Multifrequency Tympanometry in Neonatal Intensive Care Unit and Well Babies

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Abstract

Background: Conventional low probe tone frequency tympanometry has not been successful in identifying middle ear effusion in newborn infants due to differences in the physiological properties of the middle ear in newborn infants and adults. With a rapid increase in newborn hearing screening programs, there is a need for a reliable test of middle ear function for the infant population. In recent years, new evidence has shown that tympanometry performed at higher probe tone frequencies may be more sensitive to middle ear disease than conventional low probe tone frequency in newborn infants.

Purpose: The main goal of this study was to explore the characteristics of the normal middle ear in the NICU (neonatal intensive care unit) and well babies using conventional and multifrequency tympanometry (MFT). It was also within the scope of this study to compare conventional and MFT patterns in NICU and well babies to already established patterns in adults to identify ways to improve hearing assessment in newborns and young infants.

Methods: Three experiments were conducted using standard and MFT involving healthy babies and NICU babies. NICU babies (n = 33), healthy three-week-old babies (n = 16), and neonates on high-priority hearing registry (HPHR) (n = 42) were tested. Thirty-two ears of 16 healthy Caucasian adults (compared to well-babies) and 47 ears of 26 healthy Caucasian adults (compared to NICU babies) were also included in this study.

Results: The distribution of the Vanhuyse patterns as well as variation of admittance phase and peak compensated susceptance and conductance at different probe tone frequencies was also explored. In general, in both well babies and NICU babies, 226 Hz tympanograms are typically multi-peaked in ears that passed or referred on transient otoacoustic emission (TEOAE), limiting the specificity and sensitivity of this measure for differentiating normal and abnormal middle ear conditions. Tympanograms obtained at 1 kHz are potentially more sensitive and specific to presumably abnormal and normal middle ear conditions. Tympanometry at 1 kHz is also a good predictor of presence or absence of TEOAE.

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

Abbreviations: ϕ = phase of admittance; AABR = automatic auditory brainstem response; ABR = auditory brainstem response; ANSI = American National Standards Institute; B = susceptance; BOA = behavioral observation audiometry; CGA = corrected gestational age; EOAE = evoked otoacoustic emission; G = conductance; GA = gestational age; HPHR = high-priority hearing registry; JCIH = Joint Committee on Infant Hearing; MFT = multifrequency tympanometry; NICU = neonatal intensive care unit; OAE = otoacoustic emission; OM = otitis media; OME = otitis media with effusion; SA = static admittance; SP = sweep pressure; TEOAE = transient otoacoustic emission; TPP = tympanometric peak pressure; TW = tympanometric width; UNHS = universal newborn hearing screening; VOA = visual observation audiometry; Y = admittance; Ya = uncompensated admittance magnitude; Ytm = compensated admittance

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Universal newborn hearing screening (UNHS) is rapidly becoming the “standard of care” in Canada and the United States. Despite the accelerating implementation of UNHS, delays in confirmation of hearing loss and initiation of intervention (e.g., medical treatment, prescription of hearing aids) continue to limit the effectiveness of UNHS programs. Current neonatal screening protocols do not distinguish between conductive and sensorineural hearing loss at the time of detection. This diagnosis is delayed until audiological tests are performed later, often at 3 and 6 months of age. Nevertheless, the identification of hearing loss type is very important because the course of medical and audiological intervention differs for conductive and sensorineural impairment. Uncertainty regarding the nature of the hearing loss may lead to potential delay in medical treatment and audiological intervention, which, in turn, may have serious consequences on health and development of speech and language. Although often temporary in nature, untreated conductive hearing loss, when present early in life, can have serious consequences for infant health and development (Sak and Ruben, 1982; Friel-Patti et al, 1986; Wallace et al, 1988; Roland et al, 1989; Menyuk, 1992; Petinou et al, 2001). The most common cause of conductive hearing loss among infants is otitis media with effusion (OME).

Infection of the middle ear, or otitis media (OM), is one of the most commonly diagnosed illnesses, and it is likely the most prevalent illness among children in...
Canada and the United States—and probably among children all over the world (Paradise et al, 1997; Koivunen, 1999). Several studies have shown that OME occurs commonly in healthy neonates. The prevalence of OME has been shown to be 20 per 1000 births (Maxon et al, 1993). The incidence of OME within the first 2 months of life has been shown to be 33% (Marchant et al, 1984). More recently, Engel et al (1999) reported the prevalence of OME in healthy newborns to be around 19%. Moreover, OME has been documented in up to 30% of infants in the neonatal intensive care unit (NICU)—a result likely due to the use of nasotracheal tubes for ventilation in the NICU (Berman et al, 1978; Petalozza et al, 1988; Salamy et al, 1989). Therefore, there is evidence that the incidence of OME is reasonably high both in normal newborns and newborns in the NICU. Currently, there are no clear guidelines for the management of OM in infants under 1 year of age. This absence is partly due to a lack of efficient diagnostic tools for detecting OM in this group, which stems from our limited understanding of the physical properties of the middle ear in infants.

