Using 1000 Hz Tympanometry in Hearing Screening of Babies in the Neonatal Intensive Care Unit (NICU)

L'usage de la tympanométrie à 1 000 Hz pour le dépistage de la surdité chez les bébés se trouvant dans les unité des soins intensifs pour nouveau-nés

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KEY WORDS

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Abstract

An issue of great concern in Universal Newborn Hearing Screening (UNHS) is the high false-positive rates, which is especially problematic in the Neonatal Intensive Care Unit (NICU) population. False-positive results may lead to unnecessary follow-up appointments, increased health care costs, and increased stress on parents. High frequency tympanometry has been recommended for healthy babies younger than 6 months of age, which may reduce false-positive results caused by transient middle-ear issues. The objectives of this study were to obtain admittance, susceptance, and conductance data from a sample of NICU babies, to compare tympanometric data obtained from the component compensation approach with the data obtained from the baseline approach, and to provide preliminary normative data for NICU babies when ABR was used as a 'gold standard'. In this study, 31 babies in the NICU were included. Admittance was obtained in 84% (n=52) of 62 ears, and susceptance and conductance were obtained in 77% (n=48) of 62 ears. Using a component compensation approach, at the 5th and 95th percentile the admittances at the tympanic membrane were 0.5 and 1.7 mmho referenced to the positive tail, and 0.6 and 2.0 mmho referenced to the negative tail. Using a baseline approach, at the 5th and 95th percentile the peak-to-tail compensated admittances were 0.2 and 1.2 mmho referenced to the positive tail, and 0.4 and 2.0 mmho referenced to the negative tail. Our results were also compared with several data sets published by other investigators, and the differences among data sets are discussed. A significant difference in admittance existed between the component compensation approach and the traditional baseline approach. Different normative data needs to be considered accordingly.

Abrégé

Le taux élevé de « faux positifs » est un problème très préoccupant dans le dépistage universel de la surdité chez les nouveau-nés. Ils sont particulièrement problématiques dans la population de bébés d'unités des soins intensifs pour nouveau-nés (USIN). Des résultats « faux positifs » peuvent mener à des rendez-vous de suivi inutiles, à une augmentation des coûts de santé et à un stress accru chez les parents. La tympanométrie à haute fréquence a été recommandée pour les bébés en santé âgés de moins de 6 ans, ce qui peut réduire les résultats « faux positifs » causés par des problèmes temporaires de l'oreille moyenne. Les objectifs de la présente étude étaient d'obtenir des données d'admittance, de susceptance et de conductance à partir d'un échantillon de bébés d'USIN, afin de comparer les données tympanométriques obtenues par l'approche de compensation des composantes à celles obtenues par l'approche de référence, et de fournir des données normatives préliminaires pour les bébés d'USIN quand la mesure des PÉATC a été utilisée comme « règle d'or ». Cette étude compte 31 bébés d'USIN. L'admittance a été obtenue dans 84 % (n=52) de 62 oreilles, et la susceptance et la conductance furent obtenues dans 77 % (n=48) de 62 oreilles. En utilisant l'approche de compensation des composantes, aux 5^{e} et 95^{e} percentiles, les admittances à la membrane du tympan furent de 0,5 et 1,7 mmho en référence à l'extrémité positive et 0,6 et 2,0 mmho en référence à l'extrémité négative. En utilisant l'approche de référence, aux 5^{e} et 95^{e} percentiles, les admittances compensées et mesurées du « sommet à la base » furent de 0,2 et 1,2 mmho en référence à l'extrémité positive et 0,4 et 2,0 mmho en référence à l'extrémité négative. Nos résultats furent aussi comparés à plusieurs données publiées par d'autres chercheurs et les différences entre les données sont discutées. Une différence significative dans l'admittance existait entre l'approche de compensation de composantes et l'approche de référence traditionnelle. Différentes données normatives doivent être considérées en conséquence.

ABBREVIATIONS:

Y = Admittance [Equation 1]; B = Susceptance; G = Conductance;
Y_{TM} = compensated admittance at tympanic membrane;
Y_{peak} = uncompensated admittance at peak;
Y_a @+ 200 daPa = uncompensated admittance at positive tail;
Y_a @- 400 daPa = uncompensated admittance at negative tail;
B_{peak} = uncompensated susceptance at peak;
B_{tail} @ +200 daPa = uncompensated susceptance at positive tail;
B_{tail} @ -400 daPa = uncompensated susceptance at positive tail;
G_{peak} = uncompensated conductance at peak;
G_{tail} @ +200 daPa= uncompensated conductance at positive tail;
G_{tail} @ -400 daPa= uncompensated conductance at negative tail;
$+200B_{TM}$: peak-to-positive tail susceptance [Equation 2];
$-400B_{TM}$: peak-to-negative tail susceptance [Equation 3];
$+200G_{TM}$: peak-to-positive tail conductance [Equation 4];
$-400G_{TM}$: peak-to-negative tail conductance [Equation 5];
$+200Y_{TM}$: positive tail component compensated admittance [Equation 6];
$-400Y_{TM}$: negative tail component compensated admittance [Equation 7];
$+200Y_a$: peak-to-positive tail admittance [Equation 8];
$-400Y_a$: peak-to-negative tail admittance [Equation 9];

EQUATIONS:

$$Y = G + jB \quad \text{Equation 1}$$

$$+200B_{TM} = B_{peak}\text{-}B_{tail} \text{ @ } +200 \text{ daPa} \quad \text{Equation 2}$$

$$-400B_{TM} = B_{peak}\text{-}B_{tail} \text{ @ } -400 \text{ daPa} \quad \text{Equation 3}$$

$$+200G_{TM} = G_{peak}\text{-}G_{tail} \text{ @ } +200 \text{ daPa} \quad \text{Equation 4}$$

$$-400G_{TM} = G_{peak}\text{-}G_{tail} \text{ @ } -400 \text{ daPa} \quad \text{Equation 5}$$

$$+200Y_{TM} = \sqrt{(Bpeak - Btail@+200)^2 + (Gpeak - Gtail@+200)^2} \quad \text{Equation 6}$$

$$-400Y_{TM} = \sqrt{(Bpeak - Btail@-400)^2 + (Gpeak - Gtail@-400)^2} \quad \text{Equation 7}$$

$$+200Y_a = Y_{PEAK} - Ya@+200 \quad \text{Equation 8}$$

$$-400Y_a = Y_{PEAK} - Ya@-400 \quad \text{Equation 9}$$

INTRODUCTION

An issue of great concern in Universal Newborn Hearing Screening (UNHS) is the high false-positive rates. A false-positive result means that a neonate who does not have a target hearing loss (typically, this is a permanent hearing loss that is at least moderate in degree) fails the UNHS and is required to undergo a full diagnostic test. It has been reported that in UNHS a substantial proportion (59% to 81%) of false positive results was due to transient conductive hearing loss caused by middle ear dysfunction (e.g., Cristobal & Oghalai, 2008; Holte, Cavanaugh, & Margolis, 1990; Keefe et al., 2000; Stuart, Yang, & Green, 1994).

