Wideband Reflectance in Neonatal Intensive Care Units

DOI: 10.3766/jaaa.19.5.4

Navid Shahnaz*

Abstract

Background: Wideband reflectance (WBR) provides important information about middle ear function and can explain variations in how the middle ear receives, absorbs, and transmits sound energy across a wide range of frequencies. However, as of yet, few normative studies have been published to guide clinicians in the practical applications of WBR. WBR has been measured more extensively in well babies than in neonatal intensive care unit (NICU) babies, who have significantly higher incidence of otitis media with effusion (OME).

Purpose: The goal of this study was to explore the characteristics of the middle ear while using energy reflectance (ER) and normalized admittance in NICU babies who passed automated auditory brainstem response (AABR) and evoked otoacoustic emission (EOAE) hearing screening criteria and to compare these characteristics to patterns in normal hearing adults. This study was done to identify ways to implement WBR so it could improve hearing assessment in newborns.

Methods: Thirty-one neonatal intensive care unit (NICU) babies with an average gestational age (GA) of 37.8 weeks (range: 32–51 weeks) and 56 adults with normal hearing between the ages of 18 and 32 years served as subjects in this study. NICU babies and adults were tested using multifrequency tympanometry (MFT) and WBR.

Results: WBR can be obtained on what appears to be a majority of NICU babies without other abnormal findings. Maximum absorption of the incident energy appears to occur at a narrower range of frequencies in normal NICU babies in comparison to normal hearing adults. This range becomes even narrower in NICU babies who fail EOAE screening. In most NICU babies who failed EOAE screening, ER values were closer to 1 (most incident energy is reflected) at a frequency below 3000 Hz. The measurements of normalized acoustic admittance may also be very useful and may supplement ER and tympanometric data in evaluating middle ear status.

Key Words: Admittance, energy reflectance, middle ear, neonatal intensive care unit, otitis media, transient otoacoustic emission, wideband reflectance

Abbreviations: AABR = automated auditory brainstem response; ABR = auditory brainstem response; CGA = corrected gestational age; CI = confidence interval; EEOA = evoked otoacoustic emission; ER = energy reflectance; GA = gestational age; G-G = Greenhouse and Geisser; HSD = honestly significantly different; MFT = multifrequency tympanometry; NICU = neonatal intensive care unit; OME = otitis media with effusion; SA = static admittance; SNR = signal-to-noise ratio; TEOAE = transient otoacoustic emission; WBR = wideband reflectance; Y = admittance

Sumario

Antecedentes: La reflectancia de banda ancha (WBR) proporciona información importante sobre la función del oído medio y puede explicar las variaciones de como el oído medio recibe, absorbe y transmite la energía sonora a lo largo de un amplio rango de frecuencias. Sin embargo, pocos estudios normativos han sido publicados para guiar al clínico en las aplicaciones prácticas de la WBR. La WBR ha sido medida más extensivamente en niños sanos que en bebés de la unidad de

School of Audiology and Speech Sciences, Faculty of Medicine, University of British Columbia, Vancouver, British Columbia

Navid Shahnaz, School of Audiology and Speech Sciences, Faculty of Medicine, University of British Columbia, 2177 Westbrook Mall, Friedman Building, Vancouver, British Columbia, Canada V6T 1Z3; Phone: 604-822-5953; Fax: 604-822-6569; E-mail: nshahnaz@audiospeech.ubc.ca

Portions of this paper were presented by Navid Shahnaz and D. R. Stapells at the XIXth International Evoked Response Audiometry Study Group (IERASG) Biennial Symposium, June 2005, Havana, Cuba.

cuidados intensivos neonatales (NICU), quienes tienen una incidencia significativamente mayor de otitis media con efusión (OME).

Propósito: La meta de este estudio fue explorar las características del oído medio al utilizar reflectancia de energía (ER) y admitancia normalizada en bebés de NICU, quienes pasaron criterios de tamizaje auditivo en pruebas de respuestas auditivas automáticas del tallo cerebral (AABR) y emisiones otoacústicas evocadas (EOAE). Además, se buscó comparar estas características a patrones de adultos con audición normal. Este estudio fue hecho para identificar formas de implementar WBR para mejorar la evaluación auditiva en recién nacidos.

Métodos: Treinta y un bebés de la unidad de cuidados intensivos neonatal (NICU) con una edad de gestación (GA) promedio de 37.8 semanas (rango de 21-51 semanas) y 56 adultos con audición normal, con edades entre 18 y 32 años, fueron los sujetos de este estudio. Tanto los bebés de la NICU como los adultos fueron evaluados con timpanometría de multi-frecuencia (MFT) y WBR.

Resultados: La WBR puede obtenerse en lo que parece ser una mayoría de bebés de la NICU sin ningún hallazgo anormal. La absorción máxima de la incidencia de energía parece ocurrir en un rango más estrecho de frecuencias en los bebés normales de NICU en comparación con los adultos normoyentes. El rango se vuelve aún más estrecho en bebés de la NICU que fallaron el tamizaje con EOAE. En la mayoría de los bebés de la NICU que fallaron el tamizaje con EOAE, los valores de ER fueron cercanos a 1 (la mayor parte de la energía es reflejada) a una frecuencia por debajo de 3000 Hz. La medición de admitancia acústica normalizada puede también ser muy útil y puede complementar la ER y los datos timpanométricos para evaluar el estado del oído medio.

Palabras Clave: Admitancia, reflectancia de energía, oído medio, unidad de cuidado intensivo neonatal, otitis media, emisión otoacústica transitoria, reflectancia de banda ancha

Abreviaturas: AABR = respuestas auditivas automáticas del tallo cerebral; ABR = respuestas auditivas del tallo cerebral; CGA = edad de gestación corregida; CI = intervalo de confianza; EEOA = emisión otoacústica evocada; ER = reflectancia de energía; GA = edad de gestación; G-G = Greenhouse y Geisser; HSD = diferencia honestamente significativa; MFT = timpanometría de multifrecuencia; NICU = unidad de cuidado intensivo neonatal; OME = otitis media con efusión; SA = admitancia estática; SNR = tasa señal-ruido; TEOAE = emisión otoacústica transitoria; WBR = reflectancia de banda ancha; Y = admitancia

INTRODUCTION

Wideband reflectance (WBR) is a relatively new middle ear analysis technique. WBR measures middle ear function—often at ambient pressure across a much wider frequency range than multifrequency tympanometry (MFT) (Allen, 1986; Keefe et al, 1992; Keefe et al, 1993; Voss and Allen, 1994).[1] WBR, like tympanometry, can also be conducted at different ear-canal air pressure points (Piskorski et al, 1999; Margolis et al, 2001; Keefe and Simmons, 2003). Pressure reflectance R (f) is a complex number that is the ratio of the forward-moving (incident) pressure wave to the reflected (retrograde) pressure wave. The square of the pressure reflectance magnitude is called the power reflectance $[R\ (f)]^2$ or energy reflectance (ER) (Allen et al, 2005). Therefore, ER is not a complex number and varies from 0, where all sound energy is absorbed by the middle ear, to 1, where all sound energy is reflected by the middle ear (Stinson, 1990).