There is a need to develop standardized procedures (and criteria) for differentiating conductive hearing loss from sensorineural hearing loss in early infancy. Currently, there are no otoscopic or tympanometric criteria for identification of outer and middle ear disorders in newborns (Gravel et al, 1995; Fowler and Shanks, 2002). Physiological measures, such as the auditory brainstem response (ABR) and evoked otoacoustic emission (EOAE), have the advantage of providing noninvasive, objective, and ear-specific information in newborns, who are typically difficult to test behaviorally. ABR screening does not effectively distinguish between mild sensorineural hearing loss and conductive hearing loss (Hunter and Margolis, 1992).

A more-complicated “diagnostic” ABR that compares air-and bone-conduction can be used effectively to differentiate conductive hearing loss from sensorineural hearing impairment (Stapells, 2000). However, the analysis time and level of expertise that this procedure involves makes it too difficult, costly, and inappropriate as a screening tool. Moreover, EOAE cannot differentiate conductive hearing loss from sensorineural hearing loss and is overly sensitive to conductive hearing loss in comparison to ABR (Naeve et al, 1992; Smurzynski et al, 1992; Zhao et al, 2000). 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, 1988; 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). At this time, there is considerable interest in developing efficient and rapid procedures for separating infants who fail newborn screening by ABR or by EOAE as a result of conductive hearing loss from those infants who fail because of sensorineural hearing loss. Obviously, the course of medical and audiological hearing loss is quite sensitive to mild middle ear impairment (Owens et al, 1992; Koivunen et al, 2000). At this time, there is considerable interest in developing efficient and rapid procedures for separating infants who fail newborn screening by ABR or by EOAE as a result of conductive hearing loss from those infants who fail because of sensorineural hearing loss. Obviously, the course of medical and audiological hearing loss is quite different for the two types of impairment.

A very promising physiologic test that could address the need to differentiate conductive hearing loss from sensorineural hearing loss is multifrequency tympanometry (MFT). Standard low-frequency tympanometry (220 or 226 Hz) was first conducted with infants under age 6 months as early as 1973 (Keith, 1973). However, tympanometric patterns observed in newborn infants do not conform to the classic patterns found in older infants, children, and adults. For example, with respect to tympanometric shape, infants younger than age 6 months who had surgically confirmed OME often present low-frequency tympanograms that appear normal and bell shaped with single or notched peak (Paradise et al, 1976; Marchant et al, 1986; Hirsch et al, 1992; Rhodes et al, 1999; Margolis et al, 2003).

These patterns are not typical of a child or adult ear with OME. 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 change up to 70% in response to the pressure changes implemented in tympanometry (Holte et al, 1990). Nevertheless, Holte et al (1990) have shown that greater mobility of the newborn ear canal is not solely responsible for the irregular tympanometric shape observed in young babies. Rather, Holte and colleagues showed that the highly distensible ear canal of the neonate has the greatest effect on the tails of the tympanograms that are used to estimate ear canal volume.

The external auditory canal and middle ear undergo structural changes over the first 2 years after birth, which can affect the physical properties of sound transmission to the cochlea. Some of these physical changes include (a) an increase in size of the external ear (Anson and Donaldson, 1981) and of the middle ear cavity and mastoid (Eby and Nadol, 1986; Ikui et al, 2000); (b) a change in the orientation of the ear drum (Eby and Nadol, 1986); (c) a decrease in the overall mass of the middle ear as a result of changes in bone density (Anson and Donaldson, 1981) or because of loss of amniotic fluid in the middle ear (Paparella et al, 1980); (d) a tightening of the joints of the middle ear bones (Anson and Donaldson, 1981); and (e) a fusing of the tympanic ring and formation of the bony ear canal wall (Saunders et al, 1993).
The presence of residual amniotic fluid and menses-chyme in the ear canal and middle ear of newborns may also be relevant in understanding the physics of the newborn ear given that small amounts of fluid or debris against the eardrum (in the middle or outer ear) increase both mass and resistance in children and adult ears. However, this argument is weakened by the finding that neonatal chinchillas with clean middle ears have the same kind of chaotic impedance characteristics as human infants (Hsu et al, 2000; Hsu et al, 2001). Although the precise factors involved are not clear, on the basis of tympanometric data, the newborns’ middle ear impedance characteristics appear to be dominated by the effect of mass and resistive elements at low probe-tone frequencies (Holte et al, 1991). This finding contrasts with the middle ear impedance characteristics in young children and adults, which are dominated by the effect of stiffness elements at low probe-tone frequencies (Shahnaz and Polka, 1997). Therefore, the tympanometric characteristics of neonates are sufficiently different from adults to deserve a unique definition of normal.

With the development of clinical instruments that can perform MFT, it is possible to record tympanograms across a wide range of probe-tone frequencies. This technique would also allow the assessment of the relative contribution of stiffness, mass, and resistive elements of the middle ear. To date, the advantage of MFT over standard frequency tympanometry has been confirmed in adults for detecting pathologies such as otosclerosis (Shahnaz and Polka, 1997, 2002) and ossicular discontinuity (Lilly, 1984; Funasaki and Kumakawa, 1988; Hunter and Margolis, 1992; Valvik et al, 1994). 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; Calandrucio et al, 2006).

