Chapter 3

Wideband Tympanometry

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Additional information is available at the end of the chapter

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Abstract

The wideband tympanometry (WBT) assesses the middle ear function with a transient wideband stimulus in order to capture the middle ear behavior at a wide range of frequencies. Data in the literature suggest that the WBT has more sensibility to detect middle ear disorders than the traditional tympanometry. In this context, pathologies, which might be more easily identified/monitored by WBT, include otosclerosis, flaccid eardrums, ossicular chain discontinuity with semicircular canal dehiscence, and negative middle ear pressure with middle ear effusion. The chapter presents information on classical tympanometry, the multifrequency tympanometry equivalent coded as WBT, clarification of terms used in WBT measurements, and a short overview of clinical applications in infants and adults.

Keywords: acoustic immitance, tympanometry, wideband tympanometry, acoustic reflectance, acoustic absorbance

1. Introduction to tympanometry

Sound stimuli can be modified by alterations of the middle ear functionality; therefore, an assessment of the middle ear function is fundamental for a proper evaluation of hearing impairment. Acoustic immittance is a general term referring to measurements related to tympanometry and acoustic stapedial reflexes, which can provide information about the middle ear (ME) status. Tympanometry measurements represent alterations in the sound absorbance characteristics of the ME system (composed by the tympanic membrane + the middle ear), as the pressure in the external acoustic canal is modified. Clinically, these pressure values range from +200 to -400 daPa. According to Shanks and Lilly [1], the most accurate measurements are those in the low pressure end.

The ME ossicular structures drive the incoming sound stimuli from the eardrum (maleus) to the inner ear (footplate of the stapes). In terms of acoustic energy transmission, there is a physical problem interfacing the middle and the inner ear. The middle ear propagation medium is gaseous while the inner ear medium is liquid. To optimize the propagating stimulus energy, it is necessary to adjust the ME impedance so that the stimulus at the stapes undergoes an "*optimal power transference into the inner ear*" also called "*minimum impedance reflection*." This operation is termed as "*the middle ear impedance matching transformer*" [2, 3] and describes the efficiency by which the acoustic sound energy at the stapes is transformed into an acoustic pressure wave inside the helix structures of the inner ear, without significant energy losses.

There is a specific terminology in the ME measurements: There is an excellent review of these terms by Block and Wiley [4] and by Hall and Chandler [5]. Most of the ME measurements refer to *acoustic immittance* values, which describe the *easiness* by which a sound stimulus can propagate across a medium (air or liquid). Most media impose a resistance to any type of propagation energy. According to this concept, the structures of the ME impose a *resistance* to the propagation of the sound energy, and this opposition/resistance is termed as *acoustic impedance* $Z(\omega)$. By definition, the reciprocal value of acoustic impedance is *acoustic admittance* $Y(\omega)$. In this context an acoustic immittance measurement can refer to either $Z(\omega)$ or $Y(\omega)$ and the measurement is conducted with the same manner. The $Z(\omega)$ and $Y(\omega)$ variables are complex and they are characterized by a real and an imaginary part. In clinical terms, this characteristic means that the values of these depend on the frequency (ω) of the propagating stimulus. There is another measurement called "static immittance" which refers to measurement under a normal atmospheric pressure (i.e., not varying) and according to Hall and Chandler [5] clinically this can be measured at 226 Hz.

Traditional tympanometry assesses the impedance of the middle ear at the frequency of 226 Hz. The measurement modality is described in **Figure 1**, and it is conducted with a sensitive probe, which seals completely the ear of the patient. Once the 226 Hz tone is emitted, the pressure variation in the external acoustic meatus displaces the eardrum. This causes the tone absorption of the ME to vary, and a sensitive microphone incorporated in the probe evaluates the total admittance of the system [2].

Tympanometry provides quantitative information about the presence of fluid in the ME, about the mobility of the tympanic-ossicular system, and about the volume of the external acoustic meatus. While it is an effective procedure to identify ME changes in children, adults, and seniors, it has its limitations. For example, there are reported cases in the literature of myringotomy surgeries where the 226 Hz tympanometric data were reported as normal [6]. Assessment outliers like these myringotomy cases, are probably caused by a lack of specific norms for the different types of populations under assessment. It is well known that the eardrum and the external acoustic meatus of neonates and children are anatomically different than those from adult subjects. In this context, the ME impedance norms of one population do not describe well the norms of the other.

