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Fundamental Concepts for Assessment and Interpretation of Wideband Acoustic Immittance Measurements

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ABSTRACT

Assessment of middle ear impedance using noninvasive electroacoustic measurements has undergone successive developments since its first clinical application in the 1940s, and gained widespread adoption since the 1970s in the form of 226-Hz tympanometry, and applications in multifrequency tympanometry. More recently, wideband acoustic immittance (WAI) is allowing unprecedented assessments of the middle ear acoustic mechanics thanks to the ability to record responses over a wide range of frequencies. The purpose of this article is to present fundamental concepts for the assessment and interpretation of wideband measures, including a review of acoustic impedance and its relation to the mass, stiffness, and resistance components of the middle ear. Additionally, an understanding of the middle ear transfer function reveals the relationship between impedance and middle-ear gain as a function of frequency. Wideband power absorbance, a WAI measure, quantifies the efficiency of sound conduction through the middle ear over a wide range of frequencies, and can serve as an analogous clinical measure to the transfer function. The interpretation of absorbance

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measures in ears with or without a conductive condition using absorbance measured at ambient pressure and pressurized conditions (wideband tympanometry) is described using clinical case examples. This article serves as an introduction to the fundamental principles of WAI measurements.

KEYWORDS: wideband acoustic immittance, acoustic impedance, wideband power absorbance, middle ear transfer function, resonance frequency

THINKING ABOUT THE MIDDLE EAR IN WIDEBAND

One of the important functions of the middle ear is its role in amplifying incoming sound from the air-filled ear canal with an upward of 30 dB of gain to sufficiently conduct sound through the oval window into the fluid-filled inner ear. This function of the middle ear is known as impedance matching, as the amplification it provides compensates for the difference between the characteristic impedance of the air and fluid media. The healthy middle ear, however, is not a perfect conductor of all frequencies of sound, with some frequencies receiving more gain than others, dependent on the impedance of the middle ear itself.

Because the middle ear processes and conducts all sound frequencies that are audible to the human ear, a realistic representation of the middle ear function is to describe middle ear gain over a wide range of frequencies, where middle ear gain is defined as the difference between the intensity of (input) sound and that of the middle ear (output) response. Unfortunately, immittance testing in routine audiological evaluations is often limited to a single probe-tone test frequency. Despite the clinical benefits of single-frequency tympanometry, the assessment of the middle ear it conveys is quite limited. Over the last two decades, clinical systems that are equipped with wideband acoustic immittance (WAI) testing capabilities have become available commercially. Using WAI, clinicians will be able to evaluate sound conduction through the outer/middle ear over a wide range of frequencies. The objective of this article is to provide clinicians with an overview of the principles underlying assessment and interpretations of WAI measurements.

In the first sections, we review the manner in which the normal middle ear transforms sound over a wide range of frequencies, and describe the physical attributes that give rise to preferential gain for some frequencies over others. Primarily, we highlight the relationship between the physical attributes of the middle ear and the concepts of acoustic impedance and resonance. The following sections will introduce typical WAI measurements in normal-hearing adults, and outline approaches to assessment and interpretation of abnormal measurements in pathological ears.

ACOUSTIC IMPEDANCE

Acoustic impedance can be defined as the inherent opposition to flow of acoustic energy in a vibrating object. Recall that for any object to vibrate, giving off sound (for a sound source) or conducting it (for a sound medium), there has to exist a balanced interplay between the elastic forces connecting its elementary subparts, and the mass that is constituted within these subparts. While the mass of the vibrating elements maintains their momentum ("inertia") during displacement from a neutral position, the interconnective elastic forces "store" energy, that is, when in states of compression or rarefaction, and "restore" the object back to its neutral position.[1]

The natural frequency of vibration for an object, also called the resonance frequency, varies from one object to another depending on its unique physical attributes including the amount of mass and elasticity (or stiffness). These physical attributes also determine how vibrations at different frequencies are *impeded* or *reinforced*.

Impedance, Reactance, Resistance, and Frequency Dependency

Impedance is represented mathematically using the complex number Z. It has magnitude and phase that vary as a function of frequency.

$$Z = iR + j(X_M - X_S) \text{ Equation (1)}$$

Equation (1) shows that impedance (Z) is composed of a real number, resistance (R), and an imaginary component, reactance (X).[2] Fig. 1 shows a phasor plot representation of Z as a vector (blue arrow), with magnitude $|Z|$ represented by the length of the vector and a phase ϕ. The subcomponents R and X are represented on the x- and y-axis, respectively. Note that Z vector magnitude and phase vary as a function of frequency, and that the example in Fig. 1 is a representation of Z for one frequency. For a detailed review of the mathematical and graphical representation of acoustic impedance, the reader is referred to Van Camp et al.[2] The scope of this presentation is to describe the subcomponents of impedance (resistance and reactance) and highlight its dependency on frequency in simplified terms.