Reliable and accurate diagnosis of middle ear function in neonates may reduce false positive rates in UNHS. Currently, auditory brainstem response (ABR) and otoacoustic emission (OAE) screening tests are used for newborn hearing screening. Unfortunately, neither test can differentiate between conductive and sensorineural hearing loss, and both tests can be affected by transient outer or middle ear dysfunction (e.g., Zhang & Abbas, 1997; Zhao, Wada, Koike, & Stevens, 2000). Therefore, a baby with normal cochlear and neural function may fail a hearing screening and be referred for a full diagnostic follow up due to a conductive problem. This is especially problematic in the Neonatal Intensive Care Unit (NICU) population as they have a higher prevalence of middle ear dysfunction. Whereas the false positive rate has been shown to be around 2% to 4% in most UNHS programs (Nelson, Bougatsos, & Nygren , 2008), the rate is as high as 15% to 20% in babies in the NICU (Keefe et al., 2000; Thompson et al., 2001).

Tympanometry is a test that is non-invasive, cost effective, and quick. Middle ear function in adults can be assessed by using a 226-Hz probe tone. For infants six months of age or younger, studies have shown that 1000-Hz tympanometry is more effective than the 226-Hz test (Alaerts, Luts, & Wouters, 2007; Baldwin, 2006; Hunter, Feeney, Lapsley Miller, Jeng, & Bohning, 2010; Hunter, Tubaugh, Jackson, & Propes, 2008; Kei et al., 2003; Margolis, Bass-Ringdahl, Hanks, Holte, & Zapala, 2003; Merchant, Horton, &Voss, 2010; Prieve, Vander Werff, Preston, & Georgantas, 2013; Resende, Ferreira, Carvalho, Oliveira & Bassi, 2012; Sanford & Feeney, 2008; Shahnaz, 2008; Shahnaz, Miranda, & Polka, 2008; Son et al. 2012;). The effectiveness of the 1000-Hz probe tone for newborns is likely due to significant anatomical differences between newborns and adults (Anson & Donaldson, 1981; McLellan & Webb, 1957; Northern & Downs, 2002; Saunders, Doan, & Cohen, 1993). Finite-element models of the newborn middle and outer ear were developed by and Qi, Liu, Lutfy, Funnell, and Daniel (2006) and Qi, Funnell, and Daniel (2008) which showed that anatomical changes in the infant's outer ear and middle ear could partially account for the differences in tympanometry between infants and adults (Gulya, 2007).

The use of 1000-Hz tympanometry on full-term healthy babies has been widely studied (Kei et al., 2003; Kei, Mazlan, Hickson, Gavranich, & Linning, 2007; Margolis et al., 2003; Mazlan et al., 2007; Shahnaz, 2008; Shahnaz & Polka, 2002; Swanepoel et al., 2007). Currently, there are few studies on the use of 1000 Hz tympanometry for babies in the NICU who are undergoing a hearing screening. Yoon, Price, Gallagher, Fleisher, and Messner (2003) reported that 37% of NICU graduates (n=82) had abnormal tympanometry in one ear and 29% had abnormal tympanograms bilaterally; however, they did not provide any qualitative data in their paper. The abnormal tympanometry was defined as either flat tympanograms or negative pressures > 200 daPa. Margolis et al. (2003) investigated 1000-Hz tympanometry in 65 babies in the NICU and 30 full term health babies at 2-4 weeks of age. They found the 5th percentile of admittance for both babies in the NICU and full term healthy babies was identical, and they recommended a single pass-fail criterion using the admittance derived from negative tail using a baseline approach, for both NICU and full-term health babies. The negative tail was recommended for clinical practice because it resulted in a larger mean value of admittance, which may make it easier to distinguish between normal tympanograms and abnormal tympanograms. Shahnaz et al. (2008) investigated multi-frequency tympanometry (MFT) and conventional tympanometry in well babies and babies in the NICU at nine frequencies (from 226 to 1000 Hz). Conventional tympanometry and MFT were performed in 33 NICU babies, 16 healthy full term three-week-old babies and 42 babies who met high priority hearing registry criteria. They used the component compensation approach in their study and provided admittance phase and peak compensated susceptance and conductance at different probe tone frequencies. They recommended that the tympanograms obtained at 1000-Hz were more sensitive and specific for presumed abnormal and normal middle-ear conditions for both groups. Alaerts et al. (2007) performed 226 and 1000-Hz tympanometry in six different age groups (131 ears in total), including NICU babies (28 ears), infants/children aged from 0 to 32 months and adults. In their study they measured middle ear admittance at +200daPa, middle ear admittance at peak, tympanometric peak pressure, tympanometric width, and ear canal volume. They found that the visual admittance classification system was more

suitable than the Vanhuyse model. In addition, for infants younger than 3 months, 1000-Hz tympanometry was more reliable and easier to interpret than traditional 226-Hz tympanometry. For older children (9 months of age), traditional 226-Hz tympanometry was more appropriate. For children between 3 and 9 months of age, 226-Hz and 1000-Hz tympanometry were equally reliable.

The admittance is a complex number including both real and imaginary parts, as shown in Equation 1, where *G* is the conductance and *B* is the susceptance. *G* is in phase with the delivered probe tone. *B* is an out-of-phase component which is comprised of two parts. One is the compliance component and the other is the mass component. Admittance obtained from Equation 1 is referred to as the component compensation approach. For adults, conductance is very negligible (e.g., Shahnaz, Cai, & Qi, 2014). Therefore, peak-to-tail difference is almost equal to the true admittance. For infants, conductance is significantly prominent (e.g. Shahnaz et al., 2008), and for this reason, phase information needs to be taken into account. Mathematically, the baseline approach, using a peak-to-tail difference, is not correct; however, from a clinician's point view, the baseline approach is easy to calculate and the value is typically calculated automatically by clinical tympanometers. It is important for clinicians to understand the different tympanometric values may be obtained by using these two different approaches. Therefore, different normative data would be applied accordingly.

To date, there are few studies of conductance and susceptance in NICU babies (Shahnaz et al., 2008). The objectives of the current study were to obtain admittance, susceptance and conductance data from a sample of babies who were in or were graduates of an NICU, to compare tympanometric data obtained from the component compensation approach with the data obtained from traditional baseline approach, and to provide preliminary normative data for NICU babies when the ABR screening was used as the 'gold standard' to indicate middle ear status.

METHODS

Subjects

Thirty one NICU infants (18 males and 13 females) were recruited during hearing screening between 2011-2013 with corrected (or adjusted) ages ranging from 0 weeks to 6 months (mean age 1.30 months; SD 1.43 months), and chronological ages ranging from 1 week to 6 months (mean age 2.22 months; SD 1.53 months). The subjects were recruited according to a protocol approved by research ethics committees at the University of Alberta, the Glenrose Rehabilitation Hospital (GRH) and the Royal Alexandra Hospital (RAH). The consents were obtained from parents or guardians. Subjects were infants admitted to the NICU at the RAH who were screened either during their stay at the RAH or at the GRH soon after discharge from the NICU.