Data in the literature suggest that in infants of approximately 6 months of age, the high-frequency ME transmission is more efficient. Tympanometry measurements with a high-frequency tone (1000 Hz) can be more sensitive to identify ME changes than those conducted

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with a 226 Hz probe tone [6–8]. High frequency tympanometry has been shown to be reliable and highly reproducible. But the data in the literature also suggest that the 1000 Hz protocol cannot always identify all children with ME alterations. As a result, discrepant data between studies are reported, as well as reports describing an interpretation difficulty of the 1000 Hz impedance tracing [9, 10]. The 1000 Hz tympanometry trace is different than the traditional trace of 226 Hz. For many subjects the 1000 Hz trace presents a double peak and its clinical interpretation can be quite complicated [11].

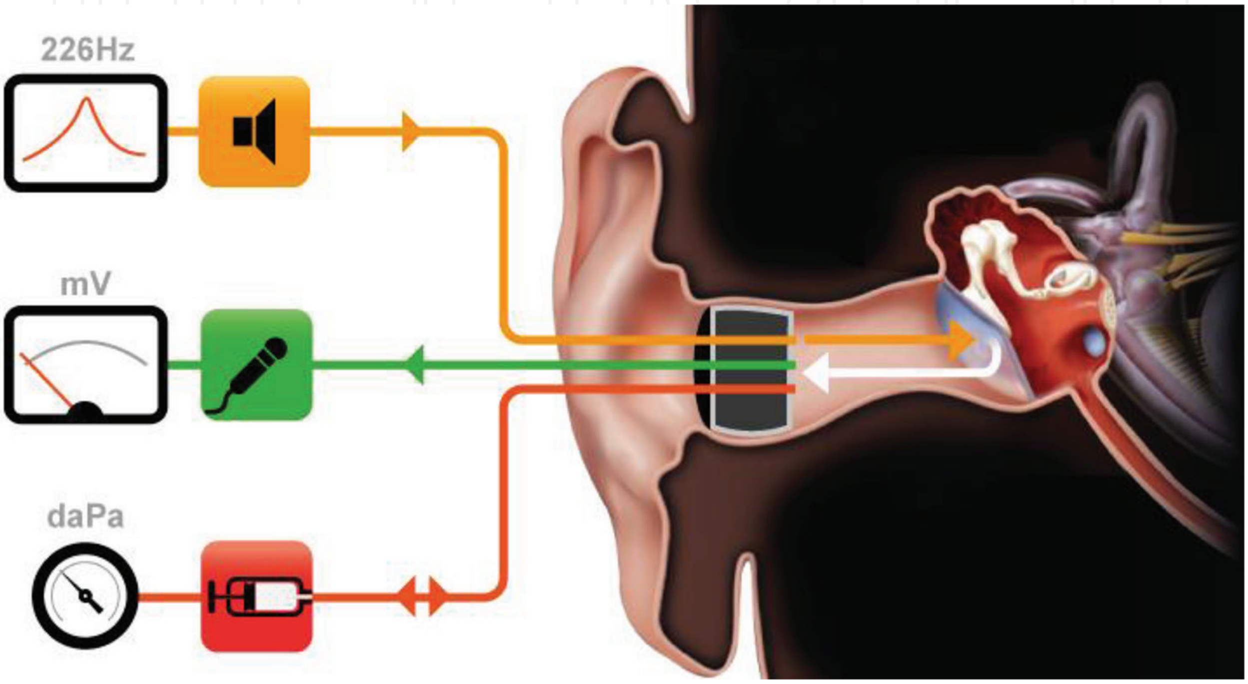

Figure 1. The tympanometry probe (shown with three major components) seals the ear of the patient. The components shown include the microphone, the pressure regulation system, and a speaker transducer.

A differential diagnosis for the evaluation of middle ear function is essential for infants presenting ME disorders, as in the case of temporary conductive hearing losses. This aspect is critical, because there is high incidence of unsuccessful results (FAIL) in neonatal hearing screening programs. These results are frequently caused by changes in the ME status and affect significantly the time and spectral characteristics of the transiently evoked otoacoustic emissions (TEOAEs), which are routinely used in the hearing screening protocols [12–15].

