar characteristics (re: lighter shaded line in Fig. 7). Findings from this individual are also similar to those found in prior studies investigating the effects of otosclerosis on WAI.[35,36]

DIAGNOSIS AND DISCUSSION

This additional piece of evidence triggered a new, more precise discussion regarding the onset of the hearing loss. The patient reported that the onset was "relatively sudden," perhaps not overnight, but over a short period of time. It is possible that small progressive changes were not perceived by the patient until such time that the difference between the ears was significant. The insidious progression may have gone unnoticed for months, and then only when there was a situation that allowed her to compare hearing between the ears, did she notice a difference. An exploratory tympanotomy with possible stapedectomy was scheduled and resulted in a diagnosis of oval window fixation due to otosclerosis. Adding WAI tympanometry provided another piece of evidence that contributed to the earlier working diagnosis and to the complete diagnostic assessment.

Case 3: Tympanic Membrane Perforation

BACKGROUND

Perforations of the TM are often seen in an ENT setting. While tympanometry results can typically identify a perforation, in some cases it may be difficult to pressurize a large cavity with a TM perforation with some immittance systems (as per anecdotal reports). In addition, sometimes it is difficult to obtain accurate and reliable leak-proof tracings, and low-frequency noise artifacts are common. While TM perforation is usually a simple case for diagnosis, it is important to become familiar with WAI findings for this common disorder and to distinguish them from other disorders.

CASE HISTORY

The case presented here includes data from a 43-year-old female with right TM perforation following the flu and reports of a sore ear.

AUDIOLOGIC/OTOLOGIC FINDINGS AND INITIAL RECOMMENDATIONS

Otoscopic examination for the right ear revealed an approximately 70% perforation, centrally located, with intact ossicular chain and mobility during perioperative examination. Audiological assessment, including WBT, was performed immediately prior to surgery (tympanoplasty). Single-frequency, 226-Hz tympanometry showed a flat tympanogram with large ear canal volume (5.07 cm^3). Air- and bone-conduction audiometry revealed a moderately severe CHL for the right ear (Fig. 8). No active ear infection was noted by the ENT.

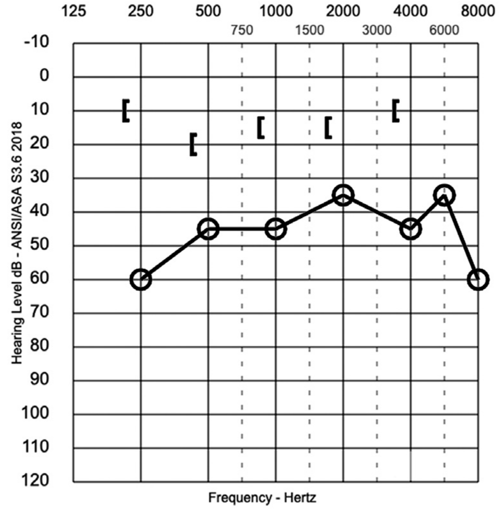

Figure 8 Pure tone air- and bone-conduction audiometric thresholds plotted as a function of frequency from the patient discussed in Case 3 (tympanic membrane perforation). Threshold levels are plotted along the y-axis using conventional audiometric symbols. Air and bone conduction audiometry revealed a moderately severe CHL for the right ear.