On one hand, resistance represents aspects of a vibrating object that loses or dissipates vibratory energy into forms other than sound, e.g., friction within the vibrating elements which dissipate energy in the form of heat. The dissipation effect of resistance on sound vibration amplitudes is independent of their frequencies. In other words, resistance "*impedes*" energy equally at all sound frequencies.

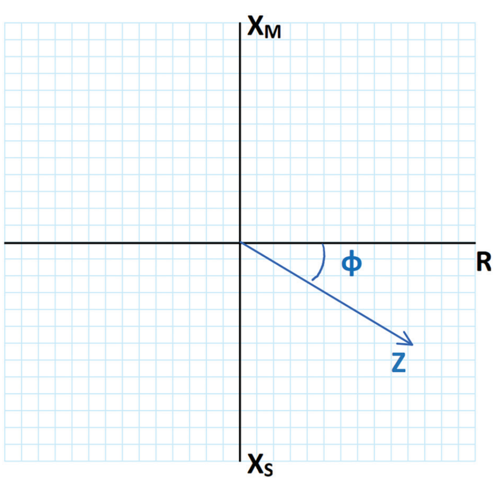

Figure 1 Phasor plot representation of the complex number impedance (Z). Represented on the plot for one frequency, Z is shown as a vector with both a magnitude that is indicated by the length of the blue solid arrow and a phase angle (ϕ). The real component of Z, resistance (R), is represented on the x-axis; the imaginary component, reactance (X), is represented on the y-axis, with M and S subscripts indicative of mass- and stiffness-reactance, respectively.

Reactance, on the other hand, relates the intertwined physical attributes of vibratory objects that maintain either vibratory motion as momentum, called mass reactance (Xm), or the elastic restorative forces that counter that motion, called stiffness reactance (Xs). Although mass and stiffness reactance both "*impede*" sound vibrations requiring energy either to accelerate the mass elements or to overcome the elastic restorative elements, the two types of reactance *impede* sound vibrations in opposition to each other (note the negative sign between Xm and Xs in Equation 1). The interplay between Xm and Xs, which is dependent on physical composition of the object (e.g., mass/density and elasticity/stiffness) determines whether some sound frequencies vibrate at greater amplitudes than other frequencies.

A vibratory object or system that has great levels of stiffness is said to be a stiffness-dominated system. In such systems, stiffness overcomes the inertia carried by its mass and quickly restores the vibration motion. The quick restoration of vibratory motion causes a stiffness-dominated object to vibrate with greater amplitudes at a faster rate. Said differently, stiffness-dominated systems *impede* low-frequency vibrations, and vibrate with greater amplitudes at higher frequencies. Alternatively, a system with greater amount of mass that overcomes the elastic restorative elements is called a mass-dominated system. Without a large restorative force to counter the inertia of a dense object, vibrations occur at slower rates as more time is needed to slow down (decelerate) mass-dominated objects in one motion direction and reverse (accelerate) it in the opposite direction. Said differently, mass-dominated objects vibrate with greater amplitude at low frequencies, and impede vibrations at high frequencies.

Impedance at the Frequency of Resonance

A vibrating object is said to be in a state of acoustic resonance when it vibrates in phase with the incoming sound. As well, an object in a state of resonance vibrates at greater amplitude compared to a nonresonant state. The frequency at which an object resonates varies depending on the object's unique mass and elasticity composition. At the resonance frequency, mass- and stiffness-reactance perfectly counter each other resulting in overall low impedance with no contribution from reactance. Stated in mathematical terms, using Equation (1), $Z = R + 0$, because $X\mathrm{m} - X\mathrm{s} = 0$, and impedance phase ($\phi$) is equal to 0 degree. In stiffness-dominated systems, resonance occurs at higher frequencies, whereas in mass-dominated systems resonance occurs at lower frequencies. Equation 2 describes this relationship, where f_0 represents the frequency of resonance, the k and m constants represent stiffness and mass of the vibrating system, respectively.[3] If stiffness and mass are modified, the k to m ratio changes and the frequency of resonance changes accordingly. If k increases, f_0 is shifted to a higher frequency. Alternatively, if m increases, f_0 is shifted to a lower frequency.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \text{ Equation (2)}$$

To illustrate the relationships between mass, stiffness, and frequency of resonance, consider the following example about tuning of guitar strings. Given the unique combination of tension (stiffness) and density of a guitar string, each string is "tuned" to vibrate at a specific frequency (i.e., resonance frequency). A guitarist may manipulate the tension of the guitar strings to make sure they are accurately tuned. Tensing up (stiffening) a string tunes it to vibrate at a higher frequency, whereas reducing tension in the string tunes it to a lower frequency. Similarly, consider the effect of density of the guitar strings; thicker strings with higher (mass) density vibrate at lower frequencies, where thinner strings vibrate at higher frequencies.