Power-based measures such as WBR provide important information about middle ear function (Keefe et al, 1993) and can explain variations in how the middle ear receives, absorbs, and transmits sound energy. The middle ear is most efficient at absorbing energy in the 2-to-4–kHz range (Keefe et al, 1993). Preliminary studies have shown that WBR has real potential for detection of otitis media with effusion (OME) and for prediction of conductive hearing loss in adults, children, and newborns (Jeng et al, 1999; Margolis et al, 1999; Piskorski et al, 1999; Keefe et al, 2003; Keefe and Simmons, 2003).

Keefe and Levi (1996) measured ER in normal adults and in healthy 1-month-old and 6-month-old infants. Their results revealed a clear separation in ER between 1-month-old infants and adults for responses below 700 Hz, with infants having lower ER values than adults. The ear-canal cross-sectional area was considered to be major contributing factor in distinguishing infant from adult responses. Keefe et al (2000) measured ER in 4031 neonatal ears. The researchers found that left ears are acoustically stiffer than right ears, and female ears are acoustically stiffer than male ears. Although the air pressure is often not changed in ER measurements, the quality of recording requires a good probe seal in the ear canal. Keefe et al (2000) also noticed that ER may be sensitive to the presence of vernix and other material in the external and middle ears that clears up within the first couple days after birth. They reported that ER "shows promise providing information on the middle-ear status of neonates, which may be useful in interpreting neonatal tests for screening hearing loss" (Keefe et al, 2000, p. 461).

At this time, there is considerable interest in developing efficient and rapid procedures for separating infants who fail newborn screening by auditory brainstem response (ABR) or evoked otoacoustic emission (EOAE) as a result of conductive hearing loss (e.g., OME) from those with sensorineural hearing loss because the course of medical and audiological intervention is quite different for the two types of impairment. Tympanometric patterns observed in newborn infants using standard low-frequency (220- or 226-Hz) tympanometry do not conform to the classic patterns found in older infants, children, and adults (Paradise et al, 1976; Marchant et al, 1986; Rhodes et al, 1999; Margolis et al, 2003). The unusual characteristics of neonate tympanograms have been attributed to the physiological and maturational differences between neonate and adult ears (Himelfarb et al, 1979; Sprague et al, 1985; Margolis and Hunter, 2000).

Several studies indicate that the most informative tympanometric recordings in neonates are derived using higher probe-tone frequencies (Marchant et al, 1986; Hirsch et al, 1992; Hunter and Margolis, 1992; Rhodes et al, 1999; Kei et al, 2003; Calandruccio et al, 2006; Shahnaz et al, in this issue). The unusual characteristics of neonate tympanograms have been attributed to the physiological differences between neonate and adult ears (Himelfarb et al, 1979; Sprague et al, 1985; Margolis and Hunter, 2000). In newborns, the nonrigid ear canal may contribute to the irregular shape of tympanograms at low frequencies (Keefe et al, 1993). The ear-canal diameter in infants and young children can be changed up to 70% in response to the pressure changes implemented in tympanometry (Holte et al, 1990).

Recent studies have shown that WBR compared to standard 226-Hz tympanometry may provide a more sensitive test for middle ear disorders and conductive hearing loss (Keefe and Levi, 1996; Piskorski et al, 1999; Feeney et al, 2003; Keefe and Simmons, 2003). However, as of yet, few normative studies have been published to guide clinicians in the practical applications of WBR (Keefe and Levi, 1996; Keefe et al, 2000; Keefe et al, 2003). WBR has been measured more extensively in well babies (Keefe et al, 2003) than in neonatal intensive care unit (NICU) babies. The incidence of OME is significantly higher for NICU babies than for well babies—a result likely due to the use of nasotracheal tubes for ventilation in the NICU babies (Berman et al, 1978; Petalozza et al, 1988; Salamy et al, 1989). A valid test of the middle ear in NICU babies would be beneficial as a part of the newborn hearing screening program and diagnostic follow up. WBR may have the potential to provide a valid and sensitive test of the middle ear function in NICU babies.

The goal of this study was to explore the characteristics of the middle ear while using ER and normalized admittance in NICU babies who passed automated auditory brainstem response (AABR) and EOAE hearing screening criteria and to compare these characteristics with patterns in normal hearing adults. It was also within the scope of this study to explore the feasibility of using WBR in the NICU babies to improve hearing assessment in newborns. Moreover, the utility of WBR reflectance was explored in a series of infant case studies in which one or two ears failed to pass one or more hearing screening criteria.

METHOD

Subjects

This study tested two groups of subjects. The first group consisted of 65 ears of 31 NICU babies with an average gestational age (GA) of 37.8 weeks (range: 32–51 weeks) recruited from Children's and Women's Health Centre of British Columbia (C&W) in Vancouver. The second group consisted of 112 ears of 56 normally hearing Caucasian adults. All adult subjects were between the ages of 18 and 32 years and were recruited from the University of British Columbia.

Inclusion Criteria

NICU Babies

All NICU babies were screened using both AABR and EOAE when they were determined to be stable by a NICU nurse (not earlier than 3 weeks before discharge). The AABR and EOAE screenings were performed to separate those with likely normal hearing status from those with possible hearing loss. EOAE provides a screening for normal cochlear and middle ear function in that it is very sensitive to cochlear hearing loss of 30 dB HL or more (Kemp et al, 1986; Bonfils and Uziel, 1989; Collet et al, 1989) and is also quite sensitive to mild middle ear impairment (Owens et al, 1992; Koivunen et al, 2000; Zhao et al, 2000).

Babies were required to pass both an EOAE and an AABR screening. A pass consisted of a good emission-to-noise ratio in four out of five half-octave bands centered at 1, 1.5, 2, 3, and 4 kHz (a signal-to-noise ratio [SNR] of 3 dB at 1 and 1.5 kHz, and an SNR of 6 dB at 2, 3, and 4 kHz). For AABR, a pass consisted of meeting the Bio-logic ABaer passing algorithm at 35 dB nHL using ear muffins. A total of 33 NICU babies (65 ears) were successfully screened using both

AABR and TEOAE screening protocol. Out of these 65 ears, 54 ears met the inclusion criteria, and 11 ears were referred on one or two of the screening criteria. Out of 54 ears that met the inclusion criteria, WBR was successfully recorded in 49 ears (26 NICU babies). Among the 11 ears that did not meet the inclusion criteria, WBR was successfully measured in 8 ears (5 NICU babies). Therefore, a total of 31 NICU babies were tested by WBR (26 who met the inclusion criteria, and 5 who failed one or both of the screening criteria).