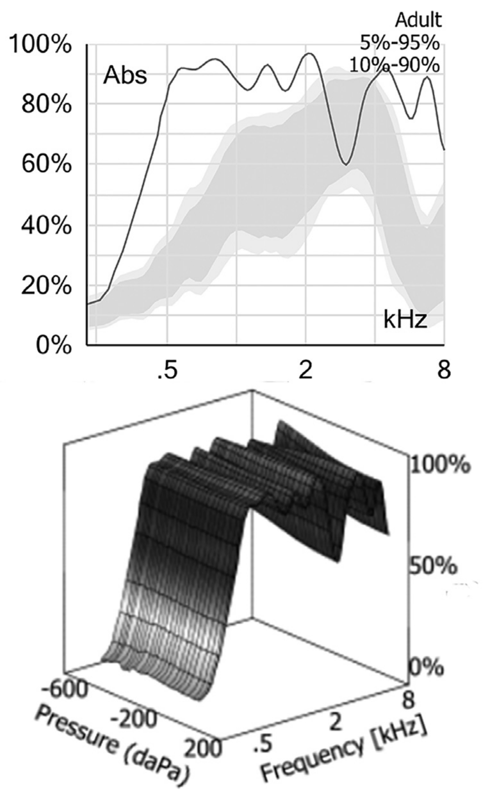

Figure 9 WBT measurements obtained from the right ear of the individual represented in Case 3 (tympanic membrane perforation). The top panel illustrates WBA_0 in the solid line, and the shaded regions (darker and lighter) in the background represent the normative 10th to 90th and 5th to 95th and percentiles, respectively. Absorbance values were significantly increased above normal limits for frequencies higher lower than 2,000 Hz. The lower panel illustrates a three-dimensional representation of WBT findings, with absorbance plotted on the z-axis as a function of frequency (x-axis) and ear-canal pressure that was swept from −600 to +200 daPa (y-axis).

WAI TESTING AND OUTCOMES

Ambient WAI and WBT show measurement patterns that are distinct from normal, healthy ears. Ambient absorbance (Fig. 9, top panel) is far above the normal range (re: the shaded gray area) from 500 to 2,000 Hz for the individual in this case. According to Voss et al,[37] the elevated absorbance is not interpreted as additional acoustic energy being transmitted to the inner ear, but energy that is dissipated/shunted within the middle ear cavity. Results from the WBT test (Fig. 9, bottom panel) show a similar pattern to that seen in the top panel, with an additional pressure (daPa) dimension perspective, with a sharply rising absorbance pattern, then undulating absorbance from 500 to 8,000 Hz.

DIAGNOSIS AND DISCUSSION

Energy dissipation in the presence of a TM perforation occurs because sound vibrations are not properly coupled to the ossicular chain and transferred into the oval window, and much of the sound vibrations interact with the enlarged air volume and are absorbed within the tympanic cavity. Therefore, the observed WBA patterns reflect the acoustic properties of the large air-filled cavity rather than the intact middle ear system. Researchers have also demonstrated that the size of the perforation affects WBA patterns.[37] For small perforation sizes, absorbance values are above the normal range at frequencies lower than 1,000 Hz, and as the size of the perforation increases, absorbance patterns begin to decrease toward the normal range.[31] WBA measurements from this case (Fig. 9) had absorbance values above the normal range for all frequencies lower than 2,000 Hz. Similar patterns have been observed in cases with PE tubes, where smaller perforations and/or openings created by PE tubes produced a secondary absorbance peak around 1,000 Hz.[11,31] Sanford and Brockett[5] reported WBA measurements from a group of 10 children (mean age = 27 months) with PE tubes, where WBA had a normal absorbance peak between 2,000 and 4,000 Hz, and an additional abnormal peak at frequencies lower than 1,000 Hz. These unique WBA patterns are helpful for confirming perforations and for detecting smaller perforations which are harder to visualize, unlike larger perforations which are easier to identify.

Case 4: Cerumen Impaction

BACKGROUND

Otoscopic inspection of the ear canal and the TM can be obstructed by a foreign object or cerumen accumulation. For cases where visualization of the TM is not possible, but a complete occlusion of the ear canal has not occurred, assessment with immittance technology can usually be accomplished.

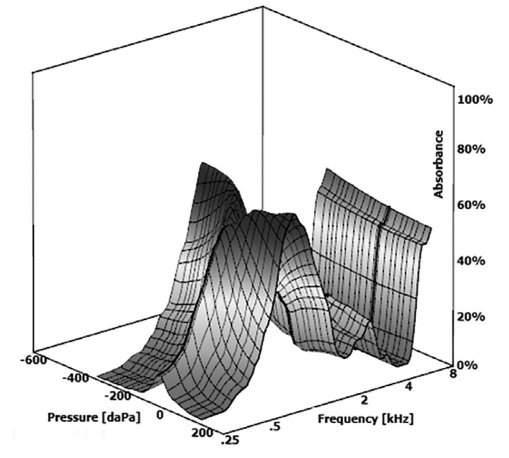

Figure 10 WBT absorbance measurements from the right ear of the individual represented in Case 4 (cerumen impaction). Findings are illustrated on three-dimensional plot, with absorbance plotted on the z-axis as a function of frequency (x-axis) and ear-canal pressure that was swept from −600 to +200 daPa (y-axis).

