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Wideband Acoustic Immittance in Children

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ABSTRACT

As wideband absorbance (WBA) gains popularity, it is essential to understand the impact of different middle ear pathologies on the absorbance patterns as a function of frequency in children with various middle ear pathologies. More recently, the use of wideband tympanometry has enabled clinicians to conduct WBA at ambient pressure (WBA_{amb}) as well as the pressurized mode (WBA_{TPP}). This article reviews evidence for the ability of WBA measurements to accurately characterize the normal middle ear function across a wide range of frequencies and to aid in differential diagnosis of common middle ear disorders in children. Absorbance results in cases of otitis media with effusion, negative middle ear pressure, Eustachian tube malfunction, middle ear tumors, and pressure equalization tubes will be compared to age-appropriate normative data. Where applicable, WBA_{amb} as well as WBA_{TPP} will be reviewed in these conditions. The main objectives of this article are to identify, assess, and interpret WBA_{amb} and WBA_{TPP} outcomes from various middle ear conditions in children between the ages of 3 and 12 years.

KEYWORDS: wideband acoustic immittance, wideband absorbance tympanometry, middle ear dysfunction, children, pediatric

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While there has been tremendous advancement in the assessment of the middle ear in newborns, children, and adults, little has been changed over the years on how we assess the middle ear function in children. For a long time, the diagnosis of the middle ear pathologies in children has been relied on the otoscopic examination of the middle ear by the physicians and pure tone audiometry, and conventional 226-Hz immittance assessment. These assessment techniques are not sensitive to subtle changes in the middle ear mechanics as well as the severity of the conductive hearing loss in children. Wideband acoustic immittance (WAI) can expand our ability to accurately characterize the middle ear function in normal and diseased conditions in children across a much wider frequency range.

WAI APPLICATIONS IN MIDDLE EAR DISORDERS IN CHILDREN

WAI refers to a host of measures that assess the mechano-acoustical properties of the middle ear over a wide range of frequencies (e.g., 250–8,000 Hz) compared to conventional tympanometry, which assesses response to one or limited number of tones (e.g., 226 Hz, 1000 Hz).[1] WAI testing is a relatively new technology that emerged nearly 30 years ago, and has increasingly gained the attention of clinical researchers in the past two decades. Power absorbance is a WAI measure that represents the proportions of acoustic power absorbed into the middle ear, at the tympanic membrane, relative to the total power of an ear canal stimulus, which is typically a broad band click or chirp stimulus. Its values range from 0 to 1 or 0 to 100%, where 1 (100%) indicates all sound energy has been absorbed and 0 (0%) indicates no energy has been absorbed. Power absorbance measurements are plotted as a function of frequency, and are often referred to as wideband absorbance (WBA). Recent studies demonstrate that WBA can detect different middle-ear pathologies in children with greater accuracy than conventional tympanometry and is more sensitive to subtle changes in the mechano-acoustical properties of the middle ear as well as a better predictor of conductive hearing loss.[2–9] Unlike conventional tympanometry, WBA is sensitive to fluid volume in the middle-ear system[5,10] and fluid viscosity.[11] Moreover, Hunter and Margolis[12] reported an abnormal WBA pattern in a confirmed case of middle-ear effusion (MEE) despite normal conventional 226-Hz tympanometry. Piskorski et al[13] have also shown that WBA, unlike tympanometry, can predict a conductive hearing loss in children as measured by an air–bone gap (ABG) in conventional audiometry.

Even though the WAI systems have been available commercially for several years, the use of this diagnostic technology has not yet achieved widespread adoption by clinicians as part of the routine test battery for the assessment of middle ear function in children. The article by AlMakdma, Kei et al in this (*Seminars in Hearing*) issue introduced two WBA test modes that are possible with commercially available instruments: (1) WBA that is measured in the ear canal at ambient static pressure, referred to as WBA_{amb}. (2) Another test mode is called wideband tympanometry (WBT), where WBA is measured repeatedly as static pressure is swept in the ear canal. The benefits of using WBT over WBA_{amb} include an added dimension of measurement that can be useful in the differential diagnosis.[3] In this article, we will focus on the use of WBT to measure WBA at one pressure point of interest, the tympanometric peak pressure (TPP), which has unique applications in children. This measure will be referred to as WBA_{TPP}. Please refer to the article by AlMakadma, Kei et al in this issue for a more detailed introduction to the use of WBT testing and the diagnostic utility of WBA_{amb} and WBA_{TPP}. As discussed earlier in previous sections, even slight positive or negative middle-ear pressure (NMEP) can significantly impact the absorbance patterns of the middle-ear[14–18]; therefore, performing WBA at the peak pressure or multiple pressure points may improve its diagnostic value.

To understand the impact of different middle ear disorders on WBA measurements in children, it is imperative to characterize and describe how absorbance values vary as a function of frequency (i.e., WBA patterns) in children with typically functioning middle ear systems. The normative data will also help us establish a baseline distribution for normal absorbance values across a wide range of

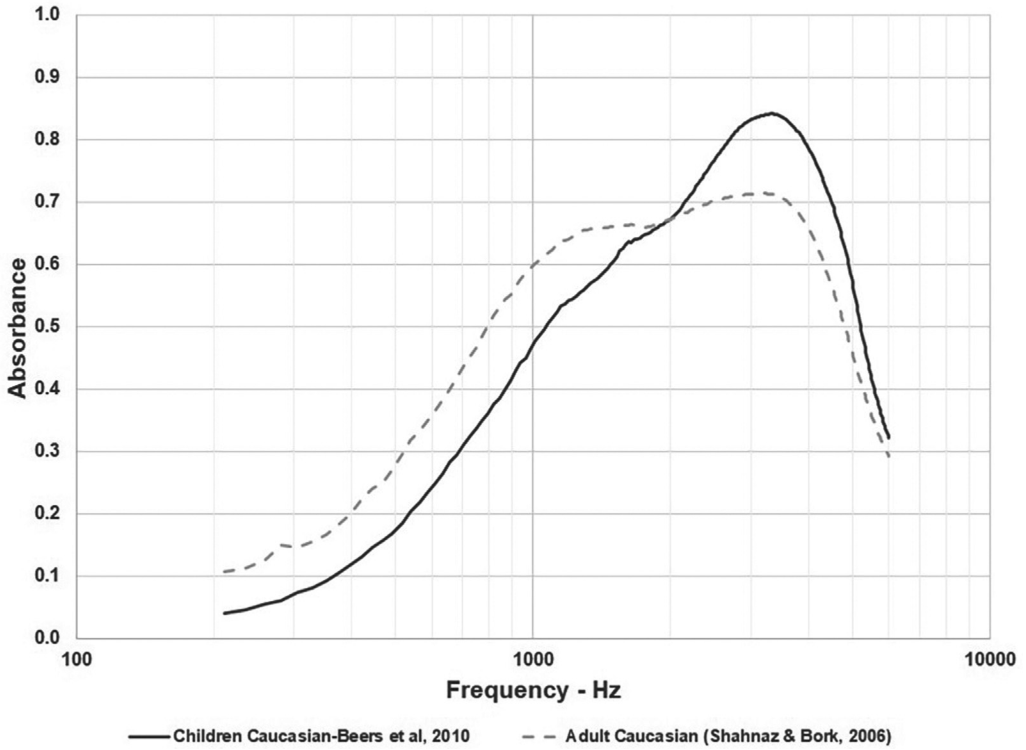

Figure 1 Mean WBA in a group of children with normal hearing and an average age of 6.15 years and a group of adults with normal hearing with an average age of 24.4 years. (Adapted from Beers AN, Shahnaz N, Westerberg BD, Kozak FK. Wideband reflectance in normal Caucasian and Chinese school-aged children and in children with otitis media with effusion. Ear Hear 2010;31(2):221–233. Shahnaz N, Bork K. Wideband reflectance norms for Caucasian and Chinese young adults. Ear Hear 2006;27(6):774–788.)

frequencies and against which the measurement can be compared to different age groups as well as different middle ear conditions. Fig. 1 compares average WBA patterns in a group of children with normal hearing and an average age of 6.15 years[2] to adults with normal hearing with an average age of 24.4 years.[19] This figure illustrates that the adult middle ear is more efficient in absorbing the sounds at mid-high frequencies, while the children's middle ear is more efficient in absorbing the sounds at higher frequencies. Beers et al[2] attributed some of the observed differences to the potential differences in body size indices and the changes in the ear canal dimension due to maturation. In the following sections, we will discuss the WBA patterns in different middle-ear disorders that are most common in children.