MIDDLE EAR ACOUSTIC MECHANICS

Natural Mass, Stiffness, and Resistance of the Middle Ear

Impedance of the healthy middle ear is dependent on the natural combination of mass, stiffness, and resistance elements in its physical structure. For example, stiffness elements are found in the tension of the tympanic membrane and ossicular joints, ligaments, tendons, and the volume of air in the tympanic cavity.[2,4] The mass elements are found in the pars flaccida of the tympanic membrane, ossicular bones, density of the perilymph in the cochlea that is coupled to the footplate of the stapes at the oval window, and mesenchyme commonly found in newborns and young infants. Resistance elements also exist at the tendons and ligaments that hold vibrating parts in place: for example, the tympanic annulus ligament at the peripheral rim of the pars tensa of the tympanic membrane, the narrow passages between the middle ear cavity and mastoid, and the viscosity of the perilymph and the mucous lining of the middle ear cavity.

Fig. 2 illustrates an acoustic-mechanical model of the middle ear by Marquet et al,[5] in which mass (denoted by m_0), stiffness (indicated by the sketched spring symbols), and resistance (indicated by the sketched fork symbol) elements that are inherent to the healthy middle ear are distributed through its interconnected anatomical parts. Interactions among these physical elements determine how sound of different frequencies is either impeded or reinforced, as well as the frequency of resonance, where the middle ear gain is expected to be greatest.

The Middle Ear Transfer Function: Gain versus Frequency

As discussed in the opening section of this article, one of the functions of the middle ear is to amplify sound. However, due the middle ear's natural impedance, sound is not amplified equally at all frequencies. Middle ear gain as a function of frequency, called the transfer function, has been measured in human cadavers and guinea pigs.[6,7] The middle ear gain at various frequencies is measured by recording the amplitude of vibrations at an input point at the beginning of the middle ear (e.g., tympanic membrane displacement/velocity) and at an output point at the end of the middle ear (e.g., stapes footplate displacement/velocity). Gain is computed as the

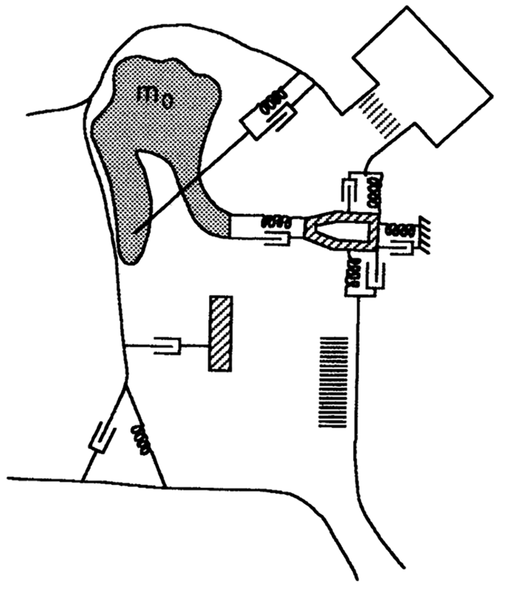

Figure 2 Model of the middle ear as an acoustic-mechanical system, with natural stiffness (shown by spring symbols), mass (denoted by m_0), and friction (fork symbol) elements. (Reprinted with permission from Marquet J, Van Camp K, Creten W, Decraemer W, Wolff H, Schepens P. Topics in physics and middle ear surgery. Acta Oto-Rhino-Laryngologica Belgica 1973;27(2):139–319.)