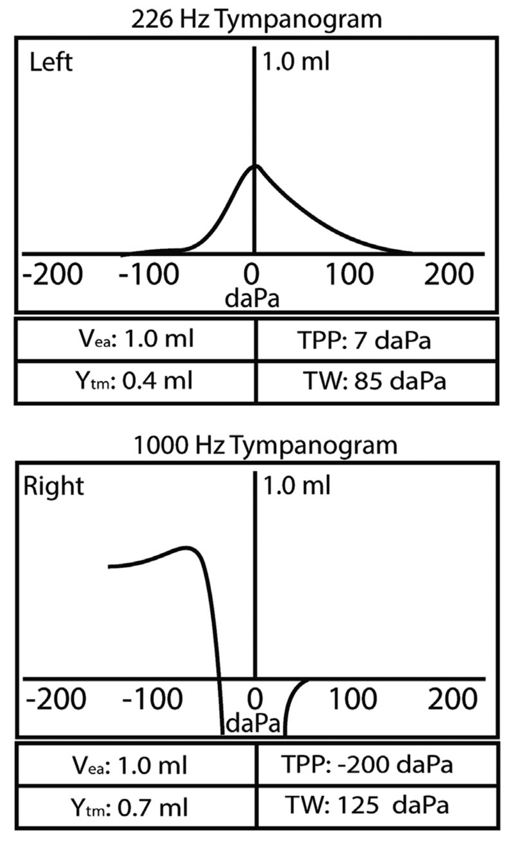

Figure 11 Single-frequency admittance tympanograms that were extracted from WBT measurements from the left ear of the individual represented in Case 4 (cerumen impaction). The top panel illustrates the 226-Hz tympanogram, and the bottom panel illustrates the 1,000-Hz tympanogram.

CASE HISTORY

This case presents data from a normal-hearing 15 year-old male who had volunteered to participate in a research study. The patient denied any aural history and presented with significant cerumen accumulation for the left ear. While cerumen removal is common practice in an ENT setting, and is often accomplished in an audiology office, the research study parameters didn't allow for cerumen removal.

WAI TESTING AND OUTCOMES

A WBT test was performed for this patient using Titan immittance system (Interacoustics A/S). Fig. 10 presents the complete three-dimensional [WBT] wideband tympanogram. This system is also equipped with a multifrequency tympanometry feature that automatically extracts admittance tympanograms from the WBT recording, e.g., 226- and 1,000-Hz admittance tympanograms (Fig. 11). An assessment of the 226-Hz tympanogram (Fig. 11, top panel) revealed a normally shaped, type A tympanogram. Based on this result, one may assume a normal middle ear function. However, examination of the 1,000-Hz tympanogram (Fig. 11, lower panel) reveals a negative going tracing or "notched" tympanogram (with the notch extending below the plotted area). Based on the Vanhuyse model,[38] which informs the interpretation of multifrequency tympanometry, this is indicative of abnormal shifting of the resonant frequency to lower than 1,000 Hz, but higher than 226 Hz. This would suggest an abnormal response due to some type of mass loading effect.[39] In addition to multifrequency tympanometry data, WBA data were also extracted from the WBT test. In Fig. 12, WBA_0 and WBA_{TPP} (at +26 daPa) are shown by the lighter shaded line and darker shaded line, respectively. For both WBA_0 and WBA_{TPP}, absorbance was significantly reduced below normal limits for frequencies 1,000 Hz to 6,000 Hz, and the absorbance peak was shifted to a lower frequency (≈700 Hz), and was predominantly within the normal range. This finding is also suggestive of abnormally mass-dominated system, where high