In this section, we will describe WBA patterns in common middle ear disorders in children, starting with the most common cause of conductive hearing loss, otitis media (OM), and MEE, followed by NMEP, tympanic membrane retraction pockets (RPs), and common middle ear tumors. As well, WBA findings in pressure equalization tube (PET), a common encounter in pediatric ENT, will be reviewed. Finally, case study presentations will demonstrate the use of WBA testing along with other audiological tests to aid in the diagnosis of various middle ear pathologies in children.

OTITIS MEDIA AND MIDDLE EAR EFFUSION

OM is one of the most common middle ear conditions in children. Broadly defined, OM is an inflammatory condition that refers to a spectrum of middle ear infections, including acute otitis media (AOM or symptomatic OM), chronic otitis media (COM), and otitis media with effusion (OME or asymptomatic).

An infected fluid characterizes AOM behind the eardrum with symptoms of an acute infection.[20] AOM is the most common cause of pediatric medical visits and antibiotic prescriptions worldwide.[21] It has been estimated that the total annual number of new AOM episodes worldwide is around 709 million cases.[20] In contrast to AOM, OME is not associated with acute symptoms and is characterized by MEE behind the eardrum. OME is often associated with fluctuating conductive hearing loss,[22–24] which may have an adverse effect on the development of speech and language, auditory perception, and cognition of young children.[25–30] It has also been shown that children who have recovered from COM have poorer extended high-frequency (8,000–20,000 Hz) hearing than children without significant OM histories.[31] Haggard and Hughes[32] have shown that unilateral conductive hearing loss can disrupt the normal development of binaural processing in the higher auditory processing pathways. The prevalence and incidence of the OME is hard to establish due to the asymptomatic nature of the disease. However, large cohort studies in the past have reported the point prevalence of OME to be around 20% in children.[33–35] The annual cost of OM's medical and surgical treatment in the United States is estimated to be $5 billion.[36] Because of the high prevalence of OM, its financial strain on the health care system due to the cost associated with its diagnosis and management, and the medical and developmental consequences that may manifest if left untreated, researchers have been motivated to develop methods for its early and accurate diagnosis.

Traditionally, OM in children is assessed using otoscopy, conventional 226-Hz tympanometry and acoustic stapedial reflex, and behavioral air- and bone-conduction audiometry to measure associated conductive hearing loss, where the degree of conductive component is determined by the difference between air- and bone-conduction thresholds (i.e., ABGs). As otoscopy relies on the subjective interpretation of the visual inspection of the ear canal and tympanic membrane, its sensitivity and specificity are highly variable and would depend on the physician's experience as well as an unobstructed view of the tympanic membrane.[37] Conventional 226-Hz tympanometry is one of the most common objective tests that are used for the diagnosis of OM. Its sensitivity and specificity in detecting MEE depend on the tympanometric parameter used. For example, Nozza et al[38,39] determined that the tympanometric width as measured in daPa (TW), which is not commonly used by audiologists, has a sensitivity of 81% and specificity of 82% for the detection of the fluid behind the eardrum. Anwar et al[40] used a type B, 226-Hz tympanogram (based on the classification system of Jerger[41]) with normal ear canal volume as a diagnostic criterion for the detection of the MEE and determined the sensitivity and specificity rates to be 85.8 and 72.2%, respectively. Other Jerger classification system such as A_s has also been reported in 10% of OM cases.[41]

In general, while conventional 226-Hz tympanometry has relatively good accuracy in detecting MEE, it is not sensitive to subtle changes in the mechano-acoustical properties of the middle ear. Moreover, 226-Hz tympanometry has a poor correlation to the severity of the conductive hearing loss in OM.[42] Additionally, Al-Salim et al[43] have shown that effusion volume, which was determined surgically, was correlated with outcomes from several audiological tests, including the degree of the conductive hearing loss as determined by ABGs, the presence of the otoacoustic emission, and ABR wave V latency, but noted no correlation with 226-Hz tympanometry. For the detection and determination of MEE volume, and the type of effusion in the middle ears of children, the American Academy of Otolaryngology has recommended the use of pneumatic otoscopy.[44] Unfortunately, the overall diagnostic accuracy (sensitivity) of pneumatic otoscopy ranges between 40 and 70% depending on the expertise of the physician.[37] Moreover, in practice, many physicians use the more readily available regular otoscopy which maybe less accurate in detecting symptomatic types of OM compared to pneumatic otoscopy.[45] A quick test that is sensitive to subtle changes in MEE is needed.

Recent evidence has demonstrated that the use of WAI and WBT testing is superior to traditional tympanometry in detecting subtle changes in relation to OM and MEE volume and type. In general, MEE results in reduced absorbance across a wide range of frequencies and a narrowed absorbance peak around 4,000 Hz.[2,4,5,8,11] Merchant et al[5] obtained WBA_{amb} and WBA_{TPP} and 226-Hz tympanometry measurements in 49 ears of children between 9 months and 11 years of age prior to tympanostomy tube placement procedures, and in 14 ears of children between 10 months and 10 years of age with no recent history of OM. Effusion volume in the surgical group was determined by the operating surgeon right before the tympanostomy tube placement, and confirmed during myringotomy. The volume of effusion in the middle ear was categorized into three levels, full, partial, or no effusion. Findings showed systematic reduction in absorbance measurements in the range of 1,000 to 5,000 Hz as a function of the MEE volume, in addition to a narrowing and reduction of the absorbance peak around 3,000 to 4,000 Hz. This is clearly shown by the WBA_{TPP} plots in Fig. 2 (data obtained from Voss[46]). Using multivariate logistic regression analysis, Merchant et al[5] reported that the WBA accurately determined the presence of the fluid in the middle ear (full or partial) with 100% sensitivity and 75% specificity. In contrast, the 226-Hz conventional tympanometry was not sensitive to the effusion volume in the middle ear. In addition, Merchant et al[5] reported that while there was no difference in WBA_{amb} and WBA_{TPP} in the full ears group, there was a trend for some improvement in the TPP condition in the other groups. This suggests that conducting WBT testing to obtain WBA_{TPP} will remove the effect of any residual static pressure, which is in agreement with findings by others.[46,47]

More recently, Won et al,[9] using optical coherence tomography (OCT), tympanometry, and physician diagnosis using otoscopy, categorized middle condition in 22 children (average age of 7 ± 4 years) into control (no MEE), mucoid (high density), and serous (low density)

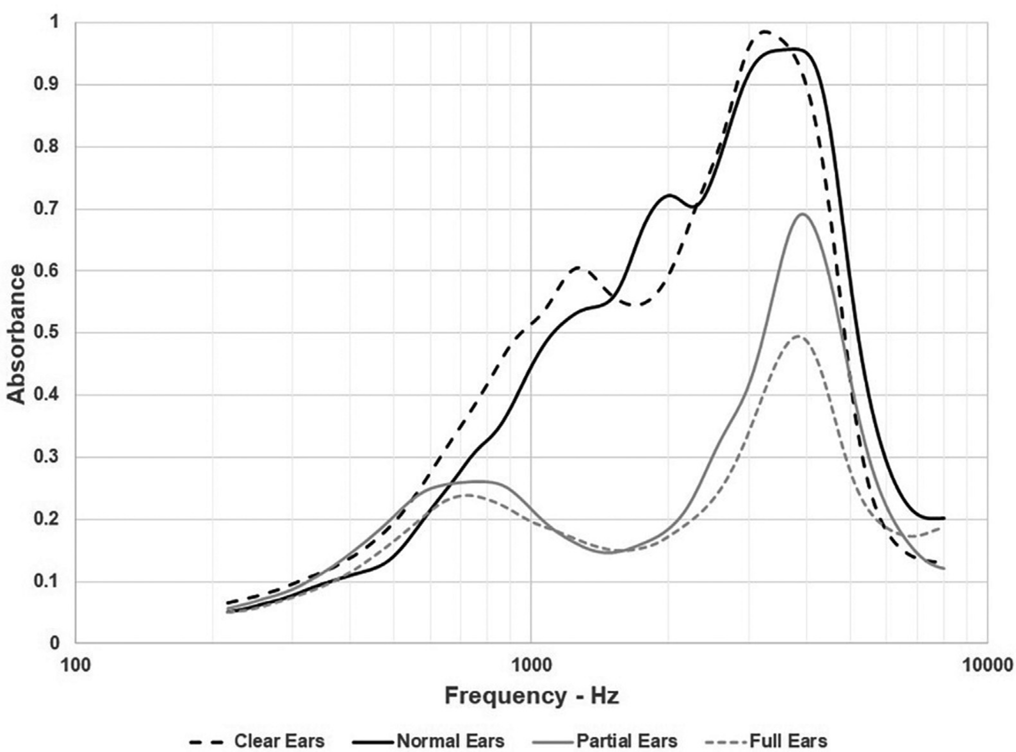

Figure 2 Mean absorbance measurements obtained at tympanometric peak pressure (TPP) for 18 ears with full effusions (dashed grey), 13 ears with partial effusions (solid grey), 18 ears clear of effusion (dashed black), and 14 normal control ears (solid black). (Data from Voss S. Wideband Acoustic Immittance Database 2022. https://r.amherst.edu/apps/nhorton/WAI/ Updated February 7, 2022. Accessed April 28, 2022. Adapted from 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(5):1183–1194. Published April 29, 2021.)