Glidden and Sutton (2001) assessed 100 NICU and 100 well babies at birth and at age 8 months using 220 Hz and 660 Hz tympanometry and acoustic reflexes. Admittance tympanograms were recorded using a Grason-Stadler GSI-33 (Version 2). Tympanograms were defined as abnormal if they (a) were flat, (b) had static admittance (SA) (derived with positive-tail compensation) below 0 mmho, or (c) had SA above 0 mmho with negative middle ear pressure of less than 100 daPa. Using these criteria, they found that, among NICU babies, an abnormal 660 Hz tympanogram at birth is one of the best predictors of OME at age 8 months.

Kei et al (2003) reported data on 226 Hz and 1000 Hz admittance tympanograms in 122 healthy neonates (age 1 to 6 days) with normal TEOAE results using a Madsen Capella OAE/middle ear analyzer. For infants who passed the TEOAE screen, they found three different types of admittance tympanograms at 1000-Hz probe-tone frequency. Type 1, the single-peak tympanogram, was the most commonly occurring (92.2%) tympanogram at this frequency. Type 2, a flat tympanogram, was observed in 5.7% of the infants, and type 3, a double-peak tympanogram, was observed in 1.2% of the infants. A notched 226 Hz tympanogram was recorded for 47.5% of these infants. Kei et al concluded that the type 1 (single-peak) tympanogram probably indicates normal middle ear function. They also noted that the few infants with type 2 tympanograms who passed the TEOAE screen exhibited a less-robust TEOAE that could indicate a compromised middle ear condition.

Margolis et al (2003) reported normative data for 1 kHz admittance tympanograms in 65 NICU graduates tested at a mean age of 3.7 weeks (gestational age [GA]: 37 weeks) and in 30 full-term infants who were tested at age 2–4 weeks and who passed an otoacoustic emission (OAE) screen. These study set the pass–fail criterion at the fifth percentile (95% passed). These norms were then applied to 1 kHz tympanograms from two groups of full-term babies and one group of NICU graduates. The negative-tail compensated SA was selected for the pass–fail criterion because the negative tail side had a larger mean value than the positive tail side. Nearly all of the infants who passed the OAE screening had a single-peak tympanogram at 1 kHz, and 91% also presented passing SA measures. Moreover, infants who passed the OAE screening had significantly higher 1 kHz SA than those who failed, suggesting a strong relationship between middle ear transmission characteristics and OAE responses.

Vanhuyse et al (1975) examined tympanometric patterns in adults at various probe-tone frequencies and developed a model that predicts the shape of susceptance (B) and conductance (G) tympanograms at 678 Hz in normal ears and in various pathologies. Later, this model was extended to higher probe-tone frequencies (Margolis and Goycoolea, 1993). The Vanhuyse model categorizes the tympanograms on the basis of the number of peaks or extrema on the B and G tympanograms, and it predicts four tympanometric patterns at 678 Hz. For example, the 1B1G pattern has one peak on the B tympanogram and one peak on the G tympanogram; 3B1G has two peaks (maxima) and one trough (minima) on the B tympanogram and one peak on the G tympanogram.

Calandrucio et al (2006), McKinley et al (1997), and Sprague et al (1985) used the Vanhuyse model to classify tympanograms recorded in neonates. Calandrucio et al (2006) measured multifrequency and multicomponent tympanometry in 33 infants at multiple times between age 4 weeks and 2 years using the Virtual-310 middle ear analyzer. They found that the typical Vanhuyse patterns observed in their younger infants and adults differed, especially at 1 kHz probe-tone frequency. Specifically, for the 1 kHz
tympanograms, most adults (80%) had a 3B1G pattern, whereas infants and toddlers were equally likely to show either a 1B1G or a 3B1G pattern.

McKinley et al (1997) recorded multicomponent tympanometry at 226, 678, and 1000 Hz in 55 healthy, full-term infants (less than 24 hours old) using the Virtual-310 middle ear analyzer. At 226 Hz, most of the infants they tested had single- or multiple-peak tympanograms, and more than half of the infants had a resonant frequency below 226 Hz. At 678 Hz, 62% of the infants had flat tympanograms, and the rest were evenly distributed between 1B1G pattern and “other” (they classified “other” as an unusual tympanometric pattern). At 1 kHz, most tympanograms could not be classified according to the Vanhuyse pattern (Vanhuyse et al, 1975). McKinley et al concluded that the Vanhuyse model is not adequate to classify tympanograms in neonates at multiple probe-tone frequencies.

Sprague et al (1985) tested 44 neonates and found that 99% showed a 1B1G pattern in their 660 Hz tympanograms, whereas IB1G was the least common pattern observed in their 220 Hz tympanograms. These differences in the Vanhuyse pattern suggest that the newborn middle ear behaves like a mass-dominated system at low-probe frequencies and a stiffness-controlled system at high-probe frequencies, which is the opposite of what is observed in the adult ear.

The goal of the present study was to explore the normal mechano-acoustical characteristics of the middle ear in NICU and healthy babies using standard 226 Hz probe-tone frequency and MFT and to compare them to adult patterns. In three experiments, we examined and compared tympanometry data obtained from healthy adults, healthy babies, and NICU babies. In addition, we explored the utility of 1 kHz tympanograms in a series of infant case studies in which one or more ears failed to pass one or more hearing screening criterion. Together, these experimental and case study findings provide insights into the clinical value of tympanometry in the assessment of middle ear function in newborns.