Adults

All adults in the study (a) had pure-tone audiometric thresholds of better than 25 dB HL at octave frequencies between 250 and 8000 Hz and an air-bone gap of less than or equal to 10 dB between 250 and 4000 Hz, (b) had no history of head trauma or middle ear disease, (c) had no gross eardrum abnormalities or excessive cerumen as documented by otoscopic examination, and (d) were required to pass TEOAE screening. A pass consisted of a greater-than-6–dB emission-to-noise ratio in three frequency bands (2000, 3000, and 4000 Hz). TEOAE screening was performed to further verify the normal condition of the cochlea and the middle ear.

Instrumentation

NICU Babies and Adults

Tympanometry was conducted using a commercially available middle ear analyzer (Grason-Stadler TympStar Version 2). AABR was performed using the Biologic AABR system (Bio-logic ABaer). TEOAEs were tested using a clinical ILO-292 Analyzer (Otodynamics Ltd., Hatfield, England) calibrated according to the operations manual of the manufacturer. Mimosa Acoustics (RMS system version 4.0.4.4) wideband reflectance equipment was used for this study. A four-cavity calibration device that is supplied with the WBR instrument was also required. The WBR equipment was calibrated using the four-cavity calibration device before testing each subject in the nursery. The tolerance region was predetermined by the manufacturer by calculating the tolerance range of the Thevenin (Norton) parameters of the source in four cavities in a manner similar to those of Allen (1985) and Voss and Allen (1994).

Procedure

NICU Babies

All NICU babies were first tested by AABR and TEOAE. Commencing the test with either AABR or TEOAE depended on the state of the baby (e.g., awake or crying) and the condition of the environment (e.g., noisy), and no specific order was chosen. Tympanometry was always performed following the TEOAE test, and WBR testing was conducted last. Initially, the admittance (Y) tympanogram was obtained at 226-Hz and 1-kHz probe-tone frequencies using a positive-to-negative-sweep pressure recording at a rate of 200 daPa/sec.

"Normal" was classified as meeting the passing criteria for both AABR and TEOAE and having a static admittance (SA) of greater than 0.1 mmho for positive compensation with normal tympanometric shapes at a 1-kHz probe-tone frequency as described by Shahnaz et al, in this issue. In cases of multi-peak tympanograms, the distance between the two maxima should have been close to 120 daPa.

"Abnormal" was defined as having an SA of less than 0.1 mmho for positive compensation or a multipeak tympanogram and having a distance of more than 150 daPa between the two maxima. To conduct the WBR test, the appropriate ear tip size for each subject was selected. Both rubber and foam ear tips are available in a variety of sizes for an ER-10C probe. All babies in this study were tested using rubber tips (size 03). A chirp signal was then introduced into the subject's sealed ear canal. In total, data from 248 frequencies, dispersed in even (approximately 23-Hz) intervals from 211 to 6000 Hz, were collected. Two WBR parameters, ER and admittance magnitude (Y), were used in this study. The admittance variable (Y) was presented in dimensionless values because it was automatically normalized by the Mimosa Acoustics equipment using the characteristic impedance of the ear canal. Measurements were accepted only if the signal was clearly above the noise value. This goal was accomplished by visually assessing the measurement spectrum window.

For researchers to accept the measurement, the signal should have been higher than noise area by roughly 3 dB at the lowest measurement frequency. The input spectrum should have also been as smooth as possible, especially at low frequencies. Because of inherent background noise in the NICUs, the noise was always high at frequencies below 400 Hz. The overall A-weighted noise level in the NICU was 65 dB SPL. Only data at 450 to 6000 Hz were included in the data analysis because the signal was clearly above the noise floor by at least 3 dB from 450 to 6000 Hz. Each WBR measurement took 5–10 seconds. To check the test–retest reliability of the measures, at least two of the measures taken must visually approximate the other using the ER curve. Because the quality of recording requires a good probe seal in the ear canal, the model suggested by Keefe et al (2000) for a good probe seal was adopted.

Table 1. ANOVA Table for Energy Reflectance

Effect	SS	DF	MS	F	P
Intercept	6204.58	1.00	6204.58	2455.85	0.00
Ear	0.29	1.00	0.29	1.46	0.74
Group	4.17	1.00	4.17	1.65	0.20
Ear by Group	4.52	1.00	4.52	1.79	0.18
Error	712.46	282.00	2.53		
Frequency	403.00	233.00	1.73	95.05	0.00
Frequency by Ear	4.00	233.00	0.02	0.94	0.72
Frequency by Group	205.12	233.00	0.88	47.82	0.00
Frequency by ear by Group	7.22	233.00	0.03	1.70	0.00
Error	1195.58	65706.00	0.02		

Note: The between-subject factors were group (neonatal intensive-care unit [NICU] versus adult) and ear (right versus left), and the within-subject factor was frequency. After the Greenhouse and Geisser (G-G) correction, only the interaction between group and frequency remained significant.

During the test, four recording windows were simultaneously available for each ear. Each recording window could be set to show different parameters that could be automatically calculated by the software. One recording window was set to ER, and the other two were set to display resistance (R) and reactance (X). Resistance and reactance tend toward very low values when there is a leak (see Keefe et al, 2000). If a leak was observed, the probe was reinserted or reoriented. The procedure used for adult data collection is explained in Shahnaz and Bork (2006) and is similar to the procedure used in this study.

Statistical Analysis

The 95% confidence intervals (CI) were computed and used to compare ER between NICU babies and adults (Shahnaz and Bork, 2006). A CI of 95% is valid for group comparison because this analysis assumes that ER data for each frequency are independent. This approach is consistent with Keefe et al (1993) and Feeney and Sanford (2004). Moreover, middle ear disorders have been shown to affect ER at a narrow range of frequencies while leaving other frequencies unaffected (Feeney et al, 2003). A CI of 95% for a group is interpreted as an interval that contains the true group mean with a 95% probability. Therefore, for two different groups (in this case NICU babies and adults), if their 95% CIs do not overlap, it can be concluded that the true means for the two groups are significantly different (i.e., the group means are significantly different at 5% significance level).

To measure the effect of ear and group (adults versus NICU babies), a similar mixed-model analysis of variance (ANOVA), as described by Shahnaz and Bork (2006), was used. In this model, ER or Y was measured in two different groups, adults and NICU babies (between-groups factor 1 with two levels), which were also separated by ears (right versus left, also between-groups factor 2 with two levels). ER was measured across 234 frequencies (repeated measures factor Frequency with 234 levels). The Greenhouse and Geisser (G-G) approach (1959) was used to compensate for the violations of compound symmetry and sphericity.