These were babies who would typically have their hearing screening in the NICU based on high-risk criteria including: prematurity (<29 weeks gestational age at birth), low birth weight (<1250 grams at birth), hyperbilirubenemia requiring exchange transfusion, sepsis requiring treatment with antibiotics, etc. These criteria are largely based on the Joint Committee on Infant Hearing (2007) recommendations.

Data collection and analysis

In this study, screening ABR results were used as the 'gold standard' to indicate the infant's middle ear function. This decision was made, in part, because the ABR is the recommended choice for hearing screening in the NICU due to the higher incidence of Auditory Neuropathy Spectrum Disorder in this population (Joint Committee on Infant Hearing, 2007). A "pass" result on the ABR screening required a repeatable Wave V evoked by click stimuli presented at 35 dB nHL for each ear. Each average waveform consisted of at least 1500 individual collections and there were a minimum of 2 average waveforms collected to ensure good replicability. The Wave V latency had to fall within normative limits for the baby's gestational age (local norms were previously collected by GRH audiologists). A Biologic NavPro System was used to collect ABR data. This was not an automated ABR. In order to be enrolled in this study, babies needed to pass the ABR screening. ABR tests and tympanometry were performed by the same tester, who was a registered audiologist. Audiologists collected data for this study were experienced with both ABR screenings and 1000-Hz tympanometry.

The GSI TympStar (version 2; North Carolina) was used for tympanometry measurement. Tympanometry was performed by presenting a 1000 Hz probe tone at 75 ±3 dB SPL into the ear canal (GSI TympStar V2.0 manual). A hand-held probe was used.

Two tympanometry measurements were made for each ear. First, 1000-Hz admittance tympanometry was performed and then the probe tip was removed and reinserted for the second measurement. For the second measurement, 1000-Hz susceptance and conductance were measured. Tympanograms were recorded using a positive to negative sweep pressure method from +200

to -400 daPa with a pump speed varying from 600 daPa/sec at the tails to 200 daPa/sec at the peak. Most tympanometry measurements could be obtained in an ear within a few minutes when the subject was sleeping or awake but inactive. The results of tympanometry were printed out for further analysis. The following tympanometric data were measured for analysis: $+200Y_{TM}$; $-400Y_{TM}$; $+200Y_a$; $-400Y_a$; Y_a @ +200 daPa; Y_a @ -400 daPa; B_{tail} @ +200 daPa; B_{tail} @ -400 daPa; G_{tail} @ +200 da Pa; G_{tail} @ -400 daPa; Y_{peak}; B_{peak}; G_{peak}.

Similar to other reports in this area of research (e.g., Calandruccio, Fitzgerald, & Prieve, 2006; Kei et al, 2003; Margolis et al., 2003; Shahnaz et al., 2008) descriptive statistics were used to analyze the results. The descriptive statistics used in this study were the median and the 5th and 95th percentiles of admittance, susceptance, and conductance.

RESULTS

Typmanometry testing was attempted on 62 ears. Admittance tympanograms were obtained in 52 ears and susceptance and conductance tympanograms were obtained in 48 ears. Tests on 10 ears and 14 ears could not be obtained for admittance measurement and for susceptance and conductance measurements, respectively. The data that could not be obtained were due to infant movement or to a poor seal between the probe and the ear canal. In addition, 8 ears were excluded from this study due to the fact that they failed ABR screening. Therefore, 44 ears were used for admittance analysis and 40 ears were used for susceptance and conductance analysis. Tympanograms were evaluated according to the classification proposed by Kei et al. (2003). They were classified as follows: Type 1 had a single peak; type 2 was flat sloping; type 3 had double peaks. All the other types of tympanograms were considered non-interpretable. Our results showed that tympanograms had a single peak (type 1) for 84% of admittance tests (37/44 ears) and for 70% of susceptance and conductance tests (28/40 ears). A type 2 pattern was found for 7% of admittance tests (3/44 ears) and for 15% of susceptance and conductance (6/40 ears). A type 3 pattern was found for 5% of admittance tests (2/44 ears) and for 8% of susceptance and conductance tests (3/40 ears). The rest were unclassified tympanograms (4% for the admittance test and 7% for the susceptance and conductance test).

In this section, we report our results and compare our data with previously published data. Table 1 shows descriptive statistics of the 1000-Hz susceptance (B) results. This includes the 5th to 95th percentile and the median for: B_{peak}, B_{tail} @+ 200 daPa, B_{tail} @ -400 daPa, $+200B_{TM}$ (Equation 2) and $-400B_{TM}$ (Equation 3). Table 2 shows 1000-Hz conductance results including the 5th to 95th percentile and the median for: G_{peak}, G_{tail} @+ 200 daPa, G_{tail} @ -400 daPa, $+200G_{TM}$ (Equation 4) and $-400G_{TM}$ (Equation 5). Table 3 shows the 5th to 95th percentile and the median results for $+200Y_{TM}$ (Equation 6) and $-400Y_{TM}$ (Equation 7). The 5th to 95th percentile for $+200Y_{TM}$ ranged from 0.5 to 1.7mmho, and the 5th to 95th percentile for $-400Y_{TM}$ ranged from 0.6 to 2.0 mmho. Shahnaz et al. (2008) reported the 5th to 95th percentile for $+250Y_{TM}$ and $-300Y_{TM}$ in 16 healthy full term 3-week old babies were 0.5 to 2.6 mmho and 0.3 to 2.4 mmho, respectively. Alaerts et al. (2007) reported the 5th to 95th percentile for $+200Y_{TM}$ ranged from 0.34 to 2.66 in a combined group of NICU babies and 0-3 month-old healthy babies.

Figure 1 compares the Y_a @ 200 daPa obtained from this study with previously published data. The 5th percentile of Y_a @ 200 daPa obtained in this study is 0.8 mmho, which is in good agreement with the 5th percentile of Y_a @ 200 daPa (0.9 mmho) obtained by Margolis et al. (2003) in 65 babies in the NICU and 0.87 mmho obtained by Shahnaz et al. (2008) in 32 babies in the NICU. The 5th percentile of Y_a @ 200 daPa obtained from healthy babies ranged from 0.37 to 1.44 mmho (Alaerts et al, 2007; Kei et al, 2003; Margolis et al., 2003; Mazlan et al., 2007). The 95th percentile of Y_a @ 200 daPa obtained in this study is 3.0 mmho, which is higher than values obtained by Margolis et al. (2003) and Shahnaz et al. (2008) in NICU babies. Our result is generally consistent with results (3.07 mmho) obtained in healthy babies reported by Alaerts et al. (2007).

Figure 2 compares the Y_a @ -400 daPa obtained from this study with previously published data. The 5th to 95th percentile of Y_a @ -400 daPa obtained in this study ranged from 0.4 to 1.8 mmho. Margolis et al. (2003) reported the 5th to 95th the percentile of Y_a @ -400 daPa to be from 0.4 to 1.0 mmho for babies in the NICU and from 0.3 to 1.4 for healthy full term babies. Shahnaz et al. (2008) reported values (using -300Y) from 0.4 to 1.2 mmho in NICU babies. Kei et al. (2007) reported values in healthy babies from 0.36 to 2.38 mmho.