**EXPERIMENT 1**

**Introduction**

In experiment 1, we explored tympanometric patterns (admittance and its rectangular components, susceptance and conductance) in normal healthy babies at multiple probe-tone frequencies, and we compared the results to already established patterns in adults. Only a few studies have explored tympanometric patterns across multiple components and probe-tone frequencies in newborns (Holte et al, 1991; Calandruccio et al, 2006). We also examined how admittance phase angle, susceptance, and conductance change as a function of probe-tone frequencies so we could gain a better understanding of the middle ear in healthy infants. This experiment also provides normative data and compares different approaches that can be used for calculating SA at 1000 Hz probe-tone frequency. Results of this experiment helped to select an optimal probe-tone frequency for experiments 2 and 3.

**Method**

**Subjects**

Experiment 1 included 31 ears of 16 healthy full-term babies with an average chronological age of 3 weeks (age 21–28 days). Babies were recruited from the Royal Victoria Hospital in Montreal. From a pool of 76 Caucasian adults, 32 ears of 16 healthy adults (age 18–32 years) were randomly selected (Shahnaz and Davies, 2006).

**Inclusion Criteria**

All babies passed an automatic auditory brainstem response (AABR) screening at the time of birth and again at age 3 weeks. A pass consisted of meeting the Algo 2 passing algorithm at 35 dB nHL (Natus Medical Inc., San Carlos, CA). All adult subjects had (a) to present pure-tone audiometric thresholds better than 25 dB HL at octave frequencies between 250 and 8000 Hz, plus an air-bone gap of $\leq$10 dB between 250 and 4000 Hz; (b) to report no history of head trauma or middle ear disease; (c) to present no gross eardrum abnormalities or excessive cerumen, as documented by otoscopic examination; and (d) pass a TEOAE screening.

**Instrumentation**

Typanometry was conducted using a clinical middle ear analyzer Virtual digital immittance instrument (model 310) that is commercially available and is equipped with a high-frequency option. Before data collection, the Virtual system was calibrated using three standard cavities (0.5, 2.0, and 5.0 cm$^3$) according to the operation manual provided by the manufacturer. The Virtual instrument was also calibrated to American National Standards Institute (ANSI) (1987) standards to verify probe-tone frequencies and intensity before the commencement of the project. AABR was conducted using Natus Algo 2 AABR.

**Procedure**

Typanometry was performed immediately after the second AABR. Nondiagnostic otoscopy was performed to ensure a clean and clear ear canal, although no babies were excluded on the basis of otoscopic observation. All babies were tested while asleep or while in a calm state of being held by a parent. Another
In the SP method, the air pressure of 2 and G and 0a tympanograms were attempted several times because of the baby’s fidgetiness before recording was successful.

To begin immittance testing, we documented a standard 226 Hz tympanogram using a sweep pressure (SP) recording. In the SP method, the air pressure of the external ear canal is decreased continuously from +250 daPa to −300 daPa at a rate of 125 daPa/sec while the probe-tone frequency is held constant. This recording was repeated at higher probe-tone frequencies in roughly 100 Hz intervals up to 1000 Hz probe-tone frequencies for a total of nine probe-tone frequencies. Adult tympanometric recordings were obtained using the same method as for the infants.

SA at 1000 Hz was calculated using two different methods. In the first method, the peak (notch in cases of multipeak tympanograms) was subtracted from the positive (+250 daPa) and negative (−300 daPa) tail on the admittance tympanogram. This method is typically performed in clinics to measure SA. In adults, negative compensation results in higher SA values (for both Y and B) compared with positive compensation (KoebSELL et al, 1988; Margolis and Goycoolea, 1993; Shanks et al, 1993; Shahnaz and Polka, 2002).

In the second method, each rectangular component, B_a and G_a, was corrected for ear canal immittance at +250 daPa (positive compensation) and at −300 daPa (negative compensation). The uncompensated admittance and phase angles were then converted back to compensated admittance (Y_m) and phase angle (ψ_m) using appropriate equations (Margolis and Hunter, 2000, p. 387). This method may ensure mathematical accuracy because admittance cannot be added or subtracted unless the phase angles of the admittance parameters are identical (Margolis and Shanks, 1985; Shanks et al, 1993). The ANSI standard (1987) was used to report peak compensated SA. Vanhuyse patterns were determined by counting the number of peaks for B_a and G_a tympanograms at different probe-tone frequencies. This determination was accomplished by plotting the admittance subcomponents, B_a and G_a, at each probe-tone frequency using the rectangular option of the Virtual-310 system. Any patterns that could not be described within this model were categorized as “other,” which included tympanograms with more peaks than 5B3G.