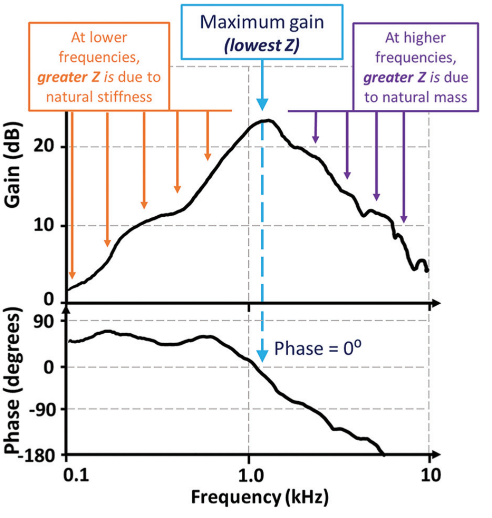

Figure 3 Upper panel illustrates mean middle ear gain as a function of frequency measured in 11 postmortem human temporal bones. Gain was determined as vestibule vibrations relative to input sound pressure measured at the surface of the tympanic membrane. The frequency at which gain is maximum is indicated by the vertical solid blue arrow. The corresponding mean phase angle as a function of frequency is shown in the lower panel. The frequency at which phase angle = 0 degrees is indicated by the dashed blue arrow, which extends vertically from the peak gain in the upper panel to highlight their correspondence. The frequency where gain is maximum and phase = 0 degrees is the frequency of resonance at which impedance is lowest. (Illustration based on report by Aibara R, Welsh JT, Puria S, Goode RL. Human middle-ear sound transfer function and cochlear input impedance. Hearing research 2001;152(1):100–109.)

difference in the amplitudes between the output and input points of measurement in decibels.

Aibara et al[6] successfully measured the middle-ear pressure gain (GME), defined as the ear canal sound pressure to cochlear vestibule pressure gain for the 0.05- to 10-kHz frequency range in 11 fresh human temporal bones. Fig. 3 is a re-illustration of the GME gain function across frequency from their work, with a mean maximum gain of 22 dB at 1,100 Hz.

Impedance and Middle Ear Resonance

The configuration of the transfer functions shows that the middle ear gain varies across frequency. This configuration is dependent on the impedance of the middle ear at various frequencies. The frequency at which the middle ear gain is greatest, 1,100 Hz, is the frequency of resonance. Recall that at this frequency, impedance is lowest (reactance = 0 Ω) and the output and input vibrations occur in phase with each other ($\phi = 0$ degrees). The highest gain is marked by the dashed blue line in Fig. 3 (top panel) which extends vertically along the 1,100 Hz frequency point (resonance frequency) on the *x*-axis. In the lower panel, the blue arrow symbol indicates the 0-degree phase occurs at the same frequency. At frequencies lower than the resonance frequency, stiffness-dominated reactance results in greater impedance and a reduction in gain, indicated by the vertical orange arrows in the figure. At frequencies higher than 1,100 Hz, mass-dominated reactance results in greater impedance and reduction in gain, indicated by the vertical purple arrows.

CLINICAL IMMITTANCE TESTING

Immittance, which is derived from the terms ***im**pedance* and *ad**mittance***, is an encompassing term which refers to a family of clinical measures that assess the acoustic-mechanical properties of the middle ear.[8] Immittance measures are derived from acoustic measurements in the ear canal where a speaker presents a "probe" stimulus and a microphone records a "response." For example, in 226-Hz tympanometry, the probe stimulus is the 226-Hz tone, and the response is the complex change in acoustic pressure in the ear canal, which is related to the change in velocity of the air volume (called volume velocity) that is trapped between the probe tip and the tympanic membrane while the latter vibrates in response to the stimulus. The recorded acoustic signal is then computed in units of admittance. Similarly, in multifrequency tympanometry (MFT), multiple probe tone frequencies from 200 to 2,000 Hz are presented to provide more information about the function of the middle ear, including frequency of resonance of the middle ear. As shown in Fig. 3, the magnitude and phase of the response of the middle ear to a series of tones varies with frequency.

In tympanometry, admittance is measured while the static (air) pressure in the ear canal is varied from 200 to −400 daPa. At the extreme static pressure points, the tympanic membrane and middle ear are stiffened, allowing for characterization of the ear canal response to the 226-Hz tone as a simple enclosed volume cavity with minimal contribution from the middle ear. Therefore, at 226 Hz, volume units are directly related to admittance units and can be computed from each other. The clinical utility of this relationship is known for compensation of the ear canal admittance and estimation of ear canal volume. This relationship also allows for simple calibration of the probe in acoustic cavities of known volume, where 1 mmho = 1 mL at 226 Hz.[9] This simple calibration has its drawbacks, including errors for probe frequencies greater than 2,000 Hz, where standing waves in the ear canal create pressure nulls.[10] As well, the underlying assumption of the ear canal as a rigid-walled cavity that does not change with pressurization holds true for older childrens' and adults' ears but not for newborns and infants.[11]

Wideband Acoustic Immittance

In the case of WAI, the probe stimulus is a transient stimulus (a click or a chirp) with acoustic components over a wide range of frequencies. Recordings in the ear canal are dependent on knowledge of probe acoustics (e.g., impedance and pressure), which are determined in the calibration step,[12,13] and sound pressure that is reflected back from the surface of the tympanic membrane and recorded by the probe microphone. Subsequently, the ratio between reflected pressure and the incident pressure of the stimulus is computed, called pressure reflectance. Rather than using a pressure measure, power reflectance has been utilized for clinical measurements. This is because power measures have uniform magnitude between the probe tip and the tympanic membrane and have no phase. By comparison, despite having uniform magnitudes, the phase of pressure measures varies depending on the location of the probe. The computation of power reflectance from ear canal recordings is reviewed in details in Rosowski et al.[14] The uniformness of power reflectance along the dimension of the enclosed ear canal volume is advantageous because reflectance theoretically has the same value at the tympanic membrane and position of measurement with certain limitations as discussed in Voss et al.[15]