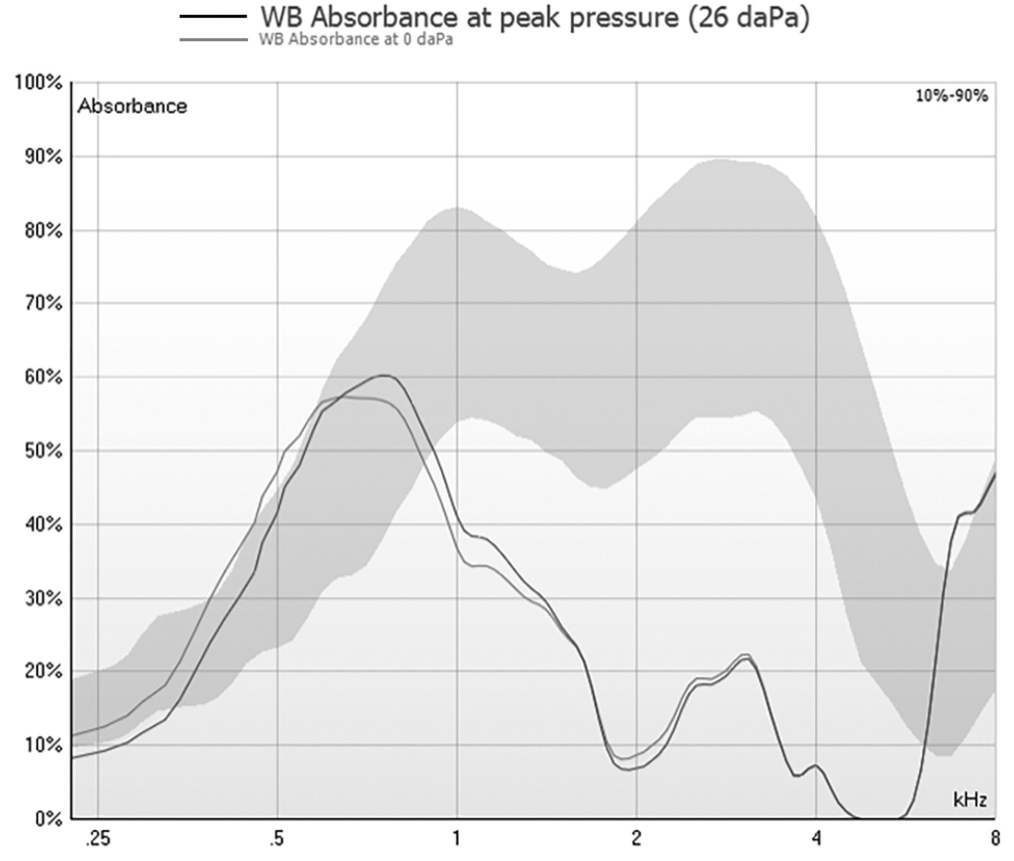

Figure 12 WBT absorbance measurements obtained from the individual in Case 4 (cerumen impaction). The dark-grey solid line represents WBA_{TPP} (TPP = +26 daPa),, and the light-grey solid line represents WBA_0. The shaded region in the background represents the normative 10th to 90th percentile of normative data. Absorbance values were significantly reduced below normal limits from 1,000 to 6,000 Hz, and at or slightly above normal limits for lower frequencies. No notable differences were observed between WBA_{TPP} and WBA_0.

frequencies are impeded and lower frequencies are enhanced.

DIAGNOSIS AND DISCUSSION

This case demonstrates the ability to examine WBA data across a range of static pressure values, in addition to the ability to obtain multifrequency admittance tympanograms with a single WBT test. This case also demonstrated the limit of relying on the 226-Hz admittance tympanogram for clinical assessment. The WBA pattern obtained from this individual was likely associated with partial ear-canal occlusion due to cerumen impaction, and/or debris present on the TM, adding a mass-loading effect. Unfortunately, follow-up data were not obtained after cerumen impaction was removed to confirm this interpretation. In summary, the additional information obtained from the 1,000-Hz admittance tympanogram, in addition to WBA data, was helpful to provide a clearer more comprehensive assessment of middle ear. The inferences made using multifrequency tympanometry paradigms (e.g., Vanhuyse model)[38] were consistent with assessment of WBA data. However, analysis of WBA pattern provided a more complete assessment beyond the approximation of resonant frequency using the Vanhuyse model.

Case 5: Excess Middle Ear Pressure and Otitis Media with Effusion

BACKGROUND

Excess middle ear pressure (EMEP) (e.g., negative middle ear pressure) is a commonly encountered condition in audiology/ENT practice, and is typically associated with ETD. It is possible for EMEP to present alone, or in conjunction with another middle ear condition. An increase in the stiffness/tension of the TM, as a result of the EMEP, is expected to cause a decrease for low frequency sounds. A number of reports demonstrated that WBAs were most sensitive to EMEP at frequencies near 1,000 Hz, lower than the frequency of peak absorbance (3,000–4,000 Hz).[40,41] Unlike in traditional tympanometry, WAI testing under ambient conditions does not directly provide for a quantitative estimate of EMEP (e.g., as estimated by TPP). Although the effect of stiffness can often be observed by analyzing WBA patterns in ambient conditions, using WBT to compare between WBA_0 and WBA_{TPP} allows for deductions to be made on whether abnormal stiffness is caused by EMEP alone or if concurrent pathologies also contribute to WBA outcomes. The following case demonstrates the utility of WBT assessment for differential diagnosis of concurrent middle ear conditions.