Results

Analysis of Tympanogram Shapes

Figure 1 (a and b) shows the proportion of ears displaying various Vanhuyse patterns at each probe-tone frequency in healthy adults (Figure 1a) and 3-week-old infants (Figure 1b). The proportions are also provided in numerical form at the bottom of each figure. As Figure 1a shows, the Vanhuyse pattern for the adult group changes in an orderly fashion from 1B1G to 3B1G, and to a 3B3G pattern as probe-tone frequency increases from 226 Hz to 1000 Hz, which is consistent with prediction of the Vanhuyse model. The most common pattern up to 630 Hz in the adult group is 1B1G. The 1B1G pattern occurs when the middle ear is stiffness-dominated and the absolute value of reactance is greater than resistance at all ear canal air pressures, that is, when the admittance phase angle is between 90° and 45°. As probe-tone frequency increases beyond 630 Hz, the tympanograms become more complex in shape in the adult group. At 800–900 Hz, the predominant pattern switches from 1B1G to 3B1G, having three extrema on the B tympanogram (two peaks on the sides and a notch in the middle) and a single peak on the G tympanogram. In the 3B1G tympanogram, the ear is most likely either stiffness-dominated or at resonance; that is, the Vanhuyse model predicts that the phase angle is between 45° and 0°. In the 3B3G pattern, the ear is most likely either near resonance or is mass-dominated; that is, the Vanhuyse model predicts that the phase angle is between 0° and −45°.

Overall, 3-week-old infants yield a wider variety of tympanometric patterns than do adults across probe-tone frequencies. At this age, complex patterns as a whole (3B1G, 3B3G, and “other”) were predominant for recordings at the standard 226 Hz probe-tone frequency. These patterns suggest that the healthy 3-week-old middle ear is either stiffness- or mass-dominated at the standard 226 Hz probe-tone frequency. This finding contrasts with the simple 1B1G tympanogram typically observed at this probe-tone frequency in adults, which indicates a stiffness-dominated middle ear system. For the infant tympanograms, as probe-tone frequency increased, the proportion of 1B1G also increased, accounting for roughly 40–50% of tympanometric shapes between 710 and 1000 Hz. The 1B1G pattern was most prevalent at 800 Hz and decreased slightly as probe frequency increased to 1000 Hz. In the infants, the 1B1G was most prevalent at 800 Hz and decreased slightly as probe frequency increased to 1000 Hz. In the infants, most of the 1000-Hz tympanograms followed the 3B1G or the 1B1G pattern; in contrast, adults did not show any 1B1G tympanogram at this probe-tone frequency.

The proportion of single-peak uncompensated admittance (Y_a) tympanograms at 226 Hz and between 630 Hz and 1000 Hz probe-tone frequencies is shown in Figure 2 for adults and 3-week-old babies. These frequencies were selected on the basis of a higher proportion of 1B1G patterns compared to other lower probe-tone frequencies. In the infant group, Y_a tympanograms become simpler in shape as probe frequency
Figure 1. Distribution of the Vanhuyse patterns at different probe-tone frequencies in adults (a) and 3-week-old infants (b). The proportion of each pattern at different probe-tone frequencies for the ears of both healthy adults and 3-week-old infants is also tabulated at the bottom of both figures.
increases, and thus the proportion of single-peak $Y_a$ tympanograms increases. This finding is the reverse of what is observed in adult ears, where $Y_a$ tympanograms become more complex as probe frequency increases and where the proportion of single-peak $Y_a$ tympanograms decreases. Most $Y_a$ tympanograms had a discernable and well-defined single peak at 900 Hz and 1000 Hz probe-tone frequencies.

**Analysis of Phase ($\varphi_y$) and Peak Compensated Rectangular Components $B_{tm}$ and $G_{tm}$**

To further investigate the observed differences between the middle ear transmission system of newborns and adults, $Y_{tm}$, $B_{tm}$, $G_{tm}$, and phase angle change as a function of probe frequency was compared between the two groups. This analysis was conducted to determine whether there are orderly patterns of change as probe frequency is increased that can provide further insights into infant and adult middle ear differences.

Figure 3 shows three measures of mean admittance phase angle plotted as a function of probe-tone frequency for infants and for adults. One measure is the mean uncompensated admittance phase angle ($\varphi_y$), and the other two measures are peak compensated phase angles computed from the positive tail ($+250\varphi_{tm}$) and the negative tail ($-300\varphi_{tm}$) of tympanogram. Phase angles above $0^\circ$ represent a stiffness-dominated middle ear system, phase angles close to $0^\circ$ (zero crossing) represent the resonant frequency, and phase angles below $0^\circ$ represent a mass-dominated middle ear system. For adults, all three measures of phase...
angle decrease in an orderly fashion as probe-tone frequency increases. For $+250\phi_{tm}$, the middle ear system in adults is stiffness dominated between 226 Hz and 710 Hz and becomes mass dominated between 800 Hz and 1000 Hz probe-tone frequencies. Similarly, for $-300\phi_{tm}$, the middle ear system in adults is stiffness dominated between 226 Hz and 800 Hz and becomes mass dominated between 900 Hz and 1000 Hz probe-tone frequencies. In adults, the uncompensated phase angle declines with frequency and changes from $80^\circ$ at 226 Hz to $30^\circ$ at 1 kHz (a $50^\circ$ change from 226 Hz to 1 kHz).

In contrast, for infants the compensated and uncompensated phase angle measures show different patterns of change as probe-tone frequency increases. For infants, the uncompensated phase angle also declines with frequency; however, it demonstrates smaller changes than the adult group across the probe-tone spectrum (a $20^\circ$ change from 226 Hz to 1 kHz). For infants, the uncompensated phase angle values are smaller than the adult values at low-probe frequencies but are similar to adult values at 560 Hz and above.