Figure 3 compares the Y_{peak} obtained from this study with previously published data. The 5th to 95th percentile of Y_{peak} obtained in this study ranged from 1.0 to 3.8 mmho. Margolis et al. (2003) reported the 5th to 95th the percentile of Y_{peak} to be from 1.3 to 2.4 mmho for babies in the NICU and from 1.2.to 4.8 mmho for healthy full term babies. Mazlan et al. (2007) reported 5th to 95th percentile of Y_{peak} to be from 0.7 to 4.2 mmho for healthy babies at

birth and 1.16 to 4.5 mmho for healthy babies of 6 to 7 weeks old.

Figure 4 compares 5th to 95th percentiles of $+200Y_a$ (Equation 8) obtained in this study with previously published data (baseline approach). In this study the 5th to 95th percentile of $+200Y_a$ ranged from 0.2 to 1.2 mmho. The published 5th percentile of $+200Y_a$ ranged from 0.1 to 0.2 mmho in NICU babies (Margolis et al., 2003; Shahnaz et al., 2008) and ranged from 0.1 to 0.35 mmho in healthy babies (Kei et al, 2007; Margolis et al., 2003; Mazlan et al., 2007). The published 95th percentile of +20000 ranged from 1.5 to 1.6 mmho in NICU babies (Margolis et al., 2003; Shahnaz et al., 2008) and ranged from 1.5 to 3.5 mmho in healthy babies (Kei et al., 2007; Margolis et al, 2003; Mazlan et al., 2007)

Figure 5 compares the 5th to 95th percentile of the $-400Y_a$ (Equation 9) obtained from this study and published data (baseline approach). In current study the 5th to 95th percentile of $-400Y_a$ ranged from 0.4 to 2.0 mmho. The 5th percentile of $-400Y_a$ was reported 0.6 mmho by Margolis et al. (2003) for both healthy and NICU babies; and 0.53 mmho in NICU babies by Shahnaz et al. (2008). The 95th percentile of $-400Y_a$ were 2.7 mmho in NICU babies and 4.3 mmho in healthy babies by Margolis et al. (2003) and 2.3 mmho in NICU babies by Shahnaz et al. (2008).

DISCUSSION AND CLINICAL IMPLICATIONS

In this study, we considered the ABR screening results as the 'gold standard' to indicate middle ear status. Normal ABR screening results do not indicate normal auditory or middle ear function. Theoretically myringotomy is the most accurate gold standard to confirm middle ear dysfunction (Marchant et al., 1986); however, it is an expensive and invasive procedure. The use of the ABR as the gold standard for middle ear function is a clear limitation of this study. As indicated in the methods section, the Joint Committee on Infant Hearing (2007) recommends ABR testing for UNHS in the NICU because it is more sensitive to auditory neuropathy spectrum disorder, which has a higher prevalence in the NICU population. It also has a more acceptable "Pass" rate in the NICU. For these reasons, the ABR is the standard screening in the NICU and it was therefore chosen as the gold standard to make this study clinically feasible.

In this study admittance tympanograms were obtained in 52 ears out of 62 ears. This "success" rate was 84%. Similar results were reported by Margolis et al. (2003). They reported that tympanograms could be obtained from 77/88 (87.5%) ears of babies in the NICU. Kei et al. (2003) performed 1000-Hz tympanometry in 170 healthy full term

Table 1. Descriptive statistics of the 1000-Hz susceptance (B) results.

	B_{peak} (mmho)	B_{tail} @ +200 daPa (mmho)	B_{tail} @ -400 daPa (mmho)	$+200B_{TM}$ (mmho)	$-400B_{TM}$ (mmho)
5%	1.1	1.0	0.5	0.3	0.5
Median	1.6	1.4	1.0	0.6	0.9
95%	3.1	2.8	2.7	1.3	1.6

Table 2. Descriptive statistics of the 1000-Hz conductance (G) results.

	G_{peak} (mmho)	G_{tail} @ +200 daPa (mmho)	G_{tail} @ -400 daPa (mmho)	$+200G_{TM}$ (mmho)	$-400G_{TM}$ (mmho)
5%	0.5	0.3	0.1	0.3	0.3
Median	1.6	0.9	0.7	0.6	0.8
95%	2.3	1.7	1.2	1.0	1.2

Table 3. Descriptive statistics of component compensation admittance at tympanic membrane.

	+200Y™ (mmho)	-400Y™ (mmho)
5%	0.5	0.6
Median	1.0	1.2
95%	1.7	2.0

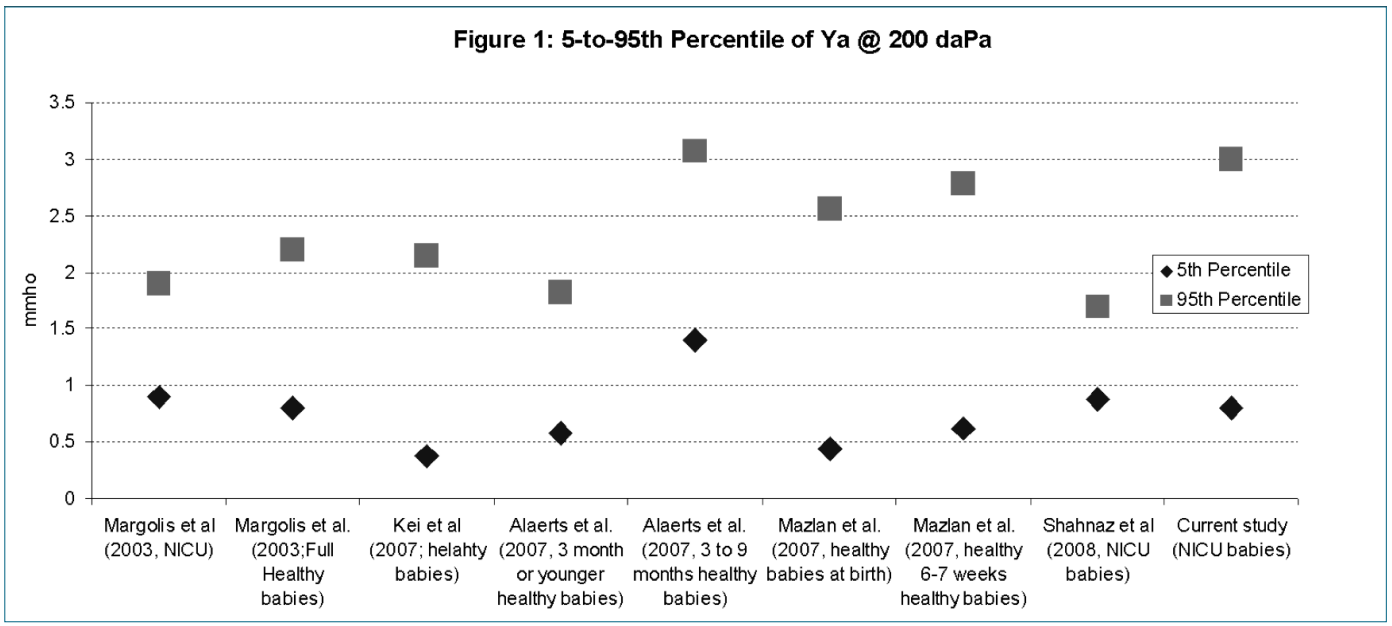

Figure 1. Comparison of Ya @ +200 daPa obtained from this study and published data.