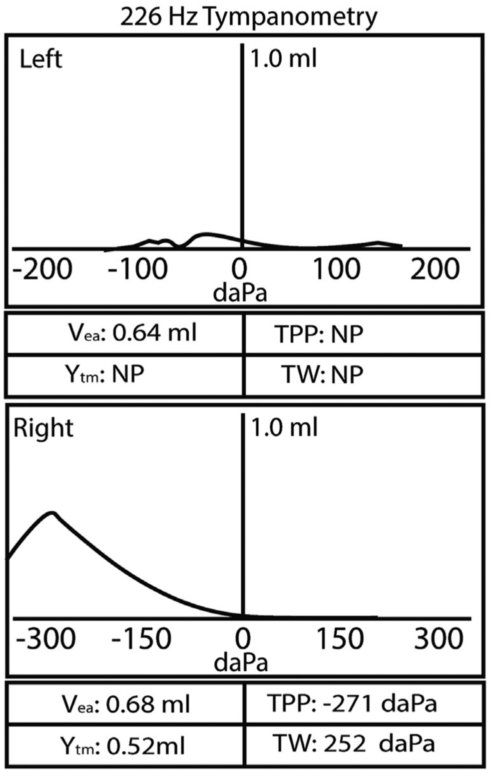

Figure 13 Conventional 226-Hz tympanogram findings obtained from the individual in Case 5 (excess middle ear pressure and otitis media with effusion). Tympanogram abbreviations are the same as in Fig. 3.

CASE HISTORY

This case includes data from a 3-year-old child with OME and EMEP in association with ETD. The patient was referred to the audiology clinic from an ENT clinic. Otologic history was significant for recurrent ear and upper respiratory tract infections and tonsillitis for at least 3 months. He was scheduled for PE tube and tonsillectomy procedures as his symptoms had not improved. He was referred to the audiology clinic for a preoperative hearing assessment, with the assessment being completed an hour before the surgery.

AUDIOLOGIC/OTOLOGIC FINDINGS AND INITIAL RECOMMENDATIONS

Single-frequency, 226-Hz tympanometry showed a flat, type B tympanogram with normal ear canal volume for the left ear and a type C tympanogram with negative middle ear pressure (TPP = −271 daPa) and normal static admittance and ear canal volume for the right ear (Fig. 13). Otoscopy revealed bilaterally "dull"-appearing TMs. Visual reinforcement audiometry was performed in sound field using insert earphones. Fig. 14 shows pure-tone air conduction thresholds, bilaterally, along with unmasked bone conduction thresholds with a right mastoid placement; air conduction thresholds were slightly better for the right ear. Although not a complete audiometric profile, overall results are consistent with at least a mild to moderate unilateral CHL.

WAI TESTING AND OUTCOMES

For this patient, WBT recordings that were obtained in both ears, and WBA_0 and WBA_{TPP}, were extracted for analysis. Fig. 15 illustrates WBA_0 (dashed lines) and WBA_{TPP} (solid lines) on the same plots, in the top panel for the left ear, and the bottom panel for the right ear. For the left ear, WBA_0 revealed a narrow absorbance peak at 4,000 Hz with significantly reduced values at frequencies lower than 3,000 Hz. These patterns are suggestive of

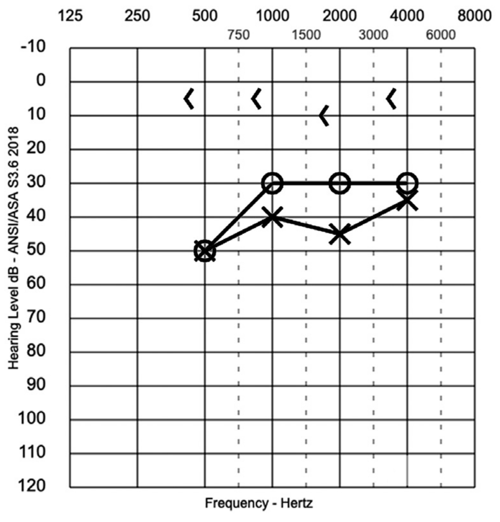

Figure 14 Pure tone air- and bone-conduction audiometric thresholds plotted as a function of frequency from the patient discussed in Case 5 (excess middle ear pressure and otitis media with effusion). Threshold levels are plotted along the y-axis using conventional audiometric symbols. Although not a complete audiometric profile, overall results are consistent with at least a mild to moderate unilateral CHL.