RESULTS

The data for the variable ER were explored using a mixed-model ANOVA. In this model, group (adult versus NICU babies) and ear (right versus left) served as between-subject factors, and frequency (234) served as a within-subject factor. A summary of the ANOVA results is shown in Table 1. The main effects of group [F (1, 282) = 1.65, p = 0.20] and ear [F (1, 282) = 1.46, p = 0.70] were not significant. However, the interaction between frequency and group [F (233, 65706) = 47.82, p = 0.000] was significant, indicating that ER varies differently across frequencies between the two groups.

The ER mean and 95% CI for 49 ears of 26 NICU babies and 112 ears of 56 normally hearing adults are shown in Figure 1. All 26 NICU babies passed both AABR and TEOAE screening protocol and had a normal tympanogram at 1 kHz, as described by Shahnaz et al (in this issue). There is a clear separation in ER 95% CI between NICU babies and adults for responses below 727 Hz, with NICU babies having lower ER values than adults. Between 1200 and 2700 Hz, the middle ear of the NICU babies is more efficient (ER is higher; i.e., closer to 0 in adults) than the adult ears in transferring energy into the middle ear system. In comparison, adult middle ears are more efficient than the ears of NICU babies in transferring energy into the middle ear system across a wider frequency range of 2800–4800 Hz (ER is higher in NICU babies). To investigate the frequencies at which the group differences occurred, a post-hoc Tukey test of honestly significantly different (HSD) was performed. The test results were consistent with the 95% CI outcome.

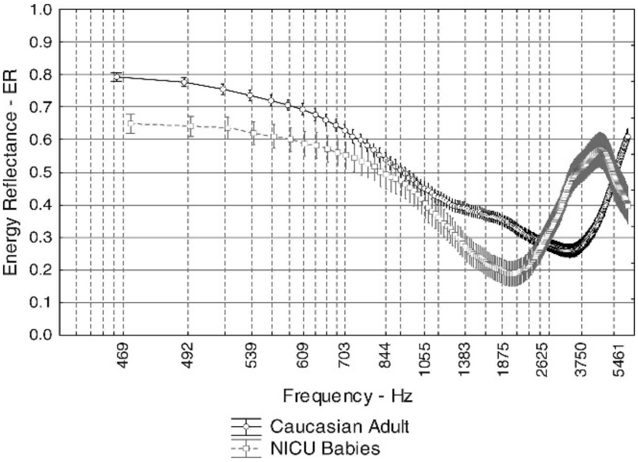

Figure 1. Energy reflectance (ER) in neonatal intensive-care unit (NICU) babies and adults. The 95% confidence interval (CI) and the mean values are shown in each group.

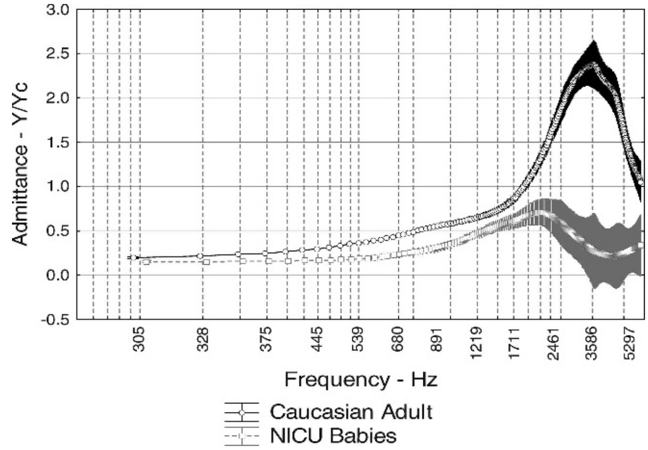

Figure 2. Normalized admittance (Y) in neonatal intensive-care unit (NICU) babies and adults. The 95% confidence interval (CI) and the mean values are shown in each group.

The data for the variable Y were explored using a mixed-model ANOVA. In this model, group (adult versus NICU) and ear (right versus left) served as between-subject factors, and frequency (248) served as a within-subject factor. A summary of the ANOVA results is shown in Table 2. The main effect of group was significant [F (1, 282) = 235.68, p = 0.000], with the NICU babies having significantly lower admittance values than the adult group. The effect of ear was not significant [F (1, 282) = 0.17, p = 0.68]. The interaction between frequency and group [F (233, 65706) = 29.11, p = 0.000] was significant, indicating that Y varies differently across frequencies between the two groups.

To investigate the frequencies at which the group differences occurred, a post-hoc Tukey HSD test was performed. At frequencies of 2200–6000 Hz, the adults had significantly higher Y values than the NICU babies. The Y mean and 95% CI for the normal NICU babies and normally hearing adults are shown in Figure 2. There is a clear separation in Y 95% CI between NICU babies and adults across all tested frequency ranges, with NICU babies having lower Y values than adults. Y magnitude reached its maximum value around 3492 Hz for the adult group and 2250 Hz for the NICU babies.

DISCUSSION

Energy Reflectance

WBR was successfully measured in 49 ears of 26 NICU babies who passed both AABR and TEOAE screening protocols and had a normal tympanogram at 1 kHz. As in Keefe and Levi (1996), there is a clear separation in ER between NICU babies and adults for responses below 727 Hz, with NICU babies having lower ER values than adults. Keefe and Levi (1996) attributed this separation to larger energy losses in an infant's ear canal. Mean ER in NICU babies is compared to 1-month-old babies (Keefe and Levi, 1996) in Figure 3. Overall, both NICU babies and 1-month-old babies had their minimum ER around 2 kHz (i.e., most of the incident energy was absorbed by the middle ear and a smaller portion was reflected).

Table 2. ANOVA Table for Normalized Admittance

Effect	SS	DF	MS	F	P
Intercept	26953.42	1.00	26953.42	682.94	0.00
Ear	6.88	1.00	6.88	0.17	0.68
Group	9301.65	1.00	9301.65	235.68	0.00
Ear by Group	47.90	1.00	47.90	1.21	0.27
Error	6117.32	282.00	39.47		
Frequency	3485.60	233.00	14.52	25.79	0.00
Frequency by Ear	94.08	233.00	0.39	0.70	1.00
Frequency by Group	3934.49	233.00	16.39	29.11	0.00
Frequency by ear by Group	58.37	233.00	0.24	0.43	1.00
Error	20948.31	65706.00	0.56		

Note: The between-subject factors were group (neonatual intensive-care unit [NICU] versus adult) and ear (right versus left) and the within-subject factor was frequency. After the Greenhouse and Geisser (G-G) correction, only the interaction between group and frequency remained significant.