Thanks to advancements in probe calibration techniques,[12,13] acoustic measurements can be recorded with accuracy even at frequencies greater than 2,000 Hz, which is not otherwise possible with conventional tympanometry methods. For a detailed review of these calibration techniques, the reader is referred to Rosowski and Wilber.[10] Because of the difference in calibration methods, WAI testing does not require pressurization of air in the ear canal and compensation for ear canal admittance. This presents an advantage for testing in newborns whose immature ear canal walls contract and expand as static pressure is varied. However, because of this methodological difference, it is important to keep in mind that WAI tests do not only measure the acoustic mechanics of the middle ear but are also affected by resonance and gain of the enclosed ear-canal volume between the probe-tip and the tympanic membrane and the mechanics of the ear canal itself.

The advantage of testing using wideband stimuli is that the immittance measures can approximate the transfer function of the outer-/middle ear over a wide range of frequencies using quick and noninvasive procedures. This allows for the clinical evaluation of middle ear acoustic mechanics in healthy and pathological ears.

Wideband Power Absorbance

Power absorbance (also known as energy absorbance or simply absorbance) is defined as the ratio of power absorbed by the middle ear to the incident power.[16] Power absorbance is computed from power reflectance (power absorbance = 1–power reflectance). The value of absorbance ranges from 0 (meaning no acoustic energy was absorbed by the middle ear) to 1 (meaning all acoustic energy was absorbed by the middle ear). Note absorbance values may also be represented as percentages from 0 to 100%.

In normal adult ears, the absorbance pattern is characterized by a broad absorbance maximum between 1,000 and 4,000 Hz and low absorbance outside this frequency range.[17] Fig. 4 illustrates examples of power absorbance measurements as a function of frequency from 5 normal-hearing adults (aged 21–35 years). The 5th to 95th percentile range of the normal absorbance values is plotted across frequencies giving rise to the grey-shaded area (based on Liu et al[18]).The five absorbance measurements exhibit prominent absorbance maxima within the 1,000- to 2,000-Hz range with individual narrow-band variations. Often individual absorbance measurements will exhibit a primary peak between 2,000 and 4,000 Hz and a secondary peak or an inflection point between 1,000 and 2,000 Hz which vary from one individual to another. Normal variations in body size and anatomy may explain these variations (e.g., differences in middle ear volume, age, and gender).[17,19,20]

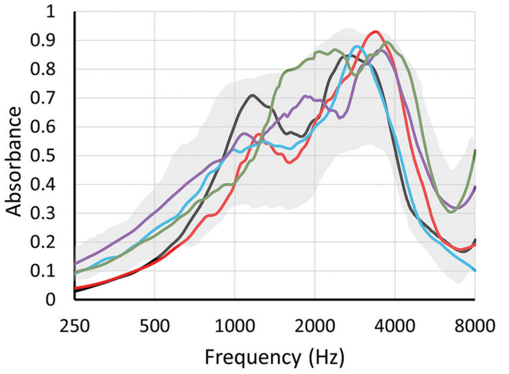

Figure 4 Examples of normal absorbance measurements plotted across frequency from five normal-hearing adults. The normative absorbance range is shown by the grey-shaded area that is bound between the 5th and 95th percentile values across frequency.

Absorbance measurements in the ear canal are dependent on the compound impedance of the middle ear system and the impedance of the ear canal wall. At frequencies where impedance is great, absorbance is low, whereas when impedance is low, absorbance is great. This relationship is illustrated in the example measurement from a normal-hearing adult (Fig. 5), where Panel A shows absorbance versus frequency and Panel B shows the corresponding impedance magnitude versus frequency function. Impedance is high in the low- and mid-frequency range caused by stiffness of the outer and middle ear system, thereby suppressing absorbance in this region. Impedance attains high values in the high-frequency region (> 3,000 Hz) due to mass elements of the middle ear, thereby suppressing absorbance in this region, too. Impedance attains a minimum value near 3,000 Hz in this case which corresponds to the frequency at which maximum absorbance occurs. Panel C of Fig. 5 shows the corresponding phase versus frequency function. Phase attains negative values in the low to mid frequencies, crosses the zero line at 3,000 Hz where minimum impedance and resonance of the system occur, and attains positive phase values beyond 3,000 Hz.