groups with different fluid volumes (scant vs. severe). The OCT is an imaging technique that uses near-infra-red light waves to take cross-section pictures of the eardrum. The effects of type and the amount of the MEE as determined by OCT were correlated to WBA_{amb}, where absorbance was significantly decreased in the mucoid group compared to the serous group. As well, greater reduction in absorbance was observed as function of fluid volume. These findings demonstrate that WBA measurements are sensitive to the type of fluid (mucoid vs. serous) and the amount of effusion in the middle ear cavity.

NEGATIVE MIDDLE-EAR PRESSURE

Tympanic membrane retraction is a condition wherein the tympanic membrane is pulled inward by the negative pressure within the middle ear due to Eustachian tube dysfunction (ETD) or RP. ETD is a condition wherein the pressure behind the tympanic membrane cannot be equalized to ambient pressure, resulting in NMEP.[48] It is a common condition in childhood, with studies reporting up to 50% of children with NMEP.[49] Due to the pivotal role of the ET in the pathogenesis of OME and cholesteatoma and the determination of middle ear surgery outcomes, it is essential to determine the status of ET function accurately.

Immittance studies showed that negative TPP is often associated with some degree of ETD. Nevertheless, TPP is a single measure of pressure in the middle ear cavity, but it is not a measure of the ET pressure regulation function under various pressure conditions. Tests such as Toynbee and Valsalva have been developed to provide serial determinations of middle ear pressure and indicate the dynamics of the tubal function. One of the limitations of these tests is the inability to precisely control the relative amounts of overpressure or underpressure generated in each individual.[48] Other tests such as nine-step inflation test and Eustachian tube dysfunction questionnaire (EDTQ-7) are not suitable for routine application with young children where ETD is common. One method to circumvent the effect of NMEP is to apply a compensatory pressure concurrent with recordings from the middle ear such as in WBT testing. For example, comparing WBA_{amb} and WBA_{TPP} could provide additional clinical information about the dynamics of the ET function that is not available by simply measuring TPP, although this would not indicate the pressure regulation function of the ET.

Beers et al[2] compared WBA measurements between a group of 78 children with normal hearing (average age of 6.15 years) and a group of 64 children with middle ear disorders (average age of 6.34 years). The middle ear disorder group had 42 ears with MEE and 54 ears with different degrees of NMEP. Fig. 3 illustrates WBA from the normal-hearing group, the mild NMEP (−100 to −199 daPa), the severe NMEP (−200 daPa or more negative), and the MEE groups.[2] NMEP resulted in significant reductions in WBA between 797 and 1,852 Hz even with a mild degree of NMEP. The figure also shows a clear trend of decreased absorbance as the degree of dysfunction progressed from normal to mild to severe NMEP to MEE. It should be noted that NMEP can occur with or without effusion; however, Beers et al[2] did not separate ears with and without effusion in ears with NMEP.

NMEP increases the tension in the tympanic membrane and the ossicular chain, as well as a reduced air volume in the middle ear cavity. This results in an overall increased stiffness of middle ear system, and consequently impedes sound in the low-mid frequencies. This is demonstrated by a decrease in WBA in frequencies between 800 and 4,000 Hz. Since the middle ear pressure cannot be measured directly, one method to circumvent the effect of NMEP is to apply a compensatory pressure in the ear canal or measure WBA at TPP. Aithal et al[50] investigated WBA_{amb} and WBA_{TPP} in 102 ears from 79 healthy children and 43 ears from 32 children with ETD and without effusion. Results suggested a differential pattern of WBA_{TPP} relative to WBA_{amb} between healthy ears and ears with ETD and without effusion. WBA_{amb} of healthy ears was only 0.06 to 0.09 lower than WBA_{TPP} between 600 and 1,250 Hz. By comparison, WBA_{amb} of the ETD group was 0.29 to 0.42 lower than the WBA_{TPP} between 600 and 1,500 Hz with the maximum reduction occurring between 1,000 and 1,500 Hz.[50] Interestingly, WBA_{TPP} of the ETD group was restored to

Figure 3 Mean WBA from the normal-hearing group, the mild negative middle-ear pressure (−100 to −199 daPa), the severe negative middle-ear pressure (−200 daPa or more negative), and the MEE groups. (Adapted from Beers AN, Shahnaz N, Westerberg BD, Kozak FK. Wideband reflectance in normal Caucasian and Chinese school-aged children and in children with otitis media with effusion. Ear Hear 2010;31(2):221–233.)

normal levels comparable to healthy ears (Fig. 4). Thus, comparing WBA_{amb} and WBA_{TPP} can provide additional information on the dynamic function of ET that is not available with tympanometry alone. This is important, especially in young children who cannot perform maneuvers such as Toynbee or Valsalva during ETD assessment.

The effect of increased stiffness in association with NMEP was further demonstrated by Aithal et al[14] who compared WBA_{amb} and WBA_{TPP} in a group of healthy ears to three NMEP groups with varying degrees of severity but without effusion. The three NMEP groups had the following TPP values: (group 1) −101 and −200 daPa, (group 2) −201 and −300, and (group 3) −301 to −400 daPa. Results shown in Fig. 5A demonstrate a systematic reduction in WBA_{amb} between 800 and 3,000 Hz as the TPP values decreased from −100 to −400 daPa. Maximum NMEP effects were observed for NMEP group 3 (TPP = − 301 to −400 daPa), suggesting a maximal increase in middle ear stiffness. When the middle ear pressure was equalized using WBT testing procedure (Fig. 5B), WBA_{TPP} measurements showed a restoration of absorbance values to normal levels in all three NMEP groups. Improvement in sound conduction occurred predominantly between 800 and 3,000 Hz, with greater improvement for group 3. This is consistent with the reversal of the effect of abnormal stiffness within the middle ear cavity in the NMEP groups. This effect of full restoration of function is expected for WBA_{TPP} where no pathologies other than NMEP are present. However, when a secondary condition concurrently presents with NMEP (e.g., MEE), WBA_{TPP} is expected to unveil the effect of the secondary condition.

Retraction Pocket

An RP is a unique condition wherein part of the tympanic membrane is stretched more than the