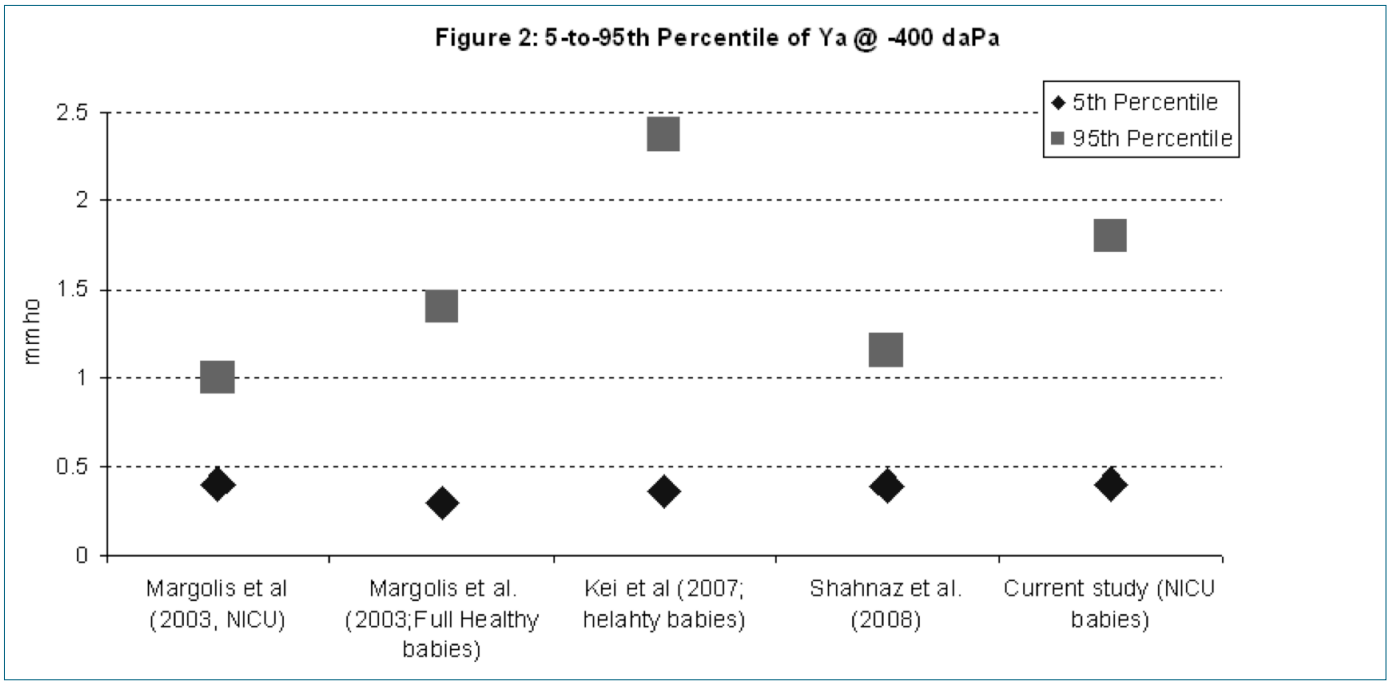

Figure 2. Comparison of Ya @ -400 daPa obtained from this study and published data.

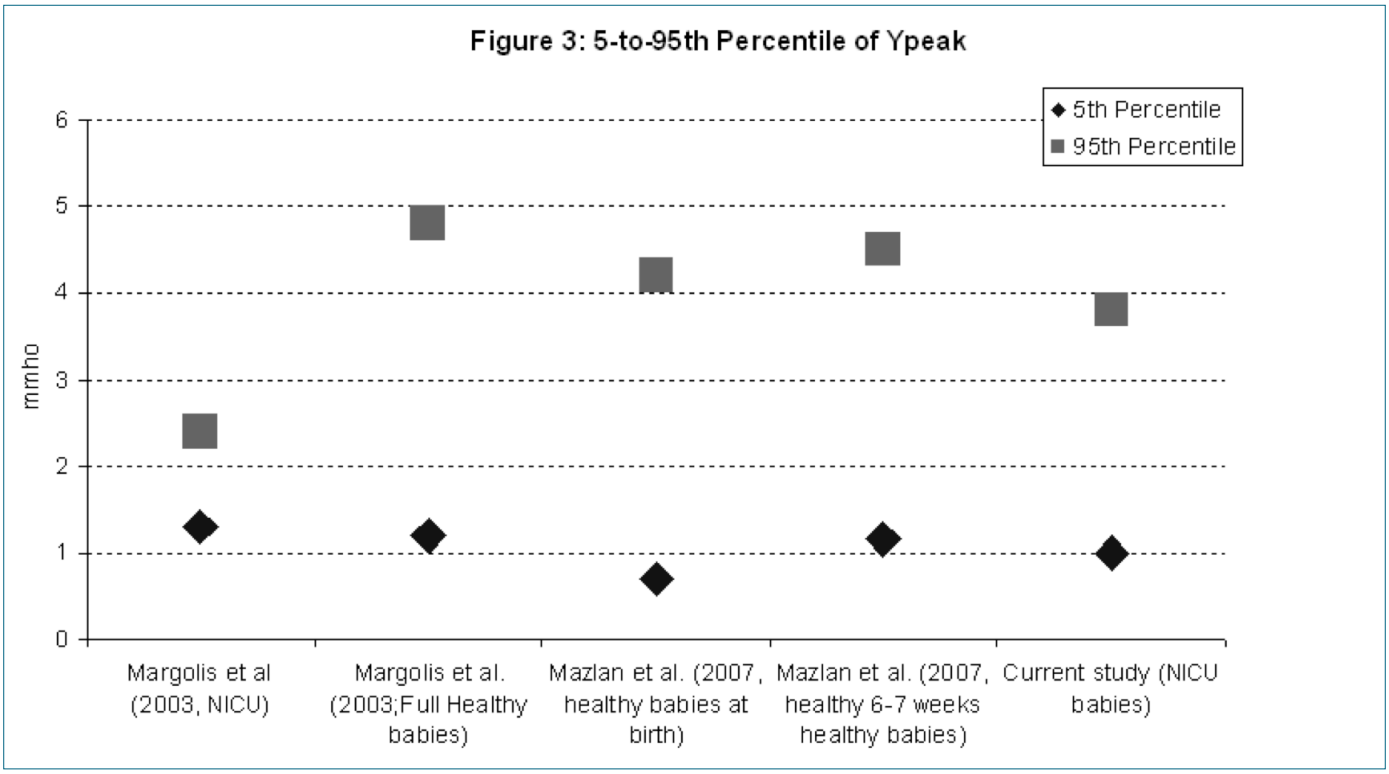

Figure 3. Comparison of the Ypeak obtained from this study and published data.