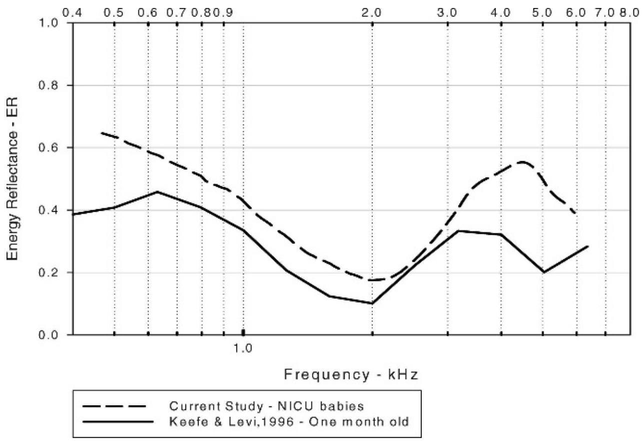

Figure 3. Comparison of the group energy reflectance (ER) mean as a function of frequency between 1-month-old babies (Keefe and Levi, 1996) and neonatal intensive-care unit (NICU) babies in the current study.

At lower frequencies, the 1-month-old babies have smaller (closer to 0) ER values than NICU babies.

The differences observed are most likely due to (a) the more stringent criteria that were used in this study to establish a better seal, (b) the different calibration procedure used in each study, and (c) the potential differences in the middle ear characteristics between NICU babies in this study and 1-month-old babies in Keefe and Levi's study. The low-frequency portion of ER tends to approach 0 when the probe is loosely fit into the ear canal. Another source of difference between the two studies was the calibration procedure. The method described by Keefe et al (1992) was used to calibrate the system in the Keefe and Levi study. The Mimosa Acoustics calibration method is based on the methods of Allen (1986) and Voss and Allen (1994). At higher frequencies, the 1-month-old babies have smaller (closer to 0) ER values than NICU babies. This finding could partly be explained by differences in the mechano–acoustical properties of the middle ear between the two age groups.

The overall mass of the middle ear will decrease postnatally due to reduction and absorption of amniotic fluid and mesenchyme. Both amniotic fluid and mesenchyme are present in the middle ear cavity at birth and may last for several weeks after birth (Paparella et al, 1980). Mass elements control the conduction of the high-frequency response of the middle ear. Moreover, the overall maturation of the middle ear may result in an increase in mass at birth, which will gradually decrease as infants become older. If overall mass of the middle ear is higher for NICU babies than for 1-month-old babies, then more incident energy will be reflected and less will be absorbed at higher frequencies. This finding is consistent with ER patterns observed in NICU babies.

Admittance Magnitude (Y)

Admittance was chosen as a measure because it was thought to be comparable to tympanometric admittance. Pressure reflectance [R (f)] is mathematically related to impedance and admittance. Therefore, it is possible to derive any tympanometric quantity, such as admittance, susceptance (B), and conductance (G) from pressure reflectance (Keefe & Levi, 1996). Keefe and Levi (1996) have shown that the susceptance (B) equivalent-volume tympanogram obtained using a clinical immittance middle ear analyzer (Virtual 310) and reflectance equivalent-volume tympanograms are essentially identical. This issue was also tested at multiple probe-tone frequencies up to 2000 Hz, and it was concluded that the B equivalent-volume tympanogram has the same qualitative shape as the reflectance equivalent-volume tympanograms (Keefe and Levi, 1996). A CI of 95% of the Y mean values was higher for the adult group than for the NICU babies across all frequencies tested.

Because the middle ear cavity is much smaller (lower compliance) and the resistive element is much higher in newborns, admittance of the middle ear is much less than that of adults (Keefe et al, 1993). As expected, this finding is consistent with tympanometric results obtained by Shahnaz et al (in this issue), who found that mean compensated Y values obtained at a 1-kHz probe-tone frequency were significantly higher for the adult group than for the NICU babies.

It should be noted that Y values in Figure 2 are not identical to compensated Y obtained in tympanometric data because no attempt has been made to compensate for the effect of equivalent ear-canal volume for the normalized Y values in Figure 2. Admittance magnitude for NICU babies reached its local maximum (Figure 2) at a lower frequency (2250 Hz) than for adults (3492 Hz). This local maximum on admittance is most likely consistent with the middle ear resonant frequency as reactance approaches 0 at this local maximum and impedance is equal to resistance.

To make the results more comparable to admittance data in Keefe and Levi's study (Figure 2 in Keefe and Levi, 1996, p. 9), normalized admittance data in the current study (Figure 2 in the current study) were converted to dB (10 log [Y/Yc]) and are shown in Figure 4. Normalized admittance data in the current study for the adult group do not compare well to normalized admittance data for the adult group in Keefe and Levi's study. The normalized admittance values in the current study are higher across all frequencies for the adults. Normalized admittance data in the current study for NICU babies at frequencies below 1 kHz are between −4.5 and −8 dB, which is comparable to 1-month-old babies in Keefe and Levi's study. In both studies, normalized

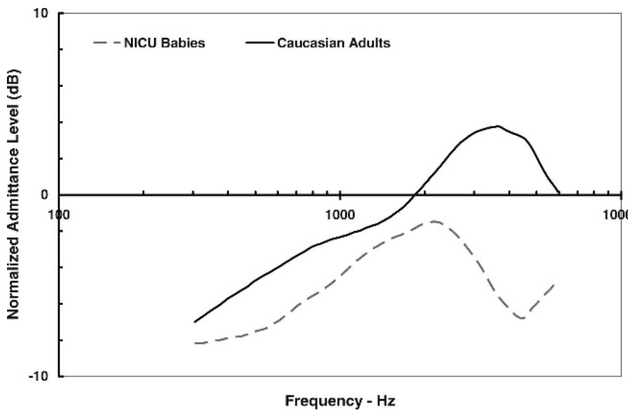

Figure 4. Comparison of normalized admittance level (dB) in neonatal intensive-care unit (NICU) babies and adults.

admittance peaks around 2 kHz and then rolls down at higher frequencies. The differences observed mainly occurred above 2 kHz. Possible sources of the observed differences between the two studies may be due to different calibration procedures, different methods for calculating the cross-sectional area of the ear canal for computation of the characteristic impedance (used to normalize Y-based measures), and different subject characteristics (NICU babies versus 1-month-old babies and Caucasian adults versus a mixed adult group).

Case Studies

Among the NICU babies, 11 ears failed the EOAE screening and had an abnormal 1-kHz tympanogram as described by Shahnaz et al (in this issue). WBR data were successfully measured in 8 of those 11 ears. Some of these infants are reviewed in the following cases, which illustrate the potential value of WBR in the assessment of the middle ear in NICU babies. WBR norms are based on 49 ears of 26 NICU babies who passed both AABR and TEOAE screening protocol and had a normal tympanogram at 1 kHz.