ASSESSMENT OF ABNORMAL SOUND CONDUCTION IN PATHOLOGIES OF MIDDLE EAR

Assessment of the middle ear function requires accurate measures of its impedance, absorbance, middle ear gain, and/or resonance. Normative values of these measures have been established for healthy neonates, children, and adults.[21–23] However, in ears with a conductive condition, their natural mass, stiffness, and resistance elements are modified resulting in different impedance, absorbance, gain, and resonance. Currently, the diagnosis of middle ear

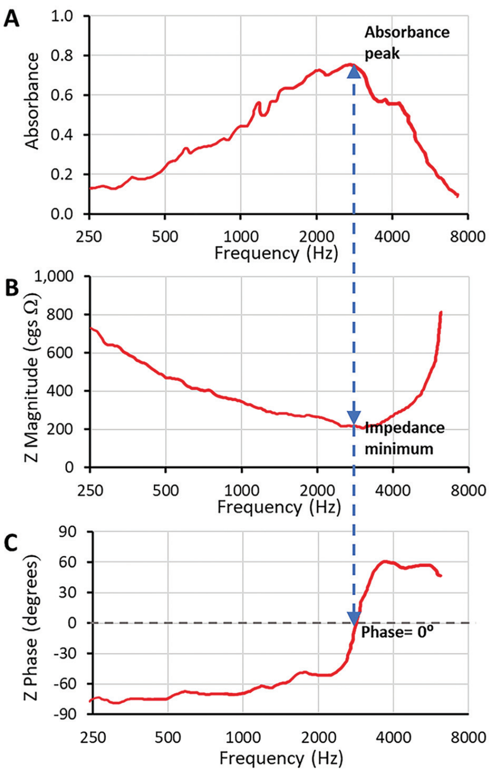

Figure 5 Example of WAI recording from a single healthy young adult showing three derived measures: (**A**) absorbance across frequency, (**B**) impedance (Z) magnitude across frequency, and (**C**) impedance phase across frequency. The vertical dashed blue line, which transverses the three panels, highlights with arrow heads the correspondence among peak absorbance in (**A**), Z magnitude minimum in (**B**), and 0 degrees Z phase in (**C**). The frequency at which these corresponding values occur represents the compound resonance of middle ear system.

dysfunction may be aided by an assessment of absorbance values across a wide range of frequencies. While due emphasis is placed on the value of absorbance at a particular frequency or frequency range, not enough attention has been paid to examining the configuration of the absorbance spectrum which changes depending on the conductive condition or disorder.[24]

Modeling of the middle ear as physical spring–mass–resistance mechanical system provides a theoretical basis for qualitative assessment and interpretation of absorbance pattern across frequencies.[3,25] According to such models, pathology-related changes in mass and/or stiffness are expected to result in differential changes in absorbance across frequencies and affect the frequency at which the main absorbance peak occurs. Consider a middle ear condition where mass is abnormally increased. As explained earlier, the addition of mass increases impedance at high frequencies due to increased mass reactance. Hence, the absorbance configuration is altered with decreased absorbance in the high frequencies and the main absorbance peak shifted to a lower frequency. In contrast, when the stiffness of the middle ear system is abnormally increased, the absorbance configuration is modified with decreased absorbance in the low-mid frequencies and the main absorbance peak shifted to a higher frequency.

The following case examples briefly demonstrate methods for assessment and interpretation of absorbance measurements across frequencies. The data represented in the cases were obtained from clinical research measurements with appropriate IRB approvals. Using the interpretative paradigms discussed earlier, it is possible to also make inferences about the acoustic mechanics of the outer/middle ear (e.g., stiffness, mass, resonance). A more expansive discussion of the application of WAI tests in various clinical populations, together with case examples, is discussed in the subsequent titles of this issue of *Seminars in Hearing*.

Case A: Hypermobile Eardrum

In the case of a hypermobile eardrum, the stiffness of the middle ear decreases, resulting in a decrease in impedance and a corresponding increase in absorbance in the low and mid frequencies. The decrease in stiffness also affects the resonance of the outer and middle ear system, resulting in a shift of the main absorbance peak to a lower frequency. Fig. 6 shows the absorbance results obtained from the right ear of a normally hearing 32-year-old adult with a monomeric tympanic membrane that was confirmed by otoscopic examination. The corresponding 226-Hz tympanogram (not shown) revealed tympanometric peak pressure (TPP) was within normal limits and a static admittance of 1.75 mmho, just outside the normal limits.