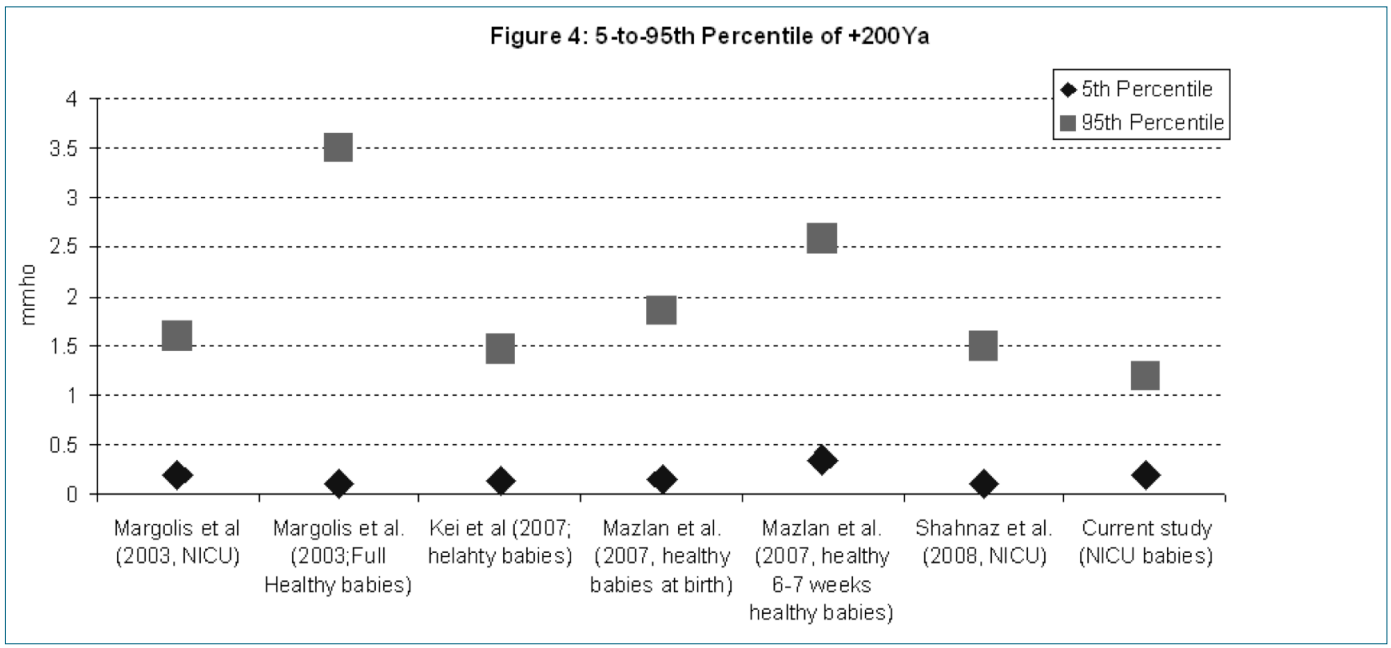

Figure 4. Comparison of the +200Ya obtained in this study and published data (baseline approach).

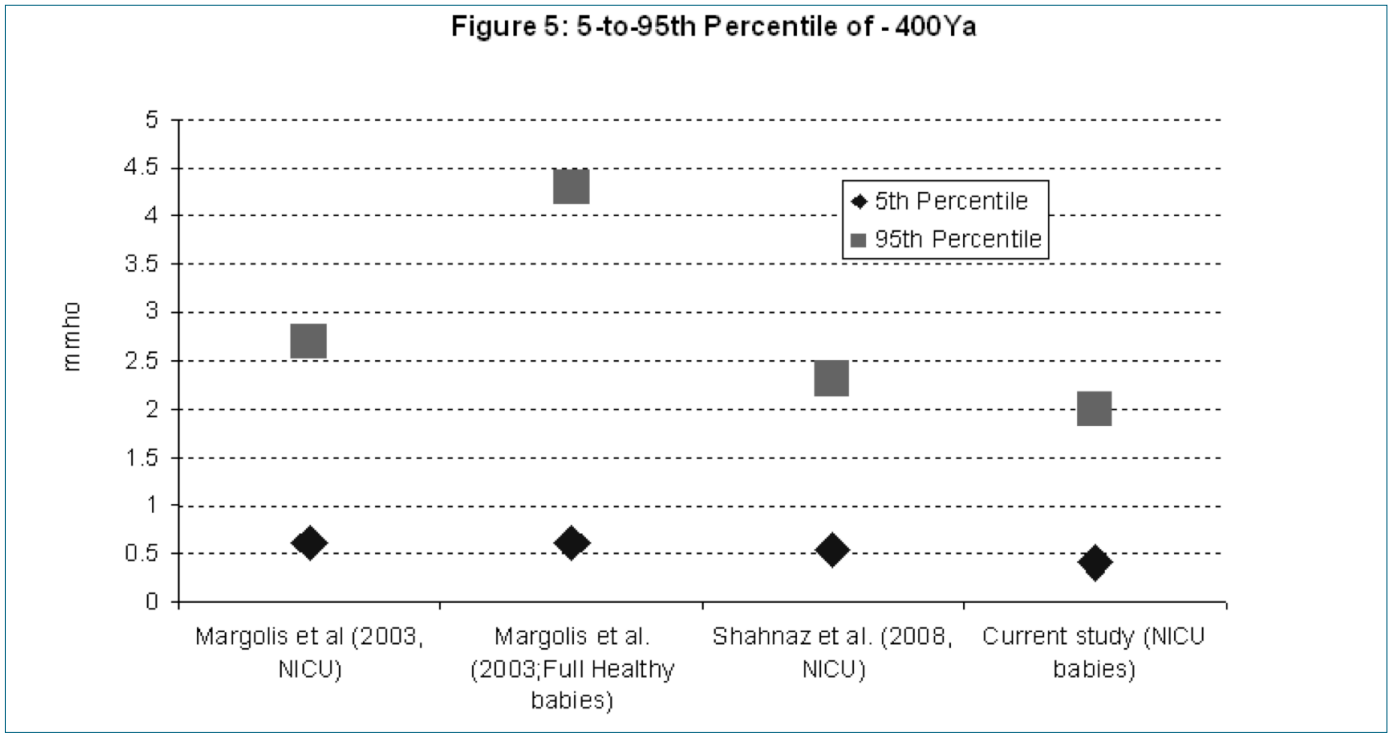

Figure 5. Comparison of -400Ya obtained from this study and published data (baseline approach).

babies (340 ears) and they obtained tympanograms in 299 ears (88%).