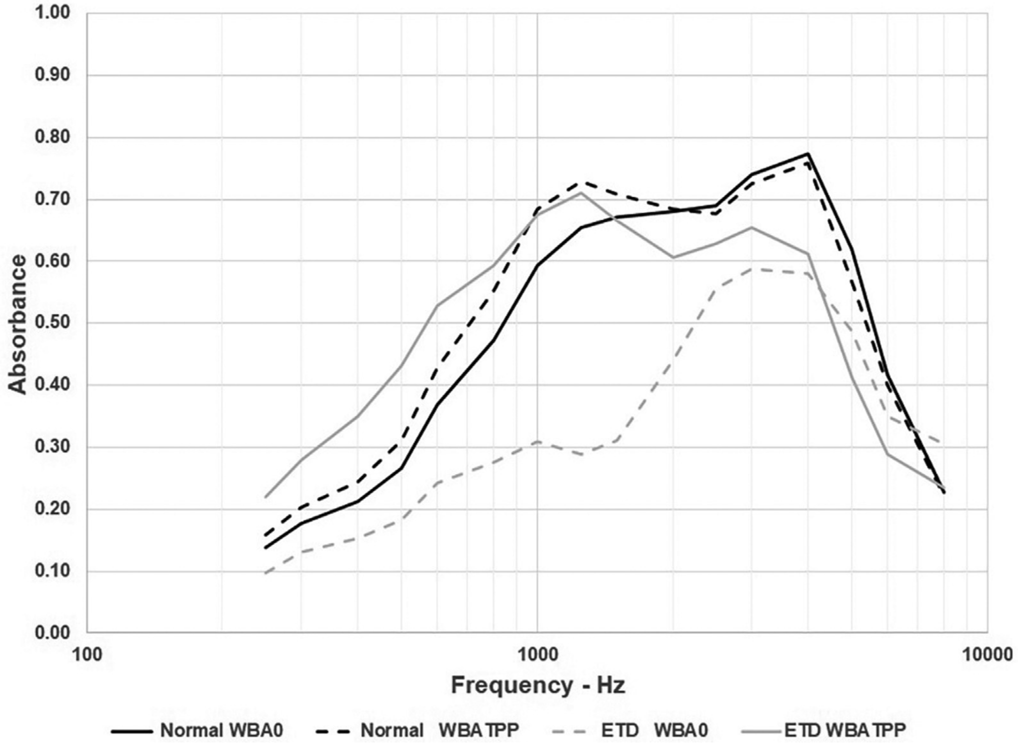

Figure 4 Group mean one-third octave WBA_{amb} and WBA_{TPP} in normal functioning ears and ears with ETD without effusion. (Adapted from Aithal S, Aithal V, Kei J, Anderson S, Liebenberg S. Eustachian tube dysfunction and wideband absorbance measurements at tympanometric peak pressure and 0 daPa. J Am Acad Audiol 2019;30(9):781–791.)

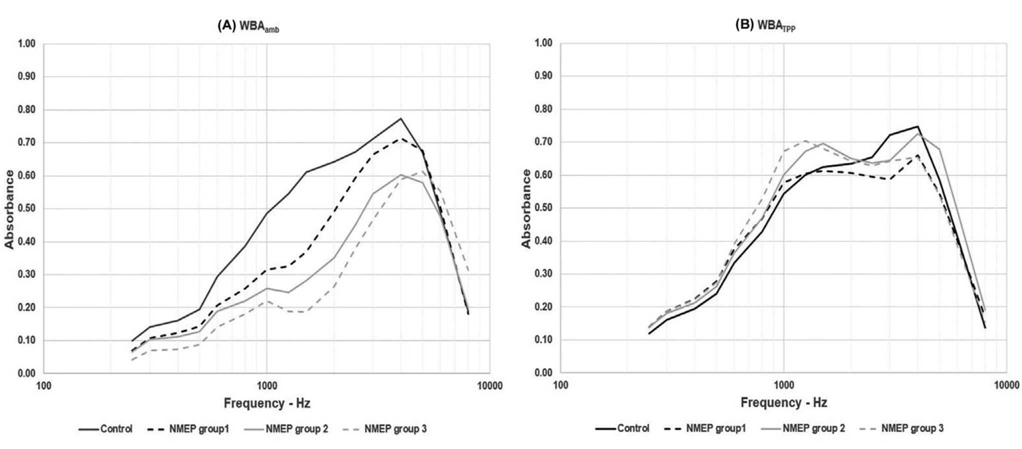

Figure 5 Mean (**A**) WBA_{amb} and (**B**) WBA_{TPP} of healthy ears and ears with different degrees of negative middle-ear pressure. (Adapted from Aithal S, Aithal V, Kei J, Manuel A. Effect of negative middle-ear pressure and compensated pressure on wideband absorbance and otoacoustic emissions in children. J Speech Lang Hear Res 2019;62(9):3516–3530.)

rest of the tympanic membrane, forming a second (or multiple) concavities.[51] The pathological invagination of the tympanic membrane associated with RP often results in the loss of the fibrous layer and prevents the tympanic membrane from its original strength and position. A chronic RP can form adhesions with surrounding structures with an accumulation of debris and epithelium, predisposing to the development of cholesteatoma.[52–54] RPs can be classified as epitympanic RP (ERP) (rising from the pars flaccida and progressing upward) or mesotympanic RP (MRP) (rising from the pars tensa and progressing medially along with the lenticular processes and stapes suprastructure). Pathological changes in middle ear structures vary depending on the site of the lesion and are reflected in changes in WBA. ERP and MRP affect middle ear structures differently, with the ERP predominantly affecting tympanic membrane mobility without affecting the ossicular chain. In contrast, MRP affects the mobility of the tympanic membrane and ossicular chain.

Aithal et al[50] investigated WBA_{amb} and WBA_{TPP} in 27 healthy ears and 11 ears with a general diagnosis of RP in children who were between 6 and 16 years of age. In the healthy ear group, WBA_{amb} and WBA_{TPP} were generally similar in patterns, and WBA_{amb} showed slightly lower absorbance values than WBA_{TPP} between 800 and 15,00 Hz (Fig. 6). By contrast, differential WBA patterns were observed in the ears with RP, where WBA_{amb} in ears with RP showed reduced absorbance values between 250 and 4,000 Hz compared to WBA_{TPP}.

Fig. 7(A) illustrates WBA_{amb} and WBA_{TPP} (S. Aithal et al, unpublished data, 2020) obtained in the right ear of a 9-year-old patient with ERP, while Fig. 7(B) illustrates WBA_{amb} and WBA_{TPP} (S. Aithal et al., unpublished data, 2020) in the left ear of an 8-year-old patient with MRP. For both ears, WBA_{amb} is represented by the solid black lines, and WBA_{TPP} is represented by the dashed grey lines. The shaded area represents the 10th to 90th percentile for WBA_{TPP} for

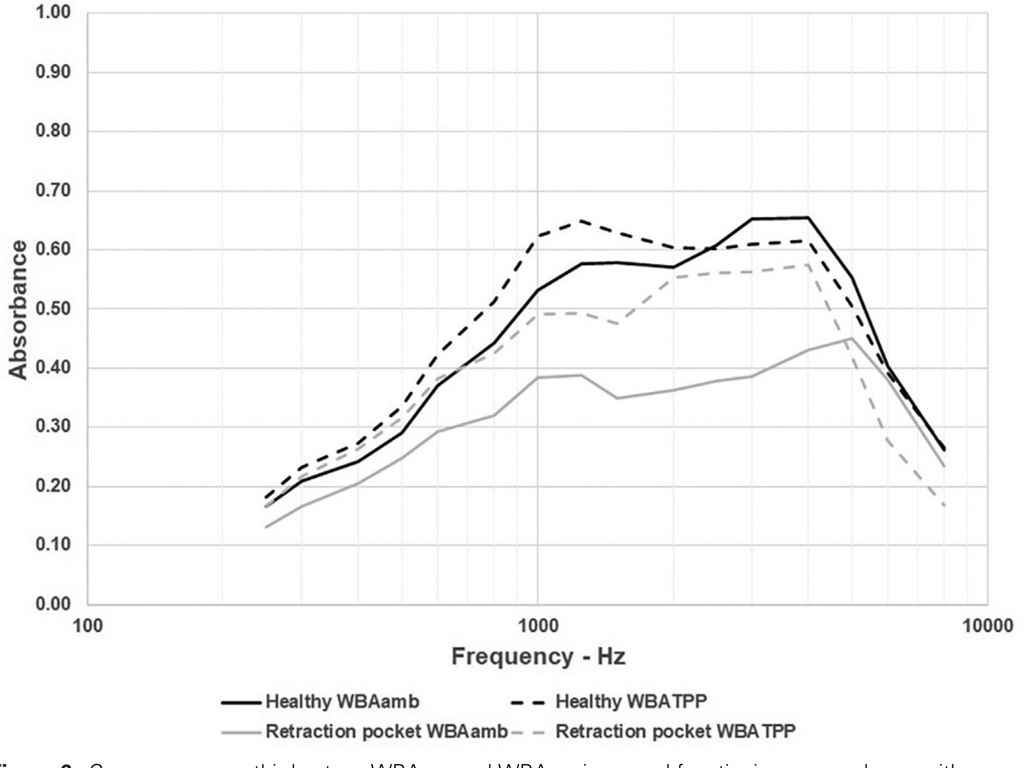

Figure 6 Group mean one-third octave WBA_{amb} and WBA_{TPP} in normal functioning ears and ears with retraction pocket. (Adapted from Aithal S, Aithal V, Kei J, Anderson S. Wideband absorbance in ears with retraction pockets and cholesteatomas: a preliminary study. J Am Acad Audiol 2020;31(10):708–718.)