Case 1 (Figures 5a and b) was born at 27 weeks GA and was tested at 39.5 weeks corrected GA (CGA) for AABR and at 40 weeks CGA for TEOAE. She referred on AABR for the left ear and passed for the right ear and failed in both ears for TEOAE. She later passed second-stage AABR in both ears close to discharge from the hospital (47 weeks CGA). Tympanograms at 1 kHz in both ears were abnormal. ER (Figure 5a) is below the 95th percentile (i.e., most incident energy has been reflected) between 586 and 3186 Hz and 4969 and 6000 Hz in the left ear, and it is below the 95th percentile between 563 and 3516 Hz and 5461 and 6000 Hz in the right ear.

As mentioned previously, in cases of middle ear effusion, ER values are expected to be closer to 1 (most incident energy is reflected) at lower frequencies. ER exceeds 1 between 961 and 3025 Hz in the left ear and

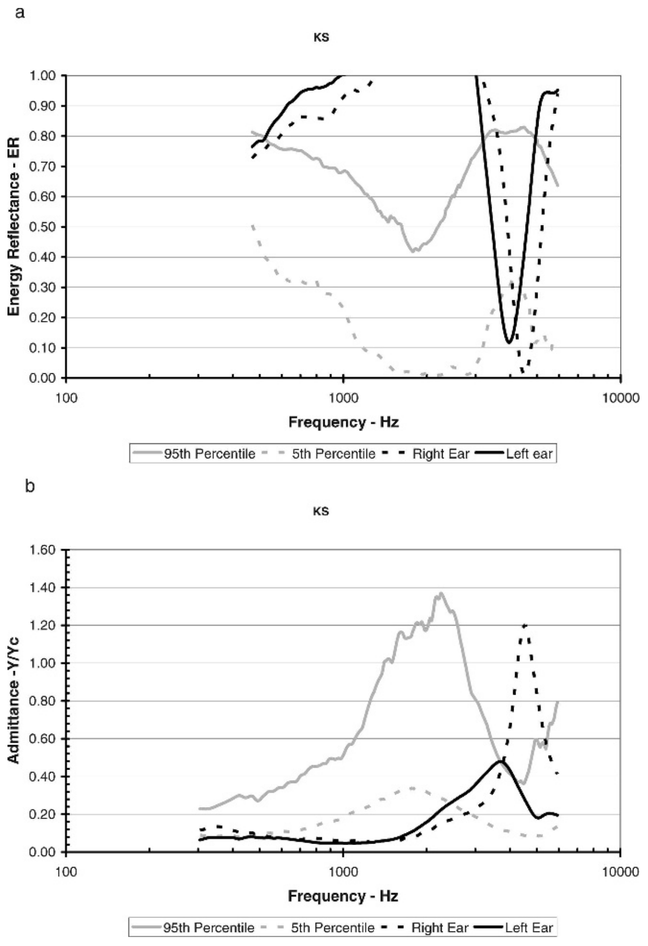

Figure 5. Energy reflectance (ER) and normalized admittance (Y) from a neonatal intensive-care unit (NICU) baby, who referred on automated auditory brainstem response (AABR) for the left ear and passed for the right ear and failed in both ears for TEOAE.

between 1289 and 3188 Hz in the right ear. These patterns were replicated several times by recalibrating the system using different rubber tips (for a total of 8 measures for each ear). Exceeding ER above 1 could be due to some unknown computation error; however, the ER patterns observed in the two ears is consistent with the patterns observed in other cases with a suspected middle ear problem due to effusion. Y values (Figure 5b) were also below the 5th percentile below 2.5 kHz in the left ear and 2.8 kHz in the right ear, which is consistent with the tympanometric Y values that are commonly observed in cases of OME.

Case 2 (Figures 6a and b) and case 3 (Figures 7a and b) are interesting cases because only the left ears failed AABR and EOAE. In both cases, the left ear passed AABR in the second stage. In both cases, right ear tympanograms were normal, and left ear tympanograms were abnormal at a 1-kHz probe-tone frequency. The ER (Figures 6a and 7a) falls within normal range in the right ear in both cases. In case 2, ER is below the 95th percentile (i.e., most incident energy has been

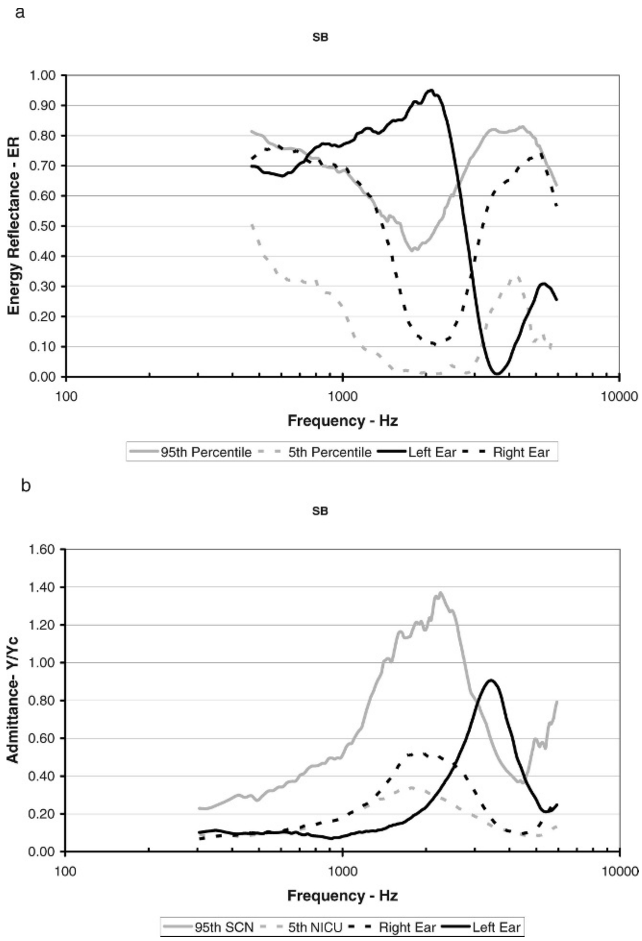

Figure 6. Energy reflectance (ER) and normalized admittance (Y) from a neonatal intensive-care unit (NICU) baby, who referred on automated auditory brainstem response (AABR) and transient otoacoustic emission (TEOAE) screening for the left ear and passed on AABR and TEOAE for the right ear.