There are marked differences between the adult and infant phase for the compensated measures of phase angle. For phase angle measures with positive compensation ($+250\phi_{tm}$), the infant middle ear appears to be either mass dominated ($<0^\circ$) or at resonance (close to $0^\circ$), except for 226 Hz and 710 Hz probe-tone frequencies. Between 226 Hz and 630 Hz probe-tone frequencies, for the $+250\phi_{tm}$ measures, phase angles are noticeably smaller than for adults but are equal or slightly larger than adult values at 710 Hz and above, and they follow the same declining pattern.

For phase angle measures with negative compensation ($-300\phi_{tm}$), the infant middle ear appears to be stiffness dominated across the probe spectrum. The infant $-300\phi_{tm}$ phase angle values are noticeably smaller than adult values at low-frequency probe tones (226 Hz to 450 Hz), equal to adult values at 560 Hz, and are noticeably larger than adult values for high-frequency probes (630 Hz and above), but they follow the declining pattern observed for adults.

Figures 4 and 5 show mean peak compensated $Y_{tm}$, $B_{tm}$, and $G_{tm}$ at $+250$ daPa (Figure 4) and at $-300$ daPa (Figure 5) plotted as a function of probe-tone frequency in adults and infants. In adults, for the positive compensation measures, $+250B_{tm}$ values are higher than $+250G_{tm}$ values at 226 Hz and 355 Hz, but they become equal at 450 Hz, which corresponds to an admittance phase angle of $45^\circ$ (see Shahnaz and Polka, 1997). Above 450 Hz, $+250G_{tm}$ increases while $+250B_{tm}$ decreases and falls below 0 mmho for probe frequencies above 710 Hz for the adult middle ear. The B value of zero represents resonant frequency of the middle ear (admittance phase angle of $0^\circ$). Negative values of B indicate a mass-dominated middle ear system.
Overall, as expected, the positive compensated measures of B, G, and Y show that the adult middle ear shifts from a stiffness-dominated system at the lowest probe-tone frequencies to a mass-dominated system at the highest probe frequencies (see Figure 4). The transition occurs between 450 Hz and 800 Hz, with resonance frequency around 710 Hz. Negative compensation measure of B, G, and Y (shown in Figure 5) follow the same pattern as the positive compensation measures for the adult middle ear, although the shift to a 45° phase angle and the shift to resonance frequency fall at higher frequencies in the negative compensation measures. This difference is due to asymmetry between negative and positive tympanometric pressures (Margolis and Smith, 1977).

The following differences were observed in the infant group:

- For infants, the positive compensated measures of B, G, and Y vary much less across the probe spectrum in comparison to adult values.
- For infants, B values fall below G values at all probe frequencies. B values also hover close to zero or just below zero at all probe frequencies.
- For infants, the negative and positive compensation measures follow the same pattern except that the negative compensation measures are a bit higher and do not extend below 0 mmho (mass dominated).
- For infants, both positive and negative compensated values of G and Y are substantially lower than adult values for all probe frequencies above 226 Hz.
- For infants, B values are also lower than adult values below 710 Hz. It should be noted that +250B\textsubscript{tm} crosses the zero line (resonant frequency) at several probe frequencies, while -300B\textsubscript{tm} reaches 0 mmho only at 1 kHz.

**Analysis of Y\textsubscript{tm} at 1 kHz**

Admittance magnitude was examined in more detail for tympanograms recorded using a 1 kHz probe-tone frequency. This probe frequency was selected for two reasons. First, a 1 kHz probe-tone is readily accessible in most commercially available middle ear analyzers. Second, in our data and in other studies, Y\textsubscript{a} tympanograms recorded with a 1 kHz probe typically have one well-defined peak, which permits us to extract admittance magnitude in a consistent way. From the infant 1 kHz tympanograms, we computed SA (in mmho), admittance phase angle (in degree), tympanometric width (TW, in daPa), and admittance at tail values.
Table 1. Mean, Median, SD, and 90% Range (5th–95th Percentile) for SA Computed from a 1 kHz Y Tympanogram at +250 daPa (+250Yq) and at −300 daPa (−300 Yq) and from Rectangular Components, Bq and Gm, at +250 daPa (+250Ytm) and at −300 daPa (−300Ytm)

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<th>3-Week-Old Infants: 1 kHz Probe Tone</th>
<th>N (ears)</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>90% Range</th>
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<tr>
<td>+250Ytm (mmho)</td>
<td>Right 16</td>
<td>1.40</td>
<td>1.30</td>
<td>0.60</td>
<td>0.60–2.30</td>
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<td></td>
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<tr>
<td></td>
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<td>−24.3</td>
<td>−22.8</td>
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<td>Overall 32</td>
<td>4.9</td>
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<td>Yq @ −300 daPa in mmho</td>
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<td>TW in daPa (compensated from +200 daPa)</td>
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<td>129.2</td>
<td>131.6</td>
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<td>Overall 32</td>
<td>−39.8</td>
<td>−37.9</td>
<td>29.0</td>
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<td>−300Ytm − degree ϕ = (\arctan \frac{B}{G})</td>
<td>Overall 32</td>
<td>−22.3</td>
<td>−19.3</td>
<td>29.2</td>
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Note: Mean, median, SD, and 90% range have also been reported for TW computed from +250Yq, the tail of Yq at +250 daPa and at −300 daPa, the Yq phase angle (ϕq in degree) at the peak, and computed from rectangular components, Bq and Gm, at +250 daPa (+250Ytm) and at −300 daPa (−300Ytm). Corresponding descriptive statistics are also reported for +250Ytm, −300Ytm, ϕq, +250ϕm, and −300ϕm in adults.