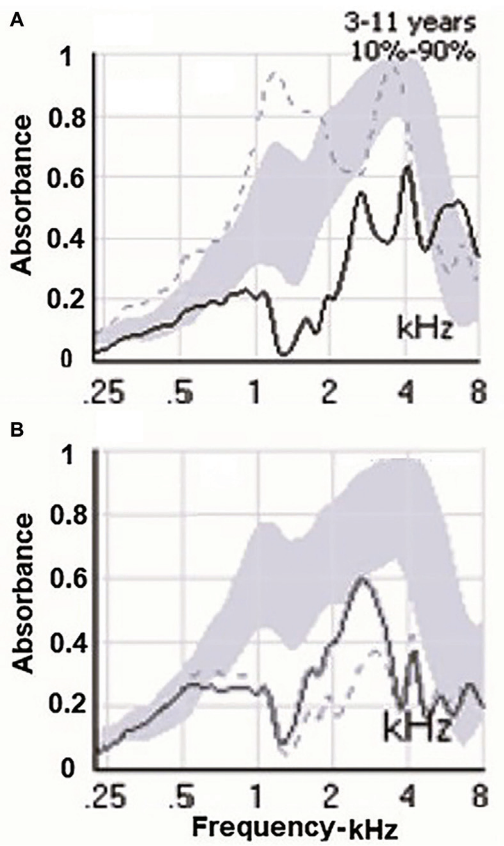

Figure 7 Examples of WBA_{amb} (dotted line) and WBA_{TPP} (solid line) for (**A**) 6-year-old child with epitympanic retraction pocket and (**B**) 7-year-old child with mesotympanic retraction pocket.

children aged 3 to 11 years. ERP and MRP demonstrate different WBA patterns. In ERP, WBA_{amb} is reduced from 250 to 2,000 Hz, while WBA_{TPP} shows a significant increase relative to WBA_{amb}, between 800 and 2,000 Hz, indicating that when pressure is equalized on either side of the tympanic membrane, normal mobility of the tympanic membrane is improved. Pathogenesis of ERP is likely related to the dysfunction of the ET, inflammation, and pneumatization of mastoid.[55] Furthermore, middle ear pressure in ears with ERP depends on the size of the RP and remaining air volume in the middle ear.[56] Thus, the improvement in tympanic membrane mobility with pressure equalization may suggest a relatively intact ossicular chain with limited movement due to decreased aeration of the middle ear. In contrast, both WBA_{amb} and WBA_{TPP} are reduced in ears with MRP, suggesting the ossicular chain mobility could also be affected as the retracted tympanic membrane drapes over the ossicular chain.

CHOLESTEATOMA

Persistent RP comprises the precursor mechanism of cholesteatoma, a well-demarcated noncancerous cystic lesion derived from the growth of keratinizing squamous epithelium that originates from the external layer of the tympanic membrane or ear canal.[57] The annual incidence of cholesteatoma ranges from 3 to 15 cases per 100,000 children[58–61] and is common in individuals with a history of recurrent ear infections. Consequences of delayed detection results in the spreading of cholesteatoma to other parts of the ear with the destruction of middle ear ossicles and adjacent bony structures. The disease burden of cholesteatoma is high, and management involves surgery to remove the cholesteatoma and reconstruct the middle ear.

Fig. 8 illustrates the mean WBA_{amb} and WBA_{TPP} in 27 healthy ears and 12 ears with cholesteatoma in children aged 6 to 16 years from a recent study (S. Aithal et al, unpublished data, 2020). Both WBA_{amb} and WBA_{TPP} in ears with cholesteatoma are significantly reduced compared to healthy ears in the frequency range of 1,000 to 6,000 Hz. Children with cholesteatomas also presented with flat tympanograms and conductive hearing loss. Conductive hearing loss and reduced WBA_{amb} and WBA_{TPP} can be attributed to the presence of cholesteatoma matrix within the middle ear, erosion or disruption of the ossicular chain, and decreased aeration of the middle ear. Mass loading of cholesteatoma is likely to be associated with reduced WBA_{amb} and WBA_{TPP} in the high frequencies between 2,000 and 6,000 Hz, while reduced compliance of ossicular chain due to impingement of cholesteatoma mass or erosion of ossicles could contribute to reduced WBA_{amb} and WBA_{TPP} in the 1,000- to 2,500-Hz region.[62,63] In comparison, the absorbance in frequencies between 250 and 800 Hz was similar to that of healthy ears, suggesting that stiffness of the middle ear system was not affected in ears with cholesteatoma.

Currently, standard tests such as tympanometry and audiometry fail to detect RP and

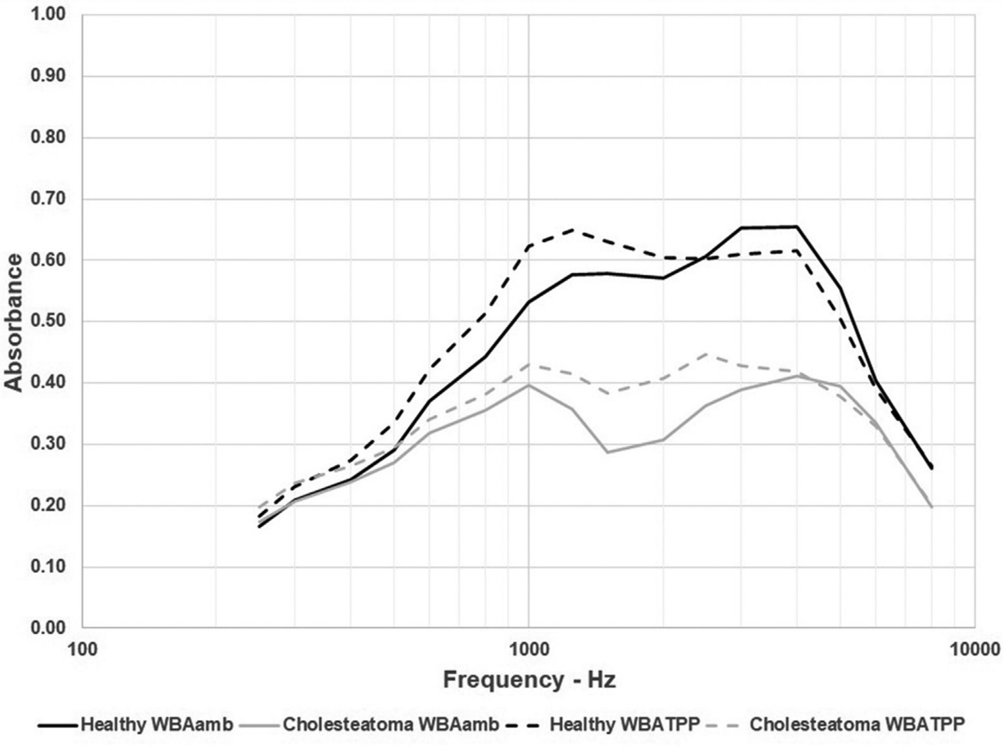

Figure 8 Mean WBA_{amb} and WBA_{TPP} in healthy ears and ears with cholesteatoma. (Adapted from Aithal S, Aithal V, Kei J, Anderson S. Wideband absorbance in ears with retraction pockets and cholesteatomas: a preliminary study. J Am Acad Audiol 2020;31(10):708–718.)

cholesteatoma accurately. In comparison, WBA shows some promise during the assessment of ears with RP and cholesteatoma. Aithal et al[64] have shown that although WBA_{amb} and WBA_{TPP} patterns are similar between RP and cholesteatoma groups, they differ between the epitympanic and mesotympanic sites of the lesion. With the epitympanic site of lesion (arising from the pars flaccida and progressing upward), ears with RP demonstrated reduced WBA_{amb} between 800 and 4,000 Hz with an increase in WBA_{TPP} to normal levels in this frequency region. In ears with cholesteatoma, both WBA_{amb} and WBA_{TPP} remained significantly lower compared to healthy ears. In comparison, with the mesotympanic site of lesion (arising from pars tens and progressing medially along the lenticular process and stapes superstructure), similar WBA_{amb} and WBA_{TPP} results were obtained for both RP and cholesteatoma. This suggests that RP with the epitympanic site of the lesion is likely to be associated with NMEP and RP, while the mesotympanic site can affect the ossicles. However, pathological changes due to cholesteatoma matrix in the middle ear and erosion of ossicular structures are common for both sites of the lesion. Hence, WBA pattern was similar between cholesteatoma and RP but dependent on the site of the lesion.