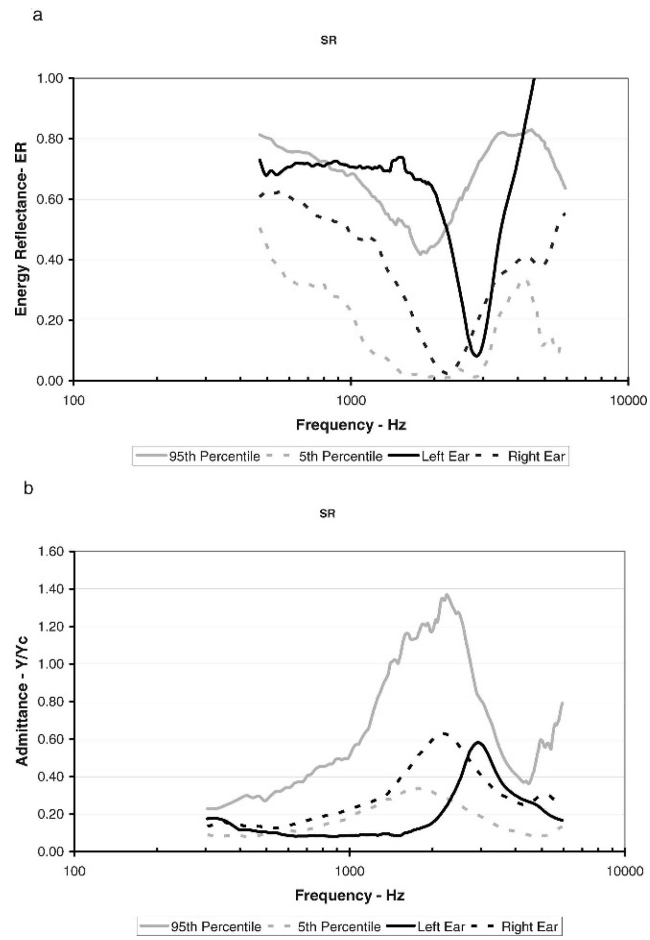

Figure 7. Energy reflectance (ER) and normalized admittance (Y) from a neonatal intensive-care unit (NICU) baby who referred on automated auditory brainstem response (AABR) screening and transient otoacoustic emission (TEOAE) screening for the left ear and passed on AABR and TEOAE for the right ear.

reflected) between 750 and 2625 Hz, and above the 5th percentile (i.e., most incident energy has been absorbed) between 3211 and 4711 Hz in the left ear. In case 3, ER is below the 95th percentile (i.e., most incident energy has been reflected) between 820 and 2203 Hz and above 4195-Hz. Y values (Figures 6b and 7b) in both cases were also within normal range in the right ear and were lower than the 5th percentile in the left ears (below 2156 Hz in case 2 and below 2320 Hz in case 3). In both cases, the tympanograms at 1 kHz and the ER and Y measures suggest a normal middle ear in the right ear and a middle ear problem in the left ear.

SUMMARY AND CONCLUSION

WBR was successfully obtained in 49 ears (26 NICU babies). Among the 11 ears that did not meet the inclusion criteria, WBR were successfully measured in 8 ears (5 NICU babies). The reason that WBR could not be obtained in all ears that had tympanometry successfully completed was that it was conducted as the last test in a series of tests. Therefore, it was quite likely that the baby would have woken up or would have become agitated during WBR. Although tympanograms were also abnormal in all cases that failed TEOAE screening, WBR still may prove to be useful in assessing middle ear function. Static pressurization of the ear canal during tympanometry may produce large changes in the diameter of a compliant ear canal in a newborn. The ear-canal diameter in infants and young children can be changed up to 70% in response to a pressure change in tympanometry (Holte et al, 1990). This study provides the preliminary WBR normative data for NICU babies with normal middle ear function and reveals how it may vary in cases with potential middle ear effusion.

Maximum absorption of the incident energy appears to occur at a narrower range of frequencies in normal NICU babies when compared with normal hearing adults. This range becomes even narrower in NICU babies who fail TEOAE screening. In most NICU babies who failed TEOAE screening, ER values are closer to 1 (most incident energy is reflected) at a frequency below 3000 Hz. This finding is consistent with ER findings among adults (Feeney et al, 2003) and children (Jeng et al, 1999) with confirmed middle ear effusion. The measurements of normalized acoustic admittance may also be very useful and supplemental to ER data in evaluating middle ear status.

One of the limitations of this study is that it did not assess test–retest reliability in NICU babies statistically; however, at least two of the ER measures taken in each NICU baby closely approximated each other. Another limitation of this study (and other similar studies) is the lack of a gold standard for confirmation of the middle ear condition, especially in infants. Although the presence of TEOAEs is a good indication of a normal cochlear function as well as a normal middle ear condition, it cannot completely rule out the absence of effusion in the middle ear (Driscoll et al, 2000). The type of effusion found within the middle ear appears to be the controlling factor affecting the presence or absence of emissions. Thicker effusions would increase the resistant loading effect on the middle ear system and account for the absence of otoacoustic emissions (Koivunen et al, 2000).

Use of a more-objective gold standard such as myringotomy raises ethical issues and is not feasible in the newborn population. Future studies should incorporate objective measures such as air- and-bone conduction ABR to further refine the application of tympanometry and WBR to identify the presence or absence, as well as the severity, of the conductive component in newborns and very young infants.

Acknowledgments. This project was supported by a grant from the Hearing Foundation of Canada, the Canadian Foundation for Innovation (CFI), and the British Columbia Knowledge Development Fund (BCKDF). I am grateful to the following people who provided essential assistance in collection and analysis of the data presented in this report. This project was facilitated by support of Dr. Ann Synnes, Ms. Laurie Usher, Ms. Sue Ann Poe, and the staff of the Special Care Nursery of Children's and Women's Health Centre of British Columbia (C&W) in Vancouver. I am also grateful for input provided by Dr. David Stapells and his contribution as well as his support through his CIHR grant during the course of this project.

NOTES

1. It should be noted that Teele and Teele (1984) earlier introduced the concept of acoustic reflectometry, which represents the sum of incident and reflected sound as a method of improving the diagnosis of OME.

2. Compound symmetry and sphericity pertains to the fact that multiple contrasts involved in testing the effects of repeated measures (with more than two levels) are not independent of each other.

REFERENCES

Allen JB. (1986) Measurement of eardrum acoustic impedance. In: Allen JB, Hall JL, Hubbard A, Neely ST, Tubis A, eds. *Peripheral Auditory Mechanisms.* New York: Springer-Verlag, 44–51.

Allen JB, Jeng PS, Levitt H. (2005) *J Rehabil Res Dev* 42(Suppl. 2):63–78.

Berman S, Balkany T, Simmons M. (1978) Otitis media in the neonatal intensive care unit. *Pediatrics* 62:198–201.

Bonfils P, Uziel A. (1989) Clinical applications of evoked otoacoustic emissions: results in normally hearing and hearing impaired subjects. *Ann Otol Rhinol Laryngol* 98:326–31.

Calandruccio L, Fitzgerald TS, Prieve PA. (2006) Normative Multifrequency Tympanometry in Infants and Toddlers. *J Am Acad Audiol* 17:470–480.

Collet L, Gartner MG, Marlin A, Kauffmann I, Disant F, Margon A. (1989) Evoked otoacoustic emissions and sensorineural hearing loss. *Arch Otolaryngol Head Neck Surg* 115:1060–1062.