In our study, among the different tympanograms, single peaked tympanograms were the most observed type (84% of admittance and 70% of susceptance and conductance). Kei et al. (2003) reported that they obtained 92% single-peaked 1000-Hz admittance in 244 ears of full term healthy babies. Margolis et al. (2003) reported that nearly all infants with single-peaked admittance passed OAE screening. Alaerts et al. (2007) reported a distribution of tympanograms types based on the Liden and Jerger classification systems and the Vanhuyse model. Their results showed that for infants younger than 3 months of age 90% of them had single-peaked admittance and about 50% had 1B1G. Similar results were also reported by other studies (e.g. Shahnaz et al., 2008; Calandruccio et al., 2006). The more complicated type of tympanogram observed in susceptance and conductance measurements were likely due to the fact that the newborn middle ear is a mass-dominated system (e.g., Shahnaz et al. 2014). From a clinician's point of view, a simple and easy-to-interpret classification system is preferred when possible. For this reason, admittance measurement would likely be favored by most clinicians since these measurements result in a higher percentage of single-peaked tympanograms, which are easier to interpret.

Middle ear admittance can be estimated using a baseline approach or a component compensation approach. For 1000-Hz tympanometry in healthy newborns, both methods have been investigated (Kei et al., 2003; Margolis et al., 2003; Prieve et al., 2013). For the baseline approach, admittance at the tympanic membrane can be estimated by subtracting the admittance at the positive tail or at the negative tail (peak-to-tail difference method). Margolis et al (2003) found that the 5th percentile of negative-tail-compensated admittance for babies in the NICU and for full-term healthy babies was identical, suggesting a single pass-fail criterion for both groups. They recommended using the negative tail to compensate middle ear admittance because the admittance obtained from negative tails has a larger value, which may make it easy for distinguishing normal results from abnormal results. Kei et al. (2007) recommended using a positive-tail compensation approach because it has higher test-retest reliability for healthy newborns. This finding may be related to the tendency of the newborn ear canal to collapse (due to the compliant nature of the canal) when using negative pressure (Keefe , Bulen, Arehart, & Burns, 1993).

The baseline and the component compensation approaches have different advantages. Most frontline clinicians are familiar with the baseline approach. In addition, middle ear admittance can be easily estimated by

using the peak-to-tail difference approach. The component compensation approach is a more accurate estimate of the middle ear admittance (Kei et al., 2007); however, it needs to be manually calculated which may significantly limit its use. The purpose of this study is not to justify one approach over another. This will require further study.

The difference in admittance values (mmho) from the various studies may be associated with the difference between the component compensation approach and the baseline approach. For example, in the current study, in which we calculated susceptance and conductance, the 5th percentiles of +200Y_{TM} (component compensated from positive tail) and -400Y_{TM} (component compensation from negative tail) were 0.5 and 0.6 mmho; these values are higher than the peak-to-tail compensated (baseline approach) admittance reported above. Such difference in admittance is consistent with a previous report by Kei et al. (2007) who showed the component compensation middle ear admittance to be greater than the baseline compensated admittance.

The difference in admittance values (mmho) from the various studies could be also due to factors, such as sample size, age, and race. Instrumentation also plays a key role in tympanometry measurement. Previous research has shown that different middle ear analyzers may have different measurement results (e.g., Margolis & Popelka, 1975). In our study, we used a middle ear analyzer (GSI TympStar version 2) as used by Margolis et al. (2003). Kei et al. (2007) used a Madsen Capella (version 2.1) OAE/middle ear analyzer. Shahnaz et al. (2008) used a Madsen Capella (version 2.1) OAE/middle ear analyzer.

Studies have also shown that age specific normative tympanometric criteria for newborns and young infants might be required (Alaerts et al., 2007; Calandruccio et al., 2006; Mazlan et al., 2007; Shahnaz et al. 2014) recently investigated 1000 Hz tympanometry and wideband reflectance energy in infants from newborn up to six months of age using a longitudinal approach. A similar study would also be valuable for NICU babies.

Recent studies have shown that different tympanometric criteria might be needed for different ethnic groups (Beers, Shahnaz, Westerberg, & Kozak, 2010; Shahnaz & Bork, 2006; Shahnaz & Davies, 2006; Shahnaz, Feeney, & Schairer, 2013). This might warrant a comparison of study of 1000-Hz tympanometry in newborns amongst different ethnic groups.

In addition to the use of the screening ABR as a 'gold standard' for middle ear status as discussed above, other limitations of this study include a relatively small sample size and the fact that the admittance, susceptance and conductance were manually estimated, which may have introduced some errors in data analysis. A larger sample size study with computer estimated data is desired. Another source of difference between current study and other published studies in NICU babies is the wider age range used in this study.

CONCLUSIONS

This study showed that 1000-Hz tympanometry can be used with some success as a part of hearing screening in the NICU. The component compensation and the traditional baseline approach have different advantages and limitations. A further study comparing clinical performance of both methods in a large NICU sample is needed. An age-related normative tympanometry study for NICU babies is desired as well.

References

Alaerts, J., Luts, H., & Wouters, J. (2007). Evaluation of middle ear function in young children: Clinical guidelines for the use of 226- and 1,000-Hz tympanometry. *Ontology & Neurotology, 28*, 727-732.

Anson, B. J., & Donaldson, J. A. (1981). *Surgical anatomy of the temporal bone*. Philadelphia, Pennsylvania: W.B. Saunders.

Baldwin M. (2006). Choice of probe tone and classification of trace patterns in tympanometry undertaken in early infancy. *International Journal of Audiology, 45*, 417-427.

Beers, A. N., Shahnaz, N., Westerberg, B. D., & Kozak, F. K. (2010). Wideband reflectance in normal Caucasian and Chinese school-aged children and in children with otitis media with effusion. *Ear and Hearing, 31*, 221-233.

Calandruccio, L., Fitzgerald, T. S., & Prieve, B. A. (2006). Normative multifrequency tympanometry in infants and toddlers. *Journal of the American Academy of Audiology, 17*, 470-480.

Cristobal, R., & Oghalai, J. S. (2008). Hearing loss in children with very low birth weight: Current review of epidemiology and pathophysiology. *Archives of Disease in Childhood: Fetal Neonatal Edition, 93*, 462-468.

Gulya, A. J. (2007). *Anatomy of the temporal bone with surgical implications* (3rd ed.). , New York: Informa Healthcare USA, Inc.

Holte, L., Cavanaugh, R. M., Jr., & Margolis, R. H. (1990). Ear canal wall mobility and tympanometric shape in young infants. *Journal of Pediatrics, 117*, 77-80.

Hunter, L. L., Feeney, M. P., Lapsley Miller, J. A., Jeng, P. S., & Bohning, S. (2010). Wideband reflectance in newborns: Normative regions and relationship to hearing-screening results. *Ear and Hearing, 31*, 599-610.

Hunter, L. L., Tubaugh, L., Jackson, A., & Propes, S. (2008). Wideband middle ear power measurement in infants and children. *Journal of American Academy of Audiology, 19*, 309-324.

Joint Committee on Infant Hearing. (2007). Year 2007 position statement: Principles and guidelines for early hearing detection and intervention programs. *Pediatrics, 120*, 898-921.

Keefe, D. H., Bulen, J. C., Arehart, K. H., & Burns, E. M. (1993). Ear-canal impedance and reflection coefficient in human infants and adults. *The Journal of the Acoustical Society of America, 94*, 2617-2638.