The incorporation of WBA measurements in presurgical assessment has the potential to inform surgical management for cholesteatomas, or procedure options for the treatment of RP depending on the functional and anatomical condition of the ear. For example, for patients with RP and significant hearing loss, surgical intervention is often recommended, while an observational "wait-and-see" approach is preferred for patients with RP and a less severe hearing loss. WBA may be used for a patient who is under observation to monitor for possible progression of the disease to a diagnosis of cholesteatoma, as indicated by changes to absorbance, especially in the frequency region between 1,000 and 4,000 Hz. As a result, the clinician may pursue further investigation and/or change in management.

Pressure Equalization Tubes

PETs or grommets are small ventilation tubes inserted into the eardrum to allow air into the middle ear and prevent recurrent OM. Given their prevalence in pediatric ENT practice, clinicians must be aware of their influence on clinical measurements. Traditional tympanometry testing provides simple criteria for verification of patent PETs, whenever a flat type B 226-Hz tympanogram is measured together with a large cavity volume exceeding normal limits. Investigators have also described WBA measurements in ears with PET.[8]

Ears with patent PETs demonstrate multiple peaks with an abnormal prominent peak in the low frequencies around 500 Hz, likely related to the decreased acoustic coupling between the ear canal and the middle ear.[65] An example of WBA in the right ear of a 6-year-old child with a patent grommet is shown in Fig. 9(A) (S. Aithal et al. 2020 unpublished data). When the PET is blocked, this low-frequency peak is absent. WBA assessment can also be helpful in determining middle ear function behind blocked PETs. If the middle ear function behind the blocked grommet is normal, WBA will be within normal limits. However, when there is MEE behind a blocked grommet, the characteristic low-frequency peak is absent, and the WBA is reduced across most of the frequency range, similar to the WBA pattern in MEE patients shown previously (e.g., Fig. 3) Fig. 9(B) (S. Aithal et al. 2020 unpublished data). illustrates WBA in the left ear of a 3-year-old child with a blocked grommet, flat tympanogram, and normal middle ear function. Fig. 9(C) (S. Aithal et al. 2020 unpublished data) shows WBA in the right ear of a 5-year-old child with a blocked grommet, flat tympanogram, middle ear dysfunction, and MEE. This demonstrates the ability of WBA to detect subtle changes in children with PET that tympanometry could not.

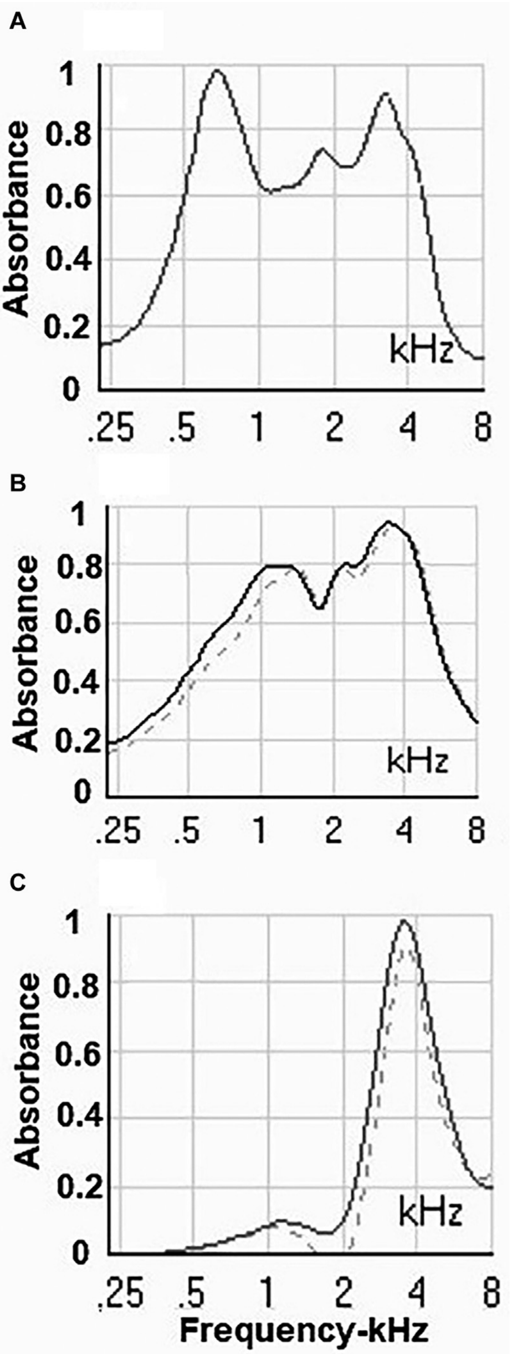

Figure 9 WBA in right ear with (A) patent grommet, (B) in left ear with blocked grommet and normal middle ear function, and (C) in the right ear with blocked grommet and middle ear effusion. Solid and dashed lines represent right and left ears, respectively; dotted lines represent WBA_{amb} and solid lines represent WBA_{TPP}.

WAI IN CHILDREN WITH DOWN SYNDROME

Down syndrome (DS) is a common genetic condition caused by an extra chromosome in pair 21. Common manifestations of this syndrome include auditory abnormalities such as low-set earlobes and external auditory canal stenosis that may result in wax accumulation. A more horizontal ET predisposes them to frequent airway infections and middle ear fluid accumulation. Up to 70% of children with DS are reported to have some degree of hearing loss with a significant risk of OM.[66,67]

Otoscopy and tympanometry can be challenging with these children due to narrow ear canals. WBA is reported to assist in the determination of middle ear function in children with DS. Studies have reported that children with DS and type A tympanogram with 226-Hz probe and normal hearing have WBA patterns similar to those of typically developing children.[68] Typically, middle ear fluid demonstrate decreased absorbance at ambient pressure and TPP across a wide range of frequencies from 800 to 4,000 Hz. WBA is also useful in determining the patency of PETs in children with DS. It is often challenging with children with DS to identify PET patency through otoscopy due to their small ear canal size.

CASE STUDIES

The following cases were obtained in British Columbia Children's Hospital in Vancouver, Canada, as a part of a larger project sponsored by an industry (Digital Diagnostics, formerly known as IDx) to correlate WAI measurements with physical characteristics of the middle ear and MEEs as determined by a pediatric otolaryngologist using otomicroscopy/surgery.

Case 1: WBT Measurements in a Normal-Hearing Child

The first case example is a normal-hearing 7-year-old child whose ears were determined pathology-clear by a pediatric otolaryngologist. In this child, the otoscopic examination was unremarkable in both ears. Acoustic stapedial reflexes at 500 Hz and broadband noise (BBN) in the ipsilateral mode were present in both ears, and distortion product otoacoustic emissions (DPOAE) were present at normal levels, bilaterally. Fig. 10 illustrates the outcomes of WBT testing that was performed in both ears. Results from the left ear are shown in the top panel (Fig. 10A) and from the right ear in the middle panel (Fig. 10B). The three-dimensional (3D) graph plots power absorbance on the *z*-axis as a function of ear canal air pressure and frequency on the *y*- and *x*-axes, respectively. This 3D representation is often referred to as the WBA tympanogram. To simplify analyses, two-dimensional WBA plots are often extracted at select static pressure values (e.g., WBA_{amb} and WBA_{TPP}). The bottom panel (Fig. 10C) illustrates WBA_{TPP} (TPP 14 daPa in the left ear and −3 daPa in the right ear) that were extracted from the left (dashed grey line) and the right ear (solid black line) wideband tympanograms in the top and middle panels, respectively. Fig. 10 will be referred to as an example of normal WBT measurements in children to aid in discussing the following abnormal cases.