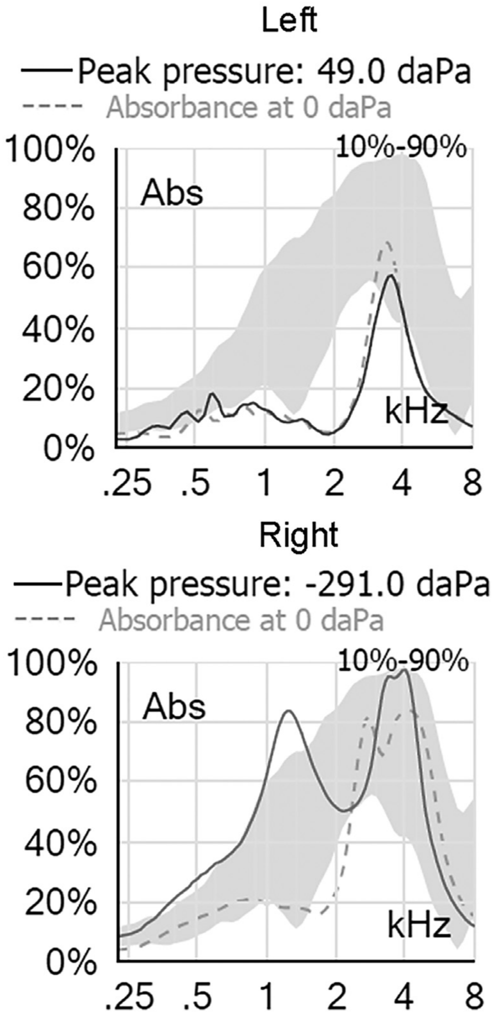

Figure 15 WBT absorbance findings from the individual in Case 5 (excess middle ear pressure and otitis media with effusion) illustrated in the top panel for the left ear, and the bottom panel for the right ear. The solid lines represent WBA_{TPP}, the dashed lines represent WBA_0, and the shaded regions in the background represent the normative 10th to 90th percentiles, plotted across frequency. Measurements from the left ear, with a diagnosis of OM and thick fluid, show reduced low-mid frequency absorbance, and no differences between WBA_{TPP} and WBA_0. Measurements from the right ear, with a diagnosis of negative middle ear pressure and "thin fluid," show a similar pattern for WBA_0, but a significantly improved WBA_0 in the low frequencies.

abnormal increases in middle stiffness. Moreover, there are no notable differences between WBA_0 and WBA_{TPP} (at +49 daPa). This lack of difference between the ambient condition and pressure compensated (TPP) measurements suggests that a dysfunction which introduces additional stiffness is unrelated to EMEP. For the right ear, the patterns of WBA_0 were similar to those observed for the left ear, though with a less "sharp" absorbance peak. However, when measured at TPP (−291 daPa), WBA_{TPP} showed marked improvements compared to WBA_0, with absorbance values falling within the normative range for most frequencies. These findings suggest that abnormal stiffness in the right ear is predominantly related to EMEP.

DIAGNOSIS AND DISCUSSION

The child underwent an adenotonsillectomy and bilateral PE tube insertion. Surgical findings included grade II tonsils, moderate adenoids, with "thick" and "thin" fluid in left and right ears, respectively. Although classification of middle ear fluid by the ENT was subjective, it revealed an interesting finding. The ears with both thick and thin fluid showed similar WBA_0 findings, with the thin fluid ear (right ear) showing slightly higher absorbance between 250 and 2,000 Hz and a less narrow peak in the range of 2,000 to 4,000 Hz. However, when negative middle ear pressure was compensated in the right ear, a significant improvement was observed bringing the overall WBA_{TPP} to within-normal limits. This is an indication that EMEP was the primary diagnosis, and that a "thin" fluid had minor or no effects on middle ear function. By contrast, the lack of improvement in WBA_{TPP} compared to WBA_0 for the left ear suggests that "thick" fluid was the primary diagnosis. Findings from this case illustrate the advantage of using WBT techniques over WAI in ambient conditions. Specifically, the ability to compensate for the effect of EMEP and unveil other underlying conditions would not be distinguishable using ambient measurements only. Being able to determine the extent to which EMEP is contributing to a given middle ear dysfunction would certainly help with differential diagnosis.[27,30,39,41]