Keefe, D. H., Folsom, R. C., Gorga, M. P., Vohr, B. R., Bulen, J. C., & Norton, S. J. (2000). Identification of neonatal hearing impairment: Ear-canal measurements of acoustic admittance and reflectance in neonates. *Ear and Hearing, 21*, 443-461.

Kei, J., Allison-Levick, J., Dockray, J., Harrys, R., Kirkegard, C., Wong, J., ... Tudehope, D. (2003). High-frequency (1000 Hz) tympanometry in normal neonates. *Journal of American Academy of Audiology, 14*, 20-28.

Kei, J., Mazlan, R., Hickson, L., Gavranich, J., & Linning, R. (2007). Measuring middle ear admittance in newborns using 1000 Hz tympanometry: A comparison of methodologies. *Journal of American Academy of Audiology, 18*, 739-748.

Marchant, C. D., McMillan, P. M., Shurin, P. A., Johnson, C. E., Turczyk, V. A., Feinstein, J. C., & Panek, D.M. (1986). Objective diagnosis of otitis media in early infancy by tympanometry and ipsilateral acoustic reflex thresholds. *Journal of Pediatrics, 109*, 590-595.

Margolis, R. H., Bass-Ringdahl, S., Hanks, W. D., Holte, L., & Zapala, D. A. (2003). Tympanometry in newborn infants--1 kHz norms. *Journal of American Academy of Audiology, 14*, 383-392.

Margolis, R.H., & Popelka, G.R. (1975) Interactions among tympanometric variables. *Journal of Speech and Hearing Research. 20*, 447-462.

Mazlan, R., Kei, J., Hickson, L., Stapleton, C., Grant, S., Lim, S., & Gavranich, J. (2007). High frequency immittance findings: Newborn versus six-week-old infants. *International Journal of Audiology, 46*, 711-717.

McLellan, M. S., & Webb, C. H. (1957). Ear studies in the newborn infant: Natural appearance and incidence of obscuring by vernix, cleansing of vernix, and description of drum and canal after cleansing. *Journal of Pediatrics, 51*, 672-677.

Merchant, G. R., Horton, N. J., & Voss, S. E. (2010). Normative reflectance and transmittance measurements on healthy newborn and 1-month-old infants. *Ear and Hearing, 31*, 746-754.

Nelson, H. D., Bougatsos, C., & Nygren, P. (2008). Universal newborn hearing screening: Systematic review to update the 2001 US Preventive Services Task Force Recommendation. *Pediatrics, 122*, e266-276.

Northern, J., & Downs, M. (2002). *Hearing in Children* (5 ed.). Baltimore, MD: Lippincott Williams & Wilkins.

Prieve, B. A., Vander Werff, K. R., Preston, J. L., & Georgantas, L. (2013). Identification of conductive hearing loss in young infants using tympanometry and wideband reflectance. *Ear and Hearing, 34*, 168-178.

Qi, L., Funnell, W. R., & Daniel, S. J. (2008). A nonlinear finite-element model of the newborn middle ear. *The Journal of the Acoustical Society of America, 124*, 337-347.

Qi, L., Liu, H., Lutfy, J., Funnell, W. R., & Daniel, S. J. (2006). A nonlinear finite-element model of the newborn ear canal. *The Journal of the Acoustical Society of America, 120*, 3789-3798.

Resende L. M., Ferreira J. S., Carvalho S. A., Oliveira I. S., & Bassi I. B. (2012). Tympanometry with 226 and 1000 Hertz tone probes in infants. *Revista Brasileira de Otorrinolaringologia, 78*, 95-102.

Sanford, C. A., & Feeney, M. P. (2008). Effects of maturation on tympanometric wideband acoustic transfer functions in human infants. *The Journal of the Acoustical Society of America, 124*, 2106-2122.

Saunders, J. C., Doan, D. E., & Cohen, Y. E. (1993). The contribution of middle-ear sound conduction to auditory development. *Comparative Biochemistry and Physiology, 106A*, 7-13.

Shahnaz, N. (2008). Wideband reflectance in neonatal intensive care units. Journal of American Academy of Audiology, 19, 419-429.

Shahnaz, N., & Bork, K. (2006). Wideband reflectance norms for Caucasian and Chinese young adults. *Ear and Hearing, 27*, 774-788.

Shahnaz, N., Cai, A., & Qi, L. (2014). Understanding the developmental course of the acoustic properties of the human outer and middle ear over the first 6 months of life by using a longitudinal analysis of power reflectance at ambient pressure. *Journal of American Academy of Audiology, 25*, 495-511.

Shahnaz, N., & Davies, D. (2006). Standard and multifrequency tympanometric norms for Caucasian and Chinese young adults. *Ear and Hearing, 27*, 75-90.

Shahnaz, N., Feeney, M. P., & Schairer, K. S. (2013). Wideband acoustic immittance normative data: Ethnicity, gender, aging, and instrumentation. *Ear and Hearing, 34*, 27s-35s.

Shahnaz, N., Miranda, T., & Polka, L. (2008). Multifrequency tympanometry in neonatal intensive care unit and well babies. *Journal of American Academy of Audiology, 19*, 392-418.

Shahnaz, N., & Polka, L. (2002). Distinguishing healthy from otosclerotic ears: Effect of probe-tone frequency on static immittance. *Journal of American Academy of Audiology, 13*, 345-355.

Son E. J., Park, Y. A., Kim, J. H., Hong, S. A., Lim, H. Y., Choi, J. Y., & Lee, W.S.. (2012). Classification of trace patterns of 226- and 1000-Hz tympanometry in healthy neonates. *Auris, Nasus, Larynx, 39,* 455-460.

Stuart, A., Yang, E. Y., & Green, W. B. (1994). Neonatal auditory brainstem response thresholds to air- and bone-conducted clicks: 0 to 96 hours postpartum. *Journal of American Academy of Audiology, 5*, 163-172.

Swanepoel, D.W., Werner, S., Hugo, R., Louw, B., Owen, R., & Swanepoel, A. (2007). High frequency immittance for neonates: A normative study. *Acta Oto-laryngologica, 127*, 49-56.

Thompson, D. C., McPhillips, H., Davis, R. L., Lieu, T. L., Homer, C. J., & Helfand, M. (2001). Universal newborn hearing screening: Summary of evidence. *Journal of the American Medical Association, 286*, 2000-2010.

Yoon, P. J., Price, M., Gallagher, K., Fleisher, B. E., & Messner, A. H. (2003). The need for long-term audiologic follow-up of neonatal intensive care unit (NICU) graduates. *International Journal of Pediatric Otorhinolaryngology, 67*, 353-357.

Zhang, M., & Abbas, P. J. (1997). Effects of middle ear pressure on otoacoustic emission measures. *The Journal of the Acoustical Society of America, 102*, 1032-1037.

Zhao, F., Wada, H., Koike, T., & Stephens, D. (2000). The influence of middle ear disorders on otoacoustic emissions. *Clinical Otolaryngology and Allied Sciences, 25*, 3-8.

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