(mmho). SA at 1 kHz probe-tone frequency was measured in two different ways: (a) compensating for ear canal volume using extreme Y values (that is, by subtracting the Y peak or notch from the positive or negative Y tail) and (b) compensating each rectangular component and then converting these compensated values into compensated Y and ϕ values (see Shahnaz and Polka, 2002). The first method is more common in clinical practice, and the second method is mathematically more accurate.

The mean, median, standard deviation (SD), and 90% range (5th–95th percentile) for the positive tail (+250 daPa), the negative tail (−300 daPa), TW, ϕq, and SA at a 1-kHz probe-tone frequency are shown in Table 1 for 3-week-old infants. SA and ϕ computed from rectangular components in 32 ears of 16 Caucasian adults are also shown for comparative purposes. For infants, the mean value for SA, TW, and ϕq, regardless of the compensation method (positive tail versus negative tail) or method of calculation, was not statistically different (p > 0.05) between the two ears. Ear differences are also not observed for these measures in adults (Shahnaz and Davies, 2006). For Ytm computed from rectangular components, adults had significantly higher values than did the infant group for both positive (independent t [62] = −7.2, p = 0.000) and negative (independent t [62] = −8.2, p = 0.000) compensation. In the infant group, Ytm computed from rectangular components was significantly higher than Ytm computed directly from
Y tympanogram for positive compensation (dependent \(t\) [31] = −8.1, \(p = 0.000\)); however, it was not statistically different for negative compensation (dependent \(t\) [31] = 1.4, \(p = 0.17\)).

**Discussion**

Results of the first experiment indicate that 3-week-old infants show a wider variety of the Vanhuyse patterns than do adults across probe-tone frequencies, which is consistent with the Calandruccio et al (2006) findings for their youngest infant group (age 4–10 weeks). As in the Calandruccio et al study, the distribution of the Vanhuyse patterns at 1 kHz was very different between the infants and adults in the current experiment. At a 1 kHz probe-tone frequency, adults had mainly 3B1G (69%) and 3B3G (31%) patterns, while infants had predominantly 3B1G (50%) and 1B1G (38%) patterns.

The majority of tympanometric patterns observed at a 900 Hz probe-tone frequency by Holte et al (1991) in their 11- to 22-day-old infant group were complex (V- or W-shape) patterns that could not be classified as Vanhuyse patterns. The distribution of complex patterns (3B1G and 3B3G for a total of 57% of the tympanograms) at a 900 Hz probe-tone frequency was also high in the current experiment; however, there were also a significant number of 1B1G patterns (42%) at this probe-tone frequency. The proportion of the Vanhuyse patterns in the 26- to 47-day-old infant group of Holte et al study is more comparable to the current experiment at 900 Hz. An equal distribution of 1B1G and 3B1G was obtained at 710 Hz in our adult group and at 900 Hz in our infant group as opposed to 800 Hz in the Calandruccio et al (2006) adult group and 1000 Hz in the youngest infant group of the Calandruccio et al study.

In the current experiment, all adults showed a 1B1G Vanhuyse pattern at the standard 226 Hz probe-tone frequency, whereas in 3-week-olds, 1B1G tympanograms described only 13% of tympanograms at this frequency, and complex multipeak tympanograms accounted for the remaining 85%. Calandruccio et al (2006) reported a higher proportion of 1B1G patterns (76.9%) than 3B1G patterns (23.1%) at a 226 Hz probe-tone frequency for their younger infant groups (age 4–10 weeks). Part of the discrepancy observed between the two studies is due to the fact that the younger infant groups studied by Calandruccio et al are older than the babies in the current experiment. Calandruccio et al have shown that, as infants become older, the proportion of 1B1G tympanogram increases at a 226 Hz probe-tone frequency.

The Vanhuyse patterns observed at a 226 Hz probe-tone frequency by Holte et al (1991) in their 11- to 22-day-old infant group also show a higher proportion of 1B1G tympanograms (54%); however, the proportion of tympanometric shapes at a 226 Hz probe-tone frequency in their 26- to 47-day-old infant group are more comparable to the current experiment. The unusual tympanometric pattern in newborns has been attributed to a highly distensible ear canal wall. However, Holte et al have shown that the effect of ear canal wall movement is less likely to affect the number of peaks. They suggested that the vibratory motion of the ear canal wall in response to the probe-tone signals may affect the resistance tympanogram and may result in unusual shape for resistive tympanograms, which is consistent with the higher incidence of 3B3G patterns in newborns compared to adults for probe-tone frequencies below 900 Hz.

Analysis of the admittance phase and peak compensated rectangular components between infants and adults (Figures 3–5) also confirmed the variation observed in the Vanhuyse patterns between infants and adults. The uncompensated admittance phase for infants was noticeably lower than for adults at low probe-tone frequencies (<560 Hz); however, it was not different from adults at frequencies between 560 and 1000 Hz. The differences observed between infants and adults for compensated admittance phase angles were noticeably larger than uncompensated admittance phase angles; however, infants had the same declining pattern as adults at frequencies above 710 Hz. This finding could be partially due to highly distensible ear canals in newborns. Holte et al (1990) showed that the highly distensible ear canal of neonates had the greatest effect on the tails of the tympanograms that are used to estimate ear canal volume.