Case B: Ossicular fixation

For an ear with ossicular fixation, the ossicular chain is abnormally stiffened, resulting in

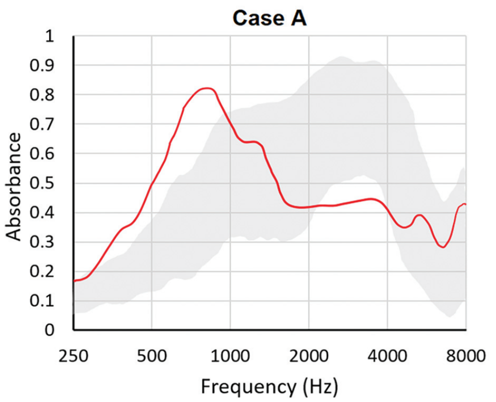

Figure 6 Case example of wideband power absorbance measured in a normal-hearing adult with a hypermobile tympanic membrane. The normative range is shown by the grey-shaded area (defined in caption of Fig. 4). Absorbance peak is abnormally shifted to a low frequency, resulting in abnormal increase in absorbance in the low frequencies, above the 95th percentile of normal. As well, absorbance in the mid-high frequency is reduced below the 5th percentile of normal, which is indicated by the lower bound of the grey-shaded area.

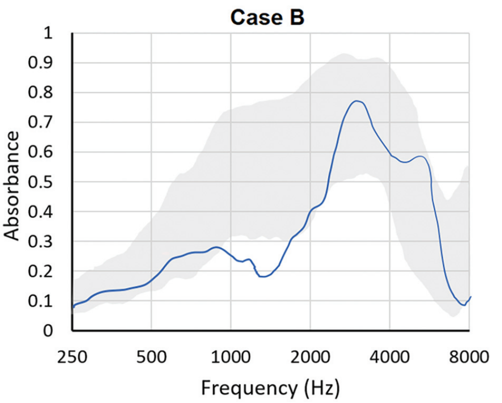

Figure 7 Case example of wideband power absorbance measured in an adult ear with surgically diagnosed otosclerosis, shown along with grey-shaded area of normal (defined in caption of Fig. 4). Absorbance in the low frequencies is generally reduced below the lower bound of the normal range. There is also a subtle high-frequency shift of the absorbance peak.

increased stiffness reactance and, hence, reduced absorbance in the low-mid frequencies. Fig. 7 shows the absorbance results obtained from a 34-year-old male who was diagnosed at the age of 4 years to have ossicular fixation with a mild conductive hearing loss in the left ear. Hearing thresholds have remained unchanged since childhood. Due to increased stiffness of the middle ear, absorbance was reduced in the low- to mid-frequencies with a notch at 1.2 kHz. The associated change in resonance also results in a shift of the main absorbance peak to a higher frequency. Tympanometry findings indicated a TPP of −35 daPa with a static admittance of 0.25 mmho, slightly below the normal range. Ipsilateral acoustic reflexes were absent at 500 to 4,000 Hz in the left ear, but present at stimulus levels of 80 to 85 dB HL in the right ear.

WIDEBAND TYMPANOMETRY

Wideband tympanometry (WBT) is a method by which wideband absorbance is measured repeatedly as ear canal air pressure is swept from +200 to −300 daPa. It generates a three-dimensional plot of absorbance as a function of frequency and ear canal pressure. Absorbance between 250 and 8,000 Hz can be extracted under a chosen applied ear canal pressure, for example, wideband absorbance at 0 daPa (WBA_0).

Furthermore, absorbance measurements extracted at TPP (WBA_{TPP}) can be used to evaluate middle ear function while compensating for the difference between atmospheric air pressure and middle ear pressure. By comparing WBA_0 with WBA_{TPP} results, a clinician can uncover underlying middle ear conditions that may be present in addition to negative middle ear pressure.[23] Currently, there are commercially available instruments with WBT capabilities (Titan device by Interacoustics A/S, and TympStar Pro by Grason-Stadler). The following case example demonstrates measurements, assessment, and interpretations of WBT.

Case C: Negative Middle Ear Pressure and Otosclerosis

A 64-year-old male, who is referred to by the alias name Joshua, was recently diagnosed with a mild sensorineural hearing loss in his right ear and a mild to moderate mixed hearing loss in his left ear. He reported a chronic muffled/blocked sensation in his left ear that he has experienced since childhood, but has never had it investigated. Routine immittance testing revealed a normal, Type A tympanogram in the right ear, and an abnormal, Type C tympanogram in the left ear. Ipsilateral acoustic reflexes were present at 500, 1,000, and 2,000 Hz in the right ear, but absent in the left ear. Following an otologic assessment, Joshua was diagnosed with chronic Eustachian tube dysfunction and otosclerosis (early stage) in the left ear.