2. Wideband tympanometry

2.1. Description and instrumentation

As described in the previous section, the traditional tympanometry probe-tone at 226 Hz evokes different results depending on the anatomical characteristics of the ME cavity, which can influence the test results. The use of a wideband stimulus (i.e., acoustic click, chirp) has been shown to be more efficient and precise for a ME assessment. Because of the presence of multiple frequencies in the transient stimuli, wideband tympanometry (WBT) is less susceptible to myogenic noise, which originates from the patient movements [3, 16].

The WBT evaluates the ME function with a transient stimulus (click or chirp) testing frequencies from 226 to 8000 Hz, in small incrementing steps. Assessment of ME function over such a broad bandwidth provides detailed information on the ME status and can assist considerably any needed diagnosis.

Currently, there are two families of devices in the market, which offer WBT measurements: (i) the Otostat, and the HearID systems from Mimosa Acoustics, USA; and (ii) the Titan system from Interacoustics, Denmark. As in the traditional tympanometry, WBT is performed by placing a sealing probe into the external auditory canal. The probe contains a microphone, a pressure system, and a speaker transducer. The Mimosa devices are PC-independent, while the Titan requires a PC connection to perform the WBT measurements. **Figure 2** shows the WBT data from the Otostat system, displayed on a PC running the Otostation data management software. All the other figures in the text are generated using WBT data from the Titan device.

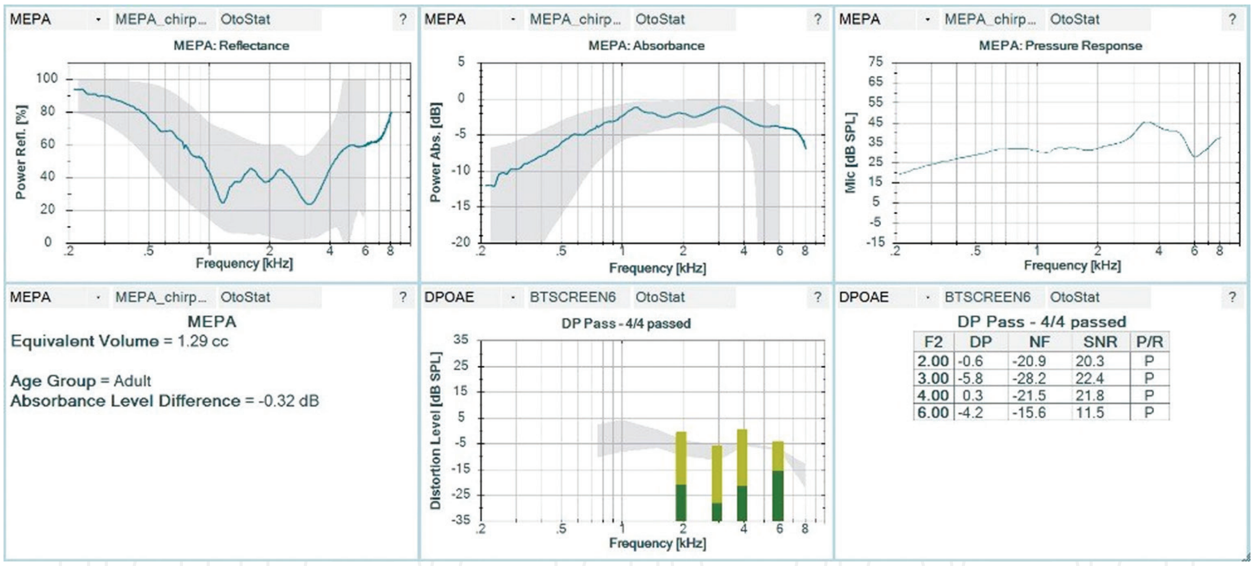

Figure 2. WBT data from the Otostat system (Mimosa Acoustics). The panels indicate WBT reflectance, absorbance, and pressure response × tested frequency (the Otostat uses a chirp stimulus). The lower panels show the distortion product OAEs in terms of spectrum and S/N ratios at the four tested frequencies. The WBT + OAE combination favors a good assessment of the ME function in neonates, and it can be used to avoid many REFER or FAIL results.

Interacoustics follows the philosophy of presenting the WBT data not in the traditional 2D manner but in a 3D format, depicting pressure (*y*-axis), frequency (*x*-axis), and absorbance (*z*-axis). An example of this 3D representation is shown in **Figure 3(A)** and **(B)** where neonatal WBT responses are depicted. The 3D graph can rotate, so the user can identify patterns in the 3D contour, which might be of interest. So far there are no data in the literature connecting the 3D pattern variations with some clinical observations. The main reason for this is the enormous amount of data (and the large number of variables represented) in the 3D graph.

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Higher absorbance values suggest a more efficient ME (**Figure 3A**). Lower values suggest some sort of energy impediment in the ME structure, with a very good probability of a hearing impairment (**Figure 3B**). Interacoustics offers in the 3D graph, an absorbance scale which is color-coded with maxima in the blue and minima in the red color region. The scale is subject-dependent and it is not normalized (thus serves only as a visual aid).

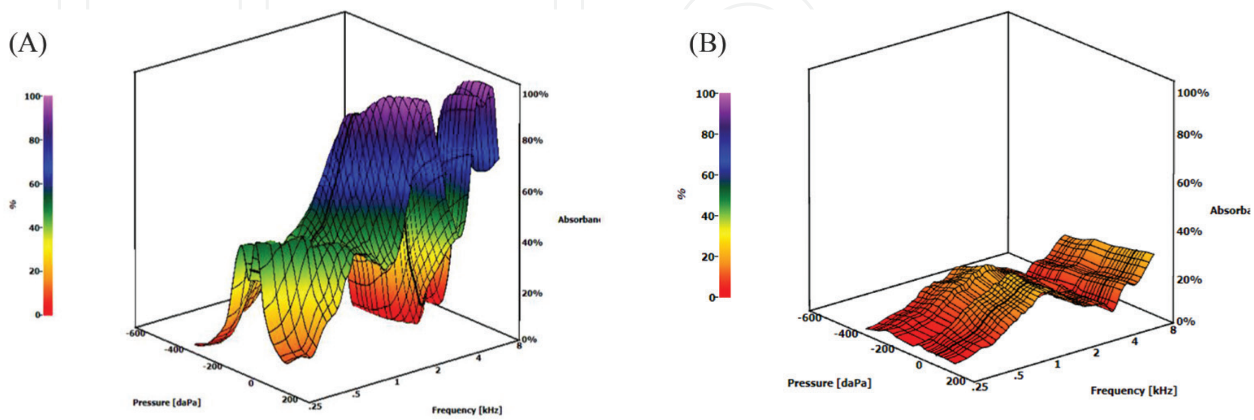

Figure 3. (A): Neonate normal WBT data. The subject passed a TEOAE screening test and it is considered as normal. The 3D curve is color-coded, showing good values in blue (high absorbance) and lower or possibly problematic absorbance values in red. The scale is relative to this subject and it is used for a visual aid. In the Appendix there are links from where the readers can download a video (avi file) showing how this 3D structure can be rotated or collapsed, in order to obtain specific frequency information. (B) Neonate WBT data from a infant who failed the TEOAE screening test. The 3D curve is color-coded, showing lower or possibly problematic absorbance values in orange red. The scale is relative to this subject and it is used for a visual aid. In the Appendix there are links from where the readers can download a video (avi file) showing how this 3D structure can be rotated or collapsed, in order to obtain specific frequency information.

2.2. Absorbance and related measurements

It is possible to collapse a number of frequencies and obtain absorbance data over an averaged frequency range (wideband averaged tympanogram), which might offer better clinical estimates for well babies and NICU residents. The WBT average range used in infants is from 800 to 2000 Hz, because it is optimized for ME transmission anomalies such as ME negative pressure and ME with effusion. In this frequency range these pathologies generate 3D graphs presenting major and significant differences between normal and abnormal ears.

According to Interacoustics, the WBT average range in adults is defined from 375 to 2000 Hz. Using average WBT data in this range it is possible to discriminate well WBT responses between children and adults. Interacoustics suggests to average the WBT data starting from 375 Hz and not from 226 Hz, since the latter frequency does not offer a high discriminative value.

It is also possible to obtained absorbance information at the resonance ME frequency, which corresponds to the frequency where mass and stiffness contribute equally to the absorbance (response with a zero phase). The resonance frequency can be useful in the diagnosis of ME abnormalities such as the disjunction of the ossicular chain or otosclerosis. For cases of ossicular chain discontinuity or of other pathologies presenting a dominant ME mass, the resonance frequency of the middle ear tends to be reduced. In the case of otosclerosis, the resonance frequency shifts to higher frequencies [17, 18]. Monitoring the resonant frequency seems to be promising as a method to follow the clinical progression of otosclerosis. It is also possible to obtain the "resonance frequency tympanogram," which is useful in the differentiation between cases of ossicular disruption and a flaccid eardrum [17–19].

From the 3D-WBT graph, it is possible to obtain information about the absorbance at a particular frequency measured in ambient pressure or at the pressure of the middle ear (see Appendix section for a video showing how this is accomplished). The acoustic absorbance (A) is defined as the ratio of (absorbed sound power)/to (incident sound power). Pathologies that can be further monitored or identified with this data modality are: otosclerosis, flaccid eardrums, ossicular chain discontinuity, and semicircular canal dehiscence and babies with negative middle ear pressure and middle ear effusion [20, 21]. The WBT devices from Mimosa Acoustics utilize the concept of acoustic reflectance. Reflectance is the amount of energy reflected by the system in relation to total energy propagating through the system, and it is measured in percentage. The reader might find useful terminology reviews by Hall and Chandler [5] and by Stinson [22].

Several publications indicate that the graph of absorbance allows a better differentiation between middle ear diseases than the traditional tympanometry. There are groups of patients where the pressurization of the ear can be difficult or unwise. Thus, an absorbance test held in nonpressurized conditions will be useful for monitoring middle ear state immediately after surgery, with perforated eardrum during neonatal hearing screening. In several studies performed in ambient pressure proved to be able to detect changes in middle ear function significantly for infants and neonatal measurements [23, 24]. In the case of patients with ventilation tubes in the eardrum, data from Groon et al. [25], suggest that: (i) for any leak larger than 0.25 mm there are absorbance alteration effects up to 10 kHz; (ii) above 1 kHz these effects are unpredictable; and (iii) absorbance values were mostly increased in the lower frequency bands (0.1–0.2 and 0.2–0.5 kHz).

Data from Keefe and Simmons [26] suggested that the absorbance measurements, if they are conducted at peak pressure level, are more sensitive to ME pathologies and complications. Analytically they have reported "comparing tests at a fixed specificity of 0.90, the sensitivities were 0.28 for peak-compensated static acoustic admittance at 226 Hz, 0.72 for ambient-pressure WBT, and 0.94 for the pressurized WBT. Pressurized WBT was accurate at predicting conductive hearing loss with an area under the receiver operating characteristic curve of 0.95."

3. Clinical applications

3.1. Otosclerosis

Otosclerosis is a disease that affects the ME and causes progressive hearing loss, occurring predominantly in women (predominant age range 20–30 years). In most cases, the disease manifests bilaterally through calcification and an abnormal growth of the Stapes. In patients

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with otosclerosis, the absorbance measures can identify an eardrum-ossicular system rigidity with more details. During the progression of the disease, the fixation of the stapes in the oval window worsens, making the ME transmission of energy very difficult [17, 27].

WBT provides more detailed and specific information on the eardrum-ossicular system and allows a differential diagnosis of otosclerosis. According to the data from Shahnaz et al. [18], the most prominent change in the absorbance pattern following an otosclerosis surgery is a sharp and deep drop in absorbance values in the range between 700 and 1000 Hz. There is also a secondary wider and smaller increase in absorbance, following the surgery, between 2000 and 4000 Hz. **Figure 4** shows a typical absorbance profile of an otosclerosis patient. The peak absorbance value has been shifted to higher frequencies, approximately at 2.8 kHz.

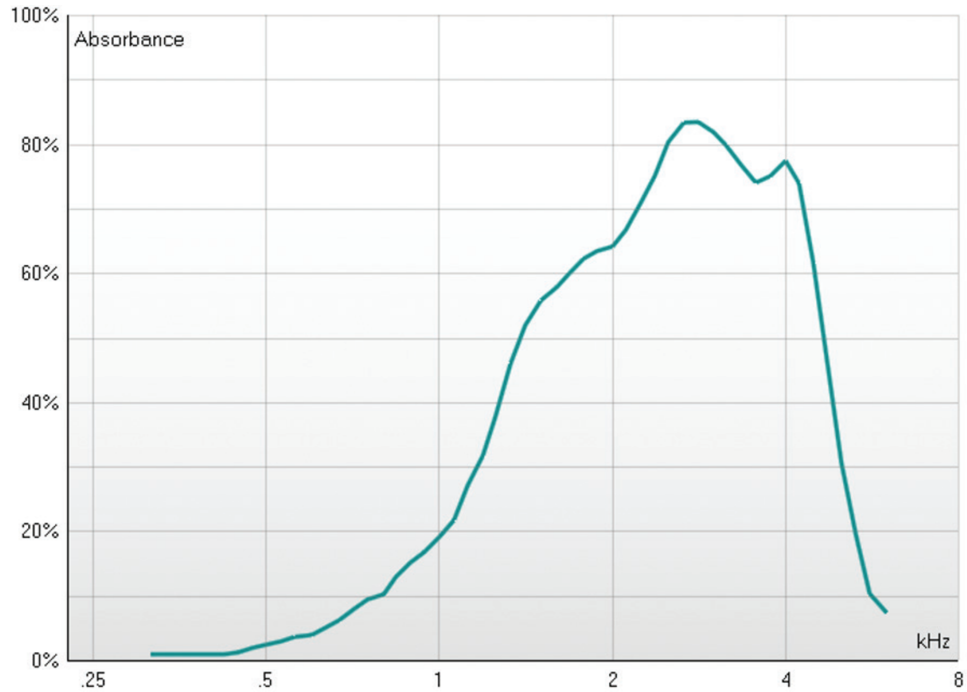

Figure 4. The characteristics of the absorbance graph (which is obtained by collapsing the pressure axis in the 3D-WBT graph) of the case of a patient presenting otosclerosis.

3.2. Immittance in neonates

Growth and thus changes in auditory canal occur rapidly in the first 6 months of life when they reach adult size. Among the possible outcomes in neonatal hearing screening program, there are false positives that may result from differences in the development of ear structures that harm the impedance mechanism [23, 28]. Due to the presence of amniotic fluid, meconium mesenchyme or the external auditory canal may cause temporary changes in hearing. These alterations increase the mass, stiffness, and resistance of the eardrum-ossicular system and consequently alter the middle ear of impedance and efficient sound of conduction [29, 30].

At birth, the neonatal external and middle ear are not fully developed. The external auditory canal is surrounded by a thin layer of elastic cartilage [31]. When performing the pressurization, as occurs in typical tympanometry, the diameter of the external auditory canal can increase or decrease depending on the applied pressure. As the infant grows, the ossification of the external canal increases its rigidity. It also increases the length of the canal, which decreases the canal's resonance frequency [23]. The eardrum will eventually decrease in thickness, will increase in size, and will modify its inclination. Changes occur in the ME as well. Data from Proctor [32] and Holborow [33] show that the neonatal Eustachian tube is shorter [30 mm], and almost horizontal [32]. The Eustachian tube opens effectively but closes more slowly, resulting in tubal inefficiency. The Eustachian tube develops slowly reaching full maturity at the age of 7 years with increased length and steepening. This may explain higher prevalence of otitis media associated with upper respiratory tract infections in early childhood [33, 34].

A number of studies have shown [23, 28, 35] that the majority of the significant modification to the values of wideband absorbance occurs is the first 6 months of life, due to the development of the external and middle ear. During this period, there is an "absorbance immaturity" at low frequencies and an absorbance significant increase in the high frequencies. After this period, the absorbance measurements start to approach the absorbance values reported from adult subjects. **Figure 5** shows a typical neonatal average absorbance (0.8–2.0 kHz) curve, from an infant who has passed the neonatal screening TEOAE test.

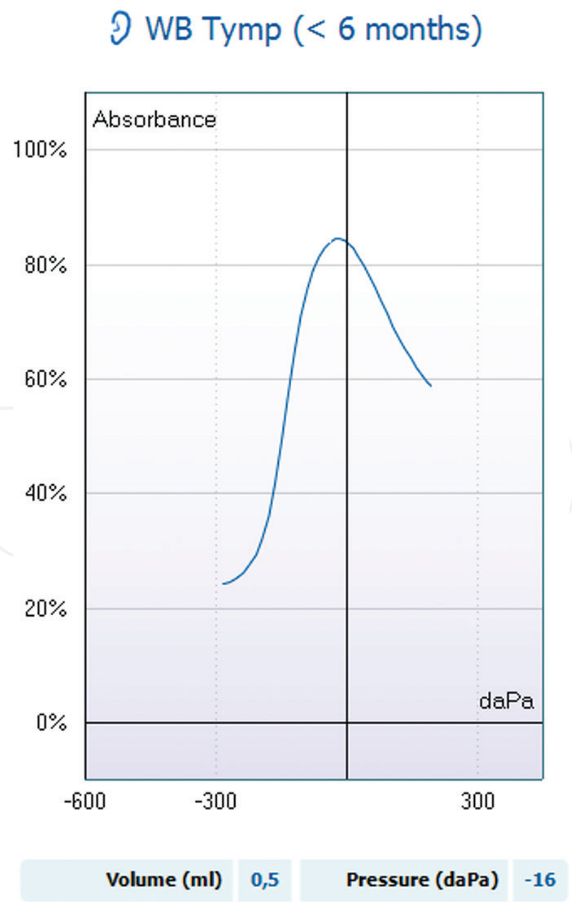

Figure 5. Example of wideband averaged tympanogram in a neonate with a normal function ME and a PASS from the TEOAE assessment.

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Because of the difference in the size of the ear canal, between an adult and a neonate, the absorbance measurements between these populations differ considerably. In the neonates, absorbance shows low values at the low frequencies and then a decrease approximately at the frequency of 6.0 kHz [36–38]. The latter also depends on the stimulus bandwidth. Some commercial systems like the Titan from Interacoustics use a stimulus bandwidth of 8 kHz.

Many references in the literature, i.e., [36–38], use and report reflectance values in their WBI assessment. **Figure 6(A)** and **(B)** shows normative neonatal data from reflectance and absorbance curves (10–95 percentiles). The reader can see that the reflectance curve can be deduced from the inverse of the absorbance curve.

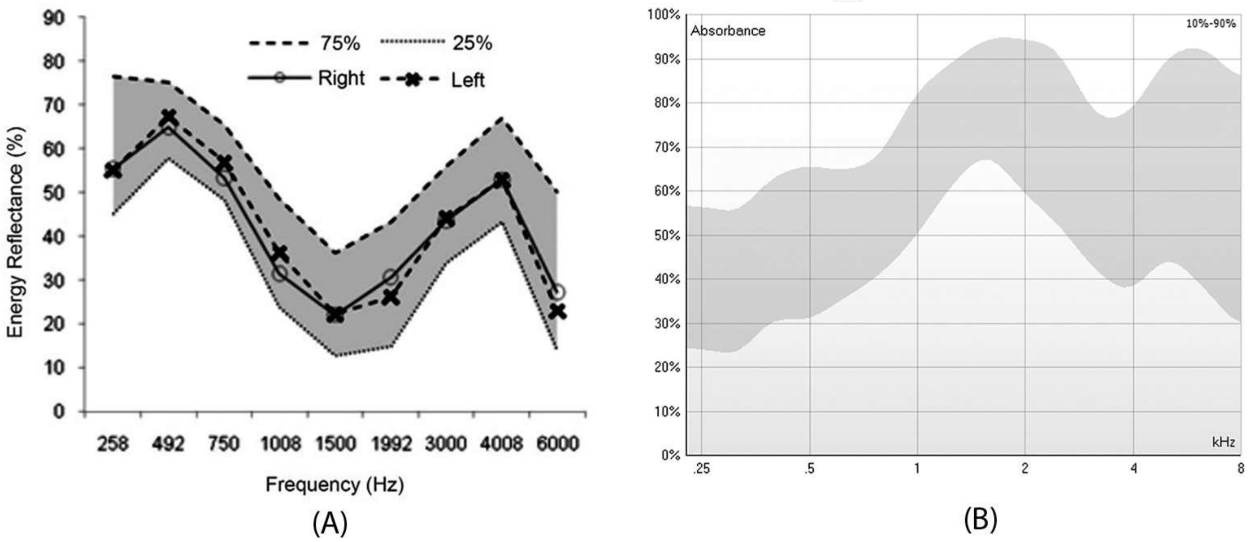

Figure 6. (A) This graph shows the normal Reflectance zone (25–75 percentiles) for neonatal WBT responses, as reported by Silva et al. [37]. The reflectance curve shows low averaged values (<25%) at the mid frequencies 1.0–2.0 kHz. Two peaks are shown, one at approximately 0.5 kHz (65%) and the other at 5.0 kHz (55%). Due to the fact that different systems were used for the generation of (A) and (B), the data in (A) are not perfectly inverse of the data of (B). (B) This graph shows the normal absorbance zone (10–90 percentiles) for neonatal WBT responses, in the Titan device. The absorbance curve shows low values (<50%) at frequencies <1.0 kHz and above 6.0 kHz. Two absorbance peaks are shown one at approximately 2.8 kHz (85%) and 5.0 kHz (82%).

4. Consensus on the terminology and research objectives

During the 2012, Eriksholm Workshop [39] sponsored by the Oticon Foundation (November 5–7, 2012), an array of consensus statements was developed, regarding the emerging field of wideband immittance measurements. These are summarized below:

(1) The term wideband acoustic immittance (WAI) describes all measurements referring to impedance or power-based variables as the power reflectance.

(2) The term transmittance, which has been defined as (1 minus power reflectance), should be used any more. It should be substituted by the term absorbance, defined as (1 minus power reflectance).

(3) The term aural acoustic immittance was chosen to describe measures of impedance and admittance in the current American National Standards Institute standard for devices to measure aural acoustic immittance (American National Standards Institute S3.39-1987-R2012).

(4) Future publications or datasets should mention: population means, population variance, effect size, and sensitivity and specificity for detecting pathologies. The frequency resolution of measurements should be specified in all research reports.

(5) The WAI data should be interpreted in light of the patient history, the physical examination, and other auditory tests.

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Appendix

Readers have the possibility to see how the Titan data (**Figure 3A** and **B**) can be manipulated in 3D, in order to observe other aspects of the 3D-WBT graph, collapsing one axis in order to see the absorbance at a particular stimulus frequency. The corresponding videos can be downloaded from the OAE Portal at the address:

http://www.otoemissions.org/index.php/en/?option=com_content&view=article&id=261

Glossary of terms

- *Acoustic absorbance* (A): The amount of acoustic energy absorbed by the ossicular chain, during the stimulus propagation. It is defined as the ratio of (absorbed sound power)/to (incident sound power) or as (1 – Reflectance^2).
- *Acoustic admittance* $Y(\omega)$: The inverse of Impedance (i.e., the facility of propagation in a medium). It is also a complex variable and stimulus frequency dependent.
- Acoustic immittance: Measurement of the sound energy flow in a medium. The immittance can be either in terms of acoustic impedance (resistance) or acoustic admittance (easiness).
- *Acoustic impedance* $Z(\omega)$: “Resistance” that a sound stimulus experiences while passing through various media. It is a complex variable and stimulus frequency dependent.
- *Acoustic reflectance*: The acoustic energy, reflected backwards, when an acoustic stimulus propagates forward in a medium (i.e., through the ossiculare chain). It is defined as (1-A).

- *Aural acoustic immittance*: Term chosen to describe measures of impedance and admittance in the current American National Standards Institute standard for devices to measure aural acoustic immittance.
- *ME*: Middle ear.
- *MEPA*: Middle Ear Power Analysis, a term which has been coined for the Mimosa Acoustic family of devices offering acoustic immittance measurements.
- *NICU*: Neonatal Intensive Care Unit.
- *Optimal power transference*: The term is used to indicate that the sound stimulus from the stapes enters (i.e., propagates) the inner ear structures with very little energy losses.
- *Otoacoustic emissions* (*OAEs*): Responses elicited from the inner ear, after its stimulation with a transient or continuous stimulus. TEOAEs are evoked by acoustic click stimuli and they are the most used protocol in Neonatal Hearing Screening (NHS). DPOAEs are evoked by two frequency tones, having a specific frequency ratio between them.
- *Static immittance*: Measurement of acoustic immittance at ambient (i.e., normal pressure conditions).
- *WAI*: Wideband acoustic immitance, according to a consensus in 2012 [39] this is the proper term to use. The term WBT (see below) belongs to the family of measurements under WAI.
- *WBT*: Wideband tympanometry.

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