It is also worth mentioning that the variation between infants and adults for \(-3000\) \(\mu\)m is quite larger than \(+2500\) \(\mu\)m between 630 and 1000 Hz. Holte et al (1990) have also shown that the mean diameter changes in the newborn’s ear canal were much bigger for negative pressures than for positive pressures. These variations between positive and negative compensation are likely due to collapse of the ear canal at high negative pressure. Therefore, it may be more feasible to attempt to compensate from the positive tail rather than the negative tail. Overall, phase angles for newborns are lower than for adults at lower probe-tone frequencies (<630 Hz), indicating substantial contributions of mass and resistance elements in infants.

This observation is also consistent with the Holte et al (1991) findings. It was further verified by plotting peak compensated \(Y_{\text{tm}}, B_{\text{tm}},\) and \(G_{\text{tm}}\) as a function of probe-tone frequencies (Figures 4 and 5). For positive compensation (Figure 4), \(Y_{\text{tm}}, B_{\text{tm}},\) and \(G_{\text{tm}}\) are noticeably smaller than for adults, and \(B_{\text{tm}}\) for infants hovers around zero (resonant frequency- maximum contribution for the resistive element) or below zero (mass and resistive contribution) at all probe-tone frequencies. In the infant group, \(+250\) \(B_{\text{tm}}\) crosses zero
at 250 Hz (0.05 mmho), 560 Hz (0.02 mmho), and 800 Hz (0.04 mmho), indicating several resonant frequencies for the middle ear, which is consistent with the Holte et al. (1991) observation in the youngest group of infants. However, −300 $B_{in}$ reaches zero only at 1 kHz. This difference, which is also observable in adults, is probably due to asymmetry between negative and positive tympanometric pressures (Margolis and Smith, 1977) and to the collapse of the ear canal at high negative pressure.

Y tympanograms obtained at a 226 Hz probe-tone frequency in well babies who pass screening tests are typically multipeak. In contrast, Y tympanograms obtained at 1 kHz probe-tone frequency in well babies who pass screening tests are typically single-peak tones and are well defined in shape. This observation is consistent with previous findings (Paradise et al., 1976; Marchant et al., 1986; Holte et al., 1991; Hirsch et al., 1992; Kei et al., 2003; Margolis et al., 2003). Kei et al. (2003) reported single-peak tympanogram in 92.2% of their 122 healthy infants. Thus, in newborns, it is easier and more straightforward to quantify the SA from a tympanogram obtained using a 1 kHz rather than a 226 Hz probe-tone frequency.

Differences between right and left ears were not significant for both SA and TW at 1 kHz, although the right ear had slightly higher SA than the left ear for positive compensation. This trend is consistent with the Kei et al. (2003) finding of statistically higher peak compensated SA for the right ear. The failure to achieve significance in the present experiment may be due to the smaller sample size. The median and the 90% range for SA obtained from rectangular components at a 1 kHz probe-tone frequency are higher and wider than for the 4- to 10-week-old infants in the Calandruccio et al. (2006) study. Both studies used similar pump speed, pressure direction, and method of calculation. The differences observed between the two studies include wider age ranges used in the Calandruccio et al. comparable infant group (their group was older) and the sample size ($n = 39$ in Calandruccio et al. and $n = 16$ in the current experiment). Our adult ($n = 16$) mean and 90% range at the same probe-tone frequency was also higher and wider than for the Calandruccio et al. adult group ($n = 33$). However, once we compared their adult norms to the norms obtained using a larger Caucasian adult samples ($n = 76$) at 226 Hz, 630 Hz, and 1 kHz probe-tone frequencies (Shahnaz and Davies, 2006), the results were more comparable. Sources of differences in adult groups between different studies were fully discussed in Shahnaz and Davies (2006). The differences observed in infants between the two studies are likely due to the larger sample size used in Calandruccio et al. study.

The mean, median, and 90% range for SA obtained directly from $Y_a$ at the 1 kHz probe-tone frequency are lower and narrower than for the Margolis et al. (2003) 2- to 4-week full-term infants for both positive and negative compensation. In this experiment, in cases of multipeak tympanograms, the notch or minima on the admittance tympanogram was used as the peak. The pressure point corresponding to the notch on the $Y_a$ was comparable to the pressure point corresponding to the peak or notch on $B_a$ and the peak or notch on $G_a$. In Margolis et al. (2003) the higher of the two peaks was used as a peak. This choice may explain why our values are lower than those in the Margolis et al. study.

The fifth percentile obtained from the positive tail, which is often being used as a pass or refer criterion for presence of middle ear effusion, was 0.1 mmho in both studies. It is difficult to compare the norms in this experiment to the Kei et al. study as a result of the difference in pump speeds (50 daPa/sec in Kei et al as opposed to 125 daPa/sec in the current experiment), which may result in smaller SA values (Margolis and Shank, 1990) in infants. Moreover, Kei et al. used a correction factor suggested by Margolis and Hunter