CONCLUSIONS AND FUTURE DIRECTIONS

This article demonstrated the implementation of WAI testing and interpretation using qualitative assessment approaches. In addition to qualitative assessment approaches, ongoing research efforts are also aimed at identifying objective analysis and interpretation methods, including the utilization of machine learning.[42,43] Distilling the vast array of WAI data down to a small number of predictors or variables, with strong associations to specific pathologies, would help improve the utility of WAI and WBT measurements. Concurrent with these efforts, researchers are working to further refine measurement quality, and address sources of variability. Machine learning and automation may prove instrumental for widespread clinical use of WAI testing in the future. Nevertheless, the ability to make qualitative analysis of WAI outcomes by trained clinicians is indispensable especially for complex or less common cases in audiology and otolaryngology settings. The authors have found that by incorporating WAI into the typical immittance test battery, one's understanding of relationships between traditional diagnostics tests and WAI is enhanced. Granted, the additional WAI data may not provide diagnosis-altering information for each patient, but for times when conflicting or limited information is at hand, WAI can be a very useful tool to aid in differential diagnosis.

The case studies presented in this article represent just a small cross-section of the variety of middle ear disorders encountered in clinical practice. Readers are encouraged to consult the variety of resources currently available from both manufacturers of WAI technology and in the literature. For example, Mimosa Acoustics (Illinois) provides guidance for clinicians with regard to interpreting data from a variety of populations (see: https://www.mimosaacoustics.com/clinicians.html). The Interacoustics (Assens, Denmark) provides resources regarding how to conduct WBT and case studies to aid in interpretation (https://www.interacoustics.com/news/wideband-tympanometry#wbt-case-studies). Also, both manufacturers present sample data from common middle ear disorders that can be viewed directly on their respective system's user interface. It is hoped that readers will use the information and examples in this paper, others that are available in the literature, and those from manufacturers as a springboard to incorporate and more fully embrace WAI technology in clinical practice.

CONFLICT OF INTEREST
None declared.

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REFERENCES

1. Approved by the ASHA Legislative Council. Preferred practice patterns for the profession of audiology. American Speech-Language-Hearing Association 2006;2006:PP2006–PP00274
2. Zazove P, Atcherson SR, Moreland C, McKee MM. Hearing loss: diagnosis and evaluation. FP Essent 2015;434:11–17
3. Kim SY, Han JJ, Oh SH, et al. Differentiating among conductive hearing loss conditions with wideband tympanometry. Auris Nasus Larynx 2019;46(01):43–49