Case 2: WBT Measurements in a Child with OM and PET

Fig. 11 provides a case example of a 3-year-old child with OM. A pediatric otolaryngologist performed an assessment of the left ear and confirmed a diagnosis of OM with full effusion. The right ear was operated on earlier for insertion of the PET, and was confirmed to be patent at the time of assessment. Traditional 226-Hz tympanograms revealed a flat type B tympanogram in the left ear with a normal ear canal volume and a flat type B tympanogram with an abnormally large ear canal volume in the right ear. 1,000-Hz tympanograms were also flat in both ears. Ipsilateral acoustic stapedial reflexes in the left ear were absent at 500 Hz and BBN, and DPOAEs were also absent. In the right ear, ipsilateral reflexes at 500 Hz and BBN were absent, and the DPOAE was robustly present, which is also a good indication of an open PET and good aeration of the middle ear cavity. WBT testing was performed in both ears and results are shown in Fig. 11. The WBA tympanograms are shown in the top panel

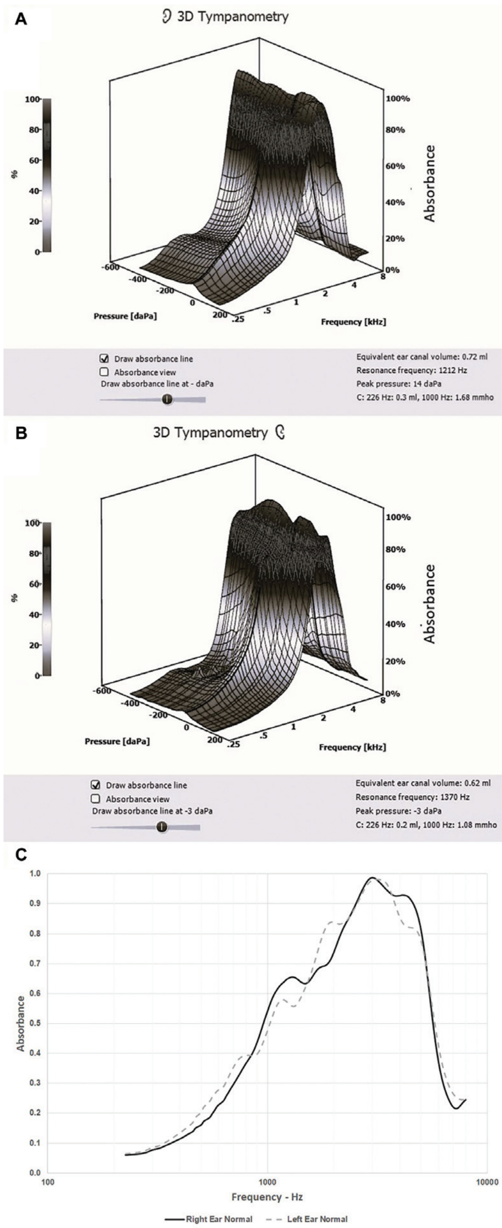

Figure 10 (**A**) Wideband absorbance tympanogram for the left ear and (**B**) right ear with absorbance plotted as a function of ear canal air pressure and frequency (3D wideband absorbance tympanogram) of a 3-year-old child with normal hearing sensitivity and normal functioning of the middle ear system. (**C**) WBA_{TPP} for left (dashed line) at TPP = 14 daPa, and for the right (solid line) ear at TPP = 3 daPa.

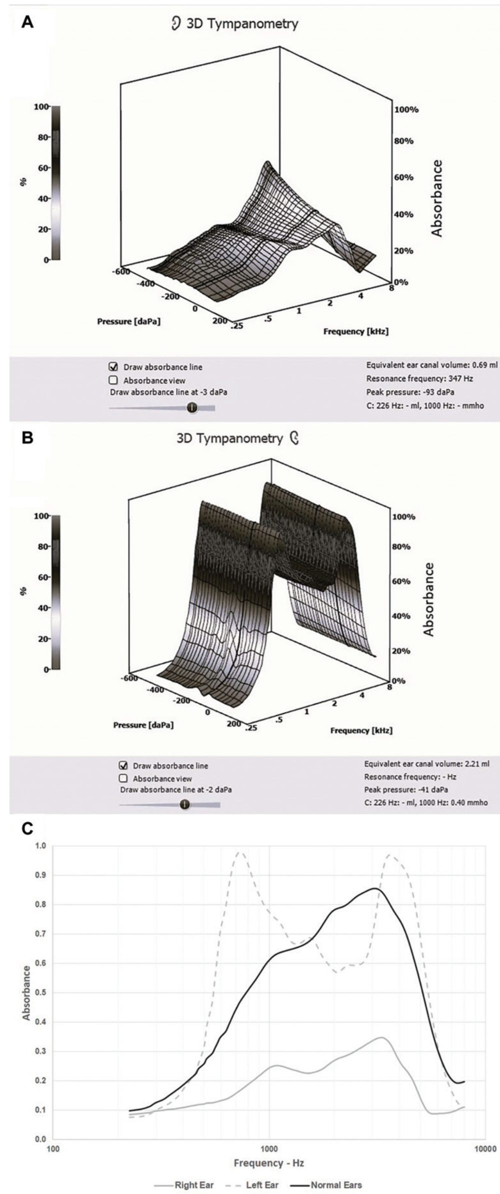

Figure 11 (**A**) Wideband absorbance tympanogram for the left ear and (**B**) right ear with absorbance plotted as a function of ear canal air pressure and frequency. Measurements were obtained from a 3-year-old child with OM with full effusion in the left ear and a right ear with a patent PET from a recent operation. (**C**) WBA_{TPP} for left (solid grey line) at TPP = − 93 daPa, and for the right (dashed grey line) ear at TPP = − 41 daPa. The solid black line represents average normal children.

(Fig. 11A) for the left ear, and in the middle panel (Fig. 11B) for the right ear. The bottom panel (Fig. 11C) provides a comparison of WBA_{TPP} for the left (dashed grey line) and right (solid grey line) ears that were extracted from the wideband tympanograms. The WBA tympanograms show unique patterns for each ear, which are quite different from the normal

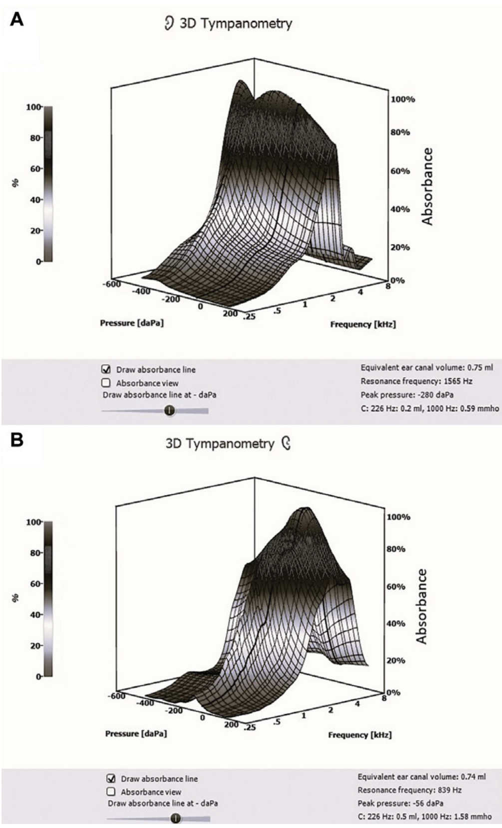

Figure 12 Wideband absorbance tympanogram for the left ear (**A**) and right ear (**B**) with absorbance plotted as a function of ear canal pressure and frequency of a 5-year-old with observable retraction on the left side with no sign of fluid in the middle ear system and normal middle ear in the right ear.

wideband tympanogram patterns (e.g., in Fig. 10). The WBA_{TPP} pattern in the right ear shows an abnormal increase in absorbance values, resulting in a secondary absorbance peak at frequencies between 600 and 1,000 Hz. For a detailed discussion on the effect of patent PET on WBA measurements, the reader is referred to the article by Sanford et al in this issue. The WBA_{TPP} pattern in the left ear shows a significant decrease in absorbance values, especially for frequencies 1,000 to 4,000 Hz.

Case 3: WBT Measurements in a Child with Varying Degrees of NMEP

Fig. 12 is from a 5-year-old child in whom 226-Hz tympanometry revealed normal configuration, with a very high NMEP in the left ear (TPP = − 280 daPa) and a slight NMEP in the right ear (TPP = − 56 daPa). The pediatric otolaryngologist performed otoscopic examination and noted a normal-appearing tympanic membrane with no sign of fluid in the middle ear system in the right ear, and a clear retraction of the tympanic membrane with no sign fluid on the left side. WBT testing was performed in both ears and the resulting wideband tympanogram revealed a reduced absorbance in the left ear, predominantly at low frequencies and pressure values around 0 daPa (Fig. 12A), and normal patterns for the right ear (Fig. 12B). As pressure was swept to more negative values, absorbance values in the left ear uniformly increased in the low frequencies and reached their highest values around the TPP value (−280 daPa).