WBT was conducted on Joshua's left ear by an experienced audiologist. Fig. 8(A) displays the WBT results in the form of a three-dimensional plot of absorbance as a function of frequency and static ear canal pressure. The color gradient indicates the range of absorbance values between 0% (0) at the red end and 100% (1) at the violet end of the spectrum. In general, this plot shows reduced absorbance in the low to mid frequencies (0.25–1.8 kHz) with notches between 1 and 2 kHz, and grossly normal absorbance in the higher frequencies. The black bold line shows absorbance at a pressure corresponding to the TPP (−136 daPa). These features may be made more clear on a two-dimensional plot as discussed next.

Fig. 8(B) is a two-dimensional absorbance versus frequency plot showing two absorbance measurements that were recorded in the WBT measurement (from Panel A) either at TPP or at 0 daPa. The black curve represents the absorbance at TPP (WBA_{TPP}) where the influence of negative middle ear pressure is counterbalanced. The WBA_{TPP} shows absorbance at or below the 5th percentile from 0.25 to 1 kHz, and normal absorbance beyond 1 kHz. These results reveal atypically high stiffness of the middle ear even after compensation for the negative middle ear pressure, consistent with the diagnosis of otosclerosis.

By comparison, the absorbance at 0 daPa (WBA_0), shown by the blue curve, shows severely reduced absorbance in the low-mid frequencies, and the main peak of absorbance shifted to a higher frequency. This is consistent with the effect of additional increase in stiffness/tension on the tympanic membrane and middle ear, caused by the negative pressure in the middle ear cavity. This illustrates the benefit of testing absorbance at TPP in addition to ambient pressure (Fig. 8B). In this case, testing at TPP did not resolve the abnormal wideband absorbance pattern, thus revealing the underlying middle ear dysfunction free from the effect of middle ear pressure.

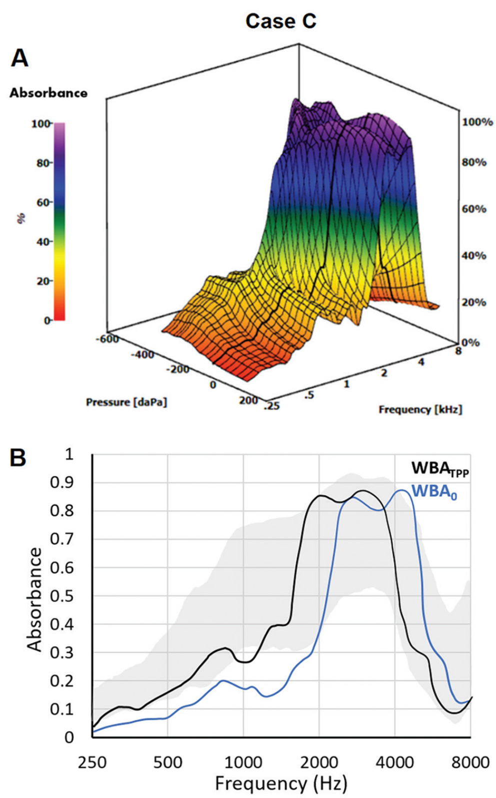

Figure 8 Case example of a wideband absorbance tympanogram (WBT) in an adult ear with negative middle ear pressure, and otosclerosis. (**A**) The WBT is shown as a three-dimensional plot with absorbance on the vertical (z-axis), and frequency and static pressure on the horizontal axes (x- and y-axes, respectively). The violet end of the color spectrum indicates high levels of absorbance, and the red end indicates low levels. The black solid lines indicate absorbance across frequency at −136 daPa, corresponding to the tympanometric peak pressure (TPP). (**B**) Wideband power absorbance (WBA) measurements extracted from the WBT in panel **A** at two static pressure points: ambient pressure at 0 daPa (WBA_0) and at TPP (WBA_{TPP}). Both WBA measurements are reduced in the low frequencies, but the WBA_0 shows greater reduction below the lower bound of the shaded area of normal (defined in caption of Fig. 5) in comparison to WBA_{TPP}. In addition, WBA_0 shows a greater high-frequency shift of absorbance maxima.

CONCLUSIONS

This article has provided an overview of the principles underlying the measurement of acoustic impedance in a middle ear system with contributions from interactions of the mass, stiffness, and resistance components. The association between impedance and gain is demonstrated by the middle ear transfer function with implications for distinctive sound conduction characteristics using wideband absorbance measures. The wideband absorbance measure is based on the principles of measurement of acoustic impedance, and is therefore not an entirely novel measure, at least conceptually. Instead, it is an advancement to existing aural acoustic-immittance measurements, which enables evaluation of middle ear function across the audible frequency spectrum (250–8,000 Hz). The assessment and interpretation of wideband absorbance measures demonstrated in the above case studies are guided by these principles.

CONFLICT OF INTEREST

None declared.

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