4. Nakajima HH, Pisano DV, Roosli C, et 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
5. Sanford CA, Brockett JE. Characteristics of wideband acoustic immittance in patients with middle-ear dysfunction. J Am Acad Audiol 2014;25(05): 425–440
6. Sim JH, Huber AM, Häfliger M, de Trey LA, Eiber A, Röösli C. Can an incomplete ossicular discontinuity be predicted by audiometric and clinical findings? Otol Neurotol 2013;34(04): 699–704
7. Ward BK, Carey JP, Minor LB. Superior canal dehiscence syndrome: lessons from the first 20 years. Front Neurol 2017;8:177
8. Zhou G, Gopen Q, Poe DS. Clinical and diagnostic characterization of canal dehiscence syndrome: a great otologic mimicker. Otol Neurotol 2007;28 (07):920–926
9. Lilly DJ, Margolis RH. Wideband acoustic immittance measurements of the middle ear: introduction and some historical antecedents. Ear Hear 2013;34 (Suppl 1):4S–8S
10. 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
11. Nakajima HH, Rosowski JJ, Shahnaz N, Voss SE. Assessment of ear disorders using power reflectance. Ear Hear 2013;34 Suppl 1(701):48S–53S
12. 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
13. 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
14. Liu YW, Sanford CA, Ellison JC, Fitzpatrick DF, Gorga MP, Keefe DH. Wideband absorbance tympanometry using pressure sweeps: system development and results on adults with normal hearing. J Acoust Soc Am 2008;124(06):3708–3719
15. Rosowski JJ, Stenfelt S, Lilly D. An overview of wideband immittance measurements techniques and terminology: you say absorbance, I say reflectance. Ear Hear 2013;34 Suppl 1(01):9S–16S
16. Jerger JF, Hayes D. The cross-check principle in pediatric audiometry. Arch Otolaryngol 1976;102 (10):614–620
17. Merchant SN, Rosowski JJ. Conductive hearing loss caused by third-window lesions of the inner ear. Otol Neurotol 2008;29(03):282–289
18. Yasan H. Predictive role of Carhart's notch in preoperative assessment for middle-ear surgery. J Laryngol Otol 2007;121(03):219–221
19. Harris PK, Hutchinson KM, Moravec J. The use of tympanometry and pneumatic otoscopy for predicting middle ear disease. Am J Audiol 2005;14(01): 3–13
20. Sanford CA, Schooling T, Frymark T. Determining the presence or absence of middle ear disorders: an evidence-based systematic review on the diagnostic accuracy of selected assessment instruments. Am J Audiol 2012;21(02):251–268
21. Browning GG, Swan IRC, Gatehouse S. The doubtful value of tympanometry in the diagnosis of otosclerosis. J Laryngol Otol 1985;99(06):545–547
22. Curtin HD. Imaging of conductive hearing loss with a normal tympanic membrane. AJR Am J Roentgenol 2016;206(01):49–56
23. Wegner I, van Waes AMA, Bittermann AJ, et al. A systematic review of the diagnostic value of CT imaging in diagnosing otosclerosis. Otol Neurotol 2016;37(01):9–15
24. 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
25. Sanford CA, Hunter LL, Feeney MP, Nakajima HH. Wideband acoustic immittance: tympanometric measures. Ear Hear 2013;34(Suppl 1): 65S–71S
26. Feeney MP. Wideband acoustic immittance measurements of middle ear function. J Am Acad Audiol 2014;25(05):424–424
27. Margolis RH, Saly GL, Keefe DH. Wideband reflectance tympanometry in normal adults. J Acoust Soc Am 1999;106(01):265–280
28. Sanford CA, Feeney MP. Effects of maturation on tympanometric wideband acoustic transfer functions in human infants. J Acoust Soc Am 2008;124 (04):2106–2122
29. Withnell RH, Parent P, Jeng PS, Allen JB. Using wideband reflectance to measure the impedance of the middle ear. Hear J 2009;62(10):36
30. 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
31. 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
32. Peng KA, House JW. Schwartze sign. Ear Nose Throat J 2018;97(03):54–54
33. Rutkowska J, Özgirgin N, Olszewska E. Cholesteatoma definition and classification: a literature review. J Int Adv Otol 2017;13(02):266–271

34. Güneri EA, Ada E, Ceryan K, Güneri A. High-resolution computed tomographic evaluation of the cochlear capsule in otosclerosis: relationship between densitometry and sensorineural hearing loss. Ann Otol Rhinol Laryngol 1996;105(08):659–664
35. Kelava I, Ries M, Valent A, et al. The usefulness of wideband absorbance in the diagnosis of otosclerosis. Int J Audiol 2020;59(11):859–865
36. Danesh AA, Shahnaz N, Hall JW III. The audiology of otosclerosis. Otolaryngol Clin North Am 2018;51(02):327–342
37. Voss SE, Rosowski JJ, Merchant SN, Peake WT. How do tympanic-membrane perforations affect human middle-ear sound transmission? Acta Otolaryngol 2001;121(02):169–173
38. Vanhuyse VJ, Creten WL, Van Camp KJ. On the W-notching of tympanograms. Scand Audiol 1975;4(01):45–50
39. Hunter LL, Margolis RH. Effects of tympanic membrane abnormalities on auditory function. J Am Acad Audiol 1997;8(06):431–446
40. Shaver MD, Sun XM. Wideband energy reflectance measurements: effects of negative middle ear pressure and application of a pressure compensation procedure. J Acoust Soc Am 2013;134(01):332–341
41. Aithal V, Aithal S, Kei J, Anderson S, Wright D. Predictive accuracy of wideband absorbance at ambient and tympanometric peak pressure conditions in identifying children with surgically confirmed otitis media with effusion. J Am Acad Audiol 2020;31(07):471–484
42. Grais EM, Wang X, Wang J, et al. Analysing wideband absorbance immittance in normal and ears with otitis media with effusion using machine learning. Sci Rep 2021;11(01):10643
43. Masud SF Diagnosis of Mechanical Ear Pathologies Using Structure-Based Modeling and Machine Learning Techniques. Dissertation. Harvard; 2020. Accessed February 5, 2022 at: https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37365115