Fig. 13 illustrates a comparison between WBA_{TPP} and WBA_{amb} in the left ear that shows greater absorbance values below 2,500 Hz for WBA_{TPP} compared to WBA_{amb}, and virtually no difference between WBA_{TPP} and the mean normal absorbance values for children above 2,500 Hz. This clearly demonstrates that when absorbance was conducted at the peak pressure, it became closer to the normal ears at low-mid frequencies. If the absorbance had been measured only at ambient pressure, the assessment would have suggested an abnormal increase in stiffness, which could have indicated a potential diagnosis of MEE for example. The additional comparison with WBA_{TPP} provided clear evidence that WBA patterns were restored to normal once pressure was compensated for, indicating that the increase in stiffness was rather due to severe NMEP. Moreover, this finding is consistent with ENT diagnosis, which ruled out the presence of concurrent effusion behind the eardrum in the left ear, otherwise, WBA_{TPP} would have shown abnormal results.

Case 4: WBT Measurements in a Child with MEE

Fig. 14 is from a 6-year-old child in whom 226-Hz tympanometry revealed abnormal type B tympanograms with normal ear canal volume on both sides (with shallow broad peaks; TPP of −398 daPa in the left and −98 daPa in the right

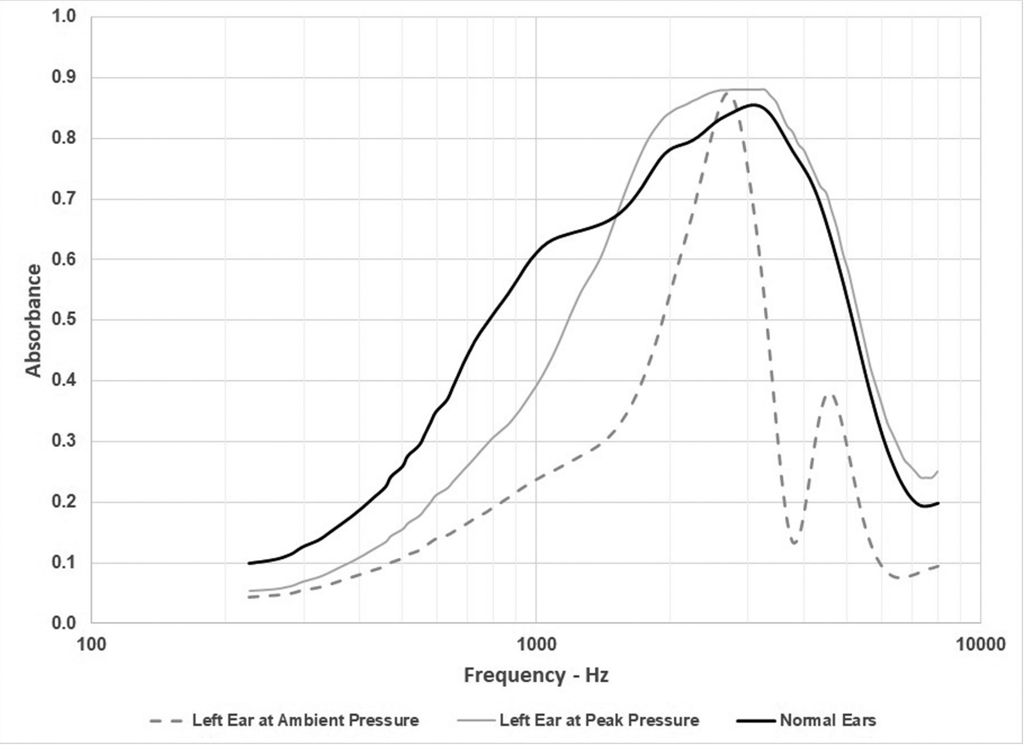

Figure 13 A comparison of WBA_{TPP} (solid grey line −280 daPa) and WBA_{amb} (dashed grey line) that were extracted from WBT measurements in the left ear of the 5-year-old child (shown in Fig 12A). The solid black line represents average normal children.

ear). The pediatric otolaryngologist performed an otoscopic examination and noted a retracted ear drum with fluid in both ears. He reported that the left ear has more fluid and retraction than the right ear. DPOAE at peak pressure was absent in the left ear and was present between 3 and 6 kHz in the right (overall absent). Ipsilateral reflexes at 500 Hz and BBN were absent in both ears. WBT testing was performed in both ears and the resulting WBA_{TPP} revealed a significant reduction compared to the average normal ears in children in both ears (Fig. 14); however, the reduction was greater on the left side with more fluid. Similar to the findings of Merchant et al,[5] the WBA was systematically reduced as a function of the MEE volume.

CONCLUSION

WAI testing is a more effective test in the diagnosis of middle-ear abnormalities in children than conventional tympanometry. In contrast to conventional tympanometry, WAI has been shown to be more accurate in detecting the presence of OM and MEE, volume and type of the effusion (mucoid vs. serous), and, more importantly, to the changes of the conductive component as measured by ABG. As this article reviewed, the use of WBT to establish a comparison between WBA_{amb} and WBA_{TPP} allows clinicians to accurately characterize the middle ear function in normal and diseased conditions in children across a wide range of frequencies. Providers can utilize WBT to differentially determine the presence of abnormal middle ear function due to fluid or to rule out the presence of fluid as demonstrated in Case 3, where the WBA_{TPP} provided clear evidence that abnormality was in association with the NMEP not MEE. Continued efforts in research will further characterize WBA patterns for rarer middle ear conditions, including glomus jugulare tumor. At its fullest potential, WBA could provide distinct patterns for different middle-ear pathologies. Furthermore, the addition of pressure variable in WBT provides an extra dimension of analysis

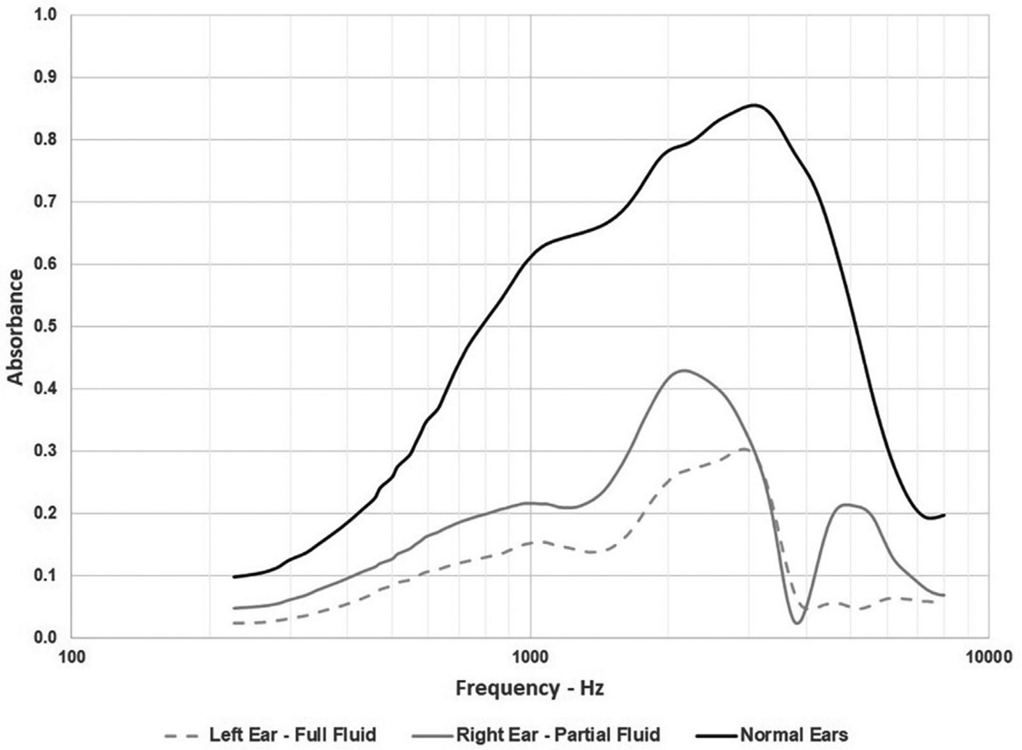

Figure 14 Example of WBA_{TPP} with retracted eardrums in both ears with full fluid in the middle ear in the left ear (dashed grey line TPP = – 398 daPa) and with partial fluid in the middle ear of the right ear (solid grey line TPP = – 98 daPa) of a 6-year-old child compared to WBA at peak pressure in normal ears (solid black line).

and is amenable to machine learning for automation in the future.

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DISCLOSURES

We have no known conflict of interest to disclose.

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