Driscoll C, Kei J, McPherson B. (2000) Transient evoked otoacoustic emissions in 6-year-old school children: a normative study. *Scand Audiol* 29:103–110.

Feeney MP, Grant IL, Marryott LP. (2003) Wideband energy reflectance measurements in adults with middle-ear disorders. *J Speech Lang Hear Res* 46:901–11.

Feeney MP, Sanford CA. (2004) Age effects in the human middle ear: wideband acoustical measures. *J Acoust Soc Am* 116:3546–3458.

Greenhouse SW, Geisser S. (1959) On methods in the analysis of profile data. *Psychometrika*, 24:95–112.

Himelfarb MZ, Popelka GR, Shanon E. (1979) Tympanometry in normal neonates. *J Speech Hear Res* 22:179–191.

Hirsch JE, Margolis RH, Rykken JR. (1992) A comparison of acoustic reflex and auditory brain stem response screening of high-risk infants. *Ear Hear* 13(3):181–186.

Holte LA, Cavanagh RM, Margolis RH. (1990) Ear canal wall mobility and tympanometric shape in young infants. *J Pediatr* 117:77–80.

Hunter LL, Margolis RH. (1992) Multifrequency tympanometry: Current clinical application. *Am J Audiol* 1(3):33–43.

Jeng P, Levitt H, Lee WW, Gravel JS. (1999) Reflectance measures for detecting OME in children: Preliminary findings. In: Lim D, ed. *Abstracts of the Seventh International Symposium on Recent Advances in Otitis Media*: Fort Lauderdale, Florida, 217.

Keefe DH, Bulen JC, Arehart KH, Burns EM. (1993) Ear-canal impedance and reflection coefficient in human infants and adults. *J Acoust Soc Am* 94:2617–38.

Keefe DH, Folsom RC, Gorga MP, Vohr BR, Bulen JC, Norton SJ. (2000) Identification of neonatal hearing impairment: Ear-canal measurements of acoustic admittance and reflectance in neonates. *Ear Hear* 21:443–461.

Keefe DH, Gorga MP, Neely ST, Zhao F, Vohr BR. (2003) Ear-canal acoustic admittance and reflectance measurements in human neonates. II. Predictions of middle-ear in dysfunction and sensorineural hearing loss. *J Acoust Soc Am* 113:407–22.

Keefe DH, Levi E. (1996) Maturation of the middle and external ears: Acoustic power-based responses and reflectance tympanometry. *Ear Hear* 17:361–73.

Keefe DH, Ling R, Bulen JC. (1992) Method to measure acoustic impedance and reflection coefficient. *J Acoust Soc Am* 91:470–485.

Keefe DH, Simmons JL. (2003) Energy transmittance predicts conductive hearing loss in older children and adults. *J Acoust Soc Am* 114:3217–38.

Kei J, Allison-Levick J, Dockray J, Harrys R, Kirkegard C, Wong J, Maurer M, Hegarty J, Young J, Tudehope D. (2003) High-frequency (1000 Hz) tympanometry in normal neonates. *J Am Acad Audiol* 14(1):20–28.

Kemp D, Bray P, Alexander L, Brown AM. (1986) Emission cochleography—practical aspects. *Scand Audiol Suppl* 25, 71–95.

Koivunen P, Uhari M, Laitakari K, Alho OP, Luotonen J. (2000) Otoacoustic emissions and tympanometry in children with otitis media. *Ear Hear* 21:212–7.

Marchant CD, McMillan PM, Shurin PA, Johnson CE, Turczyk VA, Feinstein JC, Murdell Panek D. (1986) Objective diagnosis of otitis media by tympanometry and ipsilateral acoustic reflex thresholds. *J Pediatr* 109:590–595.

Margolis R, Bass-Ringdahl S, Hanks W, Holte L, Zapala D. (2003) Tympanometry in newborn infants—1 kHz norms. *J Am Acad Audiol* 14:383–92.

Margolis RH, Hunter LL. (2000) Acoustic immittance measurements. In: Roeser R, Valente M, Hosford-Dunn H, eds. *Audiology Diagnosis.* New York: Thieme, 381–425.

Margolis RH, Paul S, Saly GL, Schachern PA, Keefe DH. (2001) Wideband reflectance tympanometry in chinchillas and human. *J Acoust Soc Am* 110:1453–1464.

Margolis RH, Saly GL, Keefe DH. (1999) Wideband reflectance tympanometry in normal adults. *J Acoust Soc Am* 106:265–80.

Owens JJ, McCoy MJ, Lonsbury-Martin BL, Martin G.K. (1992) Influence of otitis media on evoked otoacoustic emissions in children. *Semin Hear* 3:53–66.

Paparella MM, Shea D, Meyerhoff WL, Goycoolea MV. (1980) Silent otitis media. *Laryngoscope* 90:1089–1098.

Paradise J, Smith C, Bluestone C. (1976) Tympanometric detection of middle ear effusion in infants and young children. *J Pediatr* 587:198–210.

Pestalozza G, Romangnoli M, Tessitore E. (1988) Incidence and risk factors of acute otitis media and otitis media with effusion in children of different age groups. *Adv Otorhinolaryngol* 40:47–56.

Piskorski P, Keefe D, Simmons J, Gorga M. (1999) Prediction of conductive hearing loss based on acoustic ear-canal response using a multivariate clinical decision theory. *J Acoust Soc Am* 105:1749–1764.

Rhodes MC, Margolis RH, Hirsch JE, Napp AP. (1999) Hearing screening in the newborn intensive care nursery: A comparison of methods. *Otolaryngol Head Neck Surg* 120(6):799–808.

Salamy A, Eldredge M, Tooly W. (1989) Neonatal status and hearing loss in high-risk infants. *J Pediatr* 114:847–852.

Shahnaz N, Bork K. (2006) Wideband reflectance norms for Caucasian and Chinese young adults. *Ear Hear* 27:774–88.

Shahnaz N, Miranda T, Polka L. (2008) Multifrequency tympanometry in neonatal intensive care unit and well babies. *J Am Acad Audiol* 19:392–418.

Sprague BH, Wiley TL, Goldstein R. (1985) Tympanometric and acoustic reflex studies in neonates. *J Speech Hear Res* 28:265–272.

Stinson MR. (1990) Revision of estimates of acoustic energy reflectance at the human eardrum. *J Acoust Soc Am* 88:1773–1778.

Teele DW, Teele J. (1984) Detection of middle ear effusion by acoustic reflectometry. *J Pediatr* 104:832–8.

Voss SE, Allen JB. (1994) Measurement of acoustic impedence and reflectance in the human ear canal. *J Acoust Soc Am* 95:372–384.

Zhao F, Wada H, Koike T, Stephens D. (2000) The influence of middle ear disorders on otoacoustic emissions. *Clin Otolaryngol Allied Sci* 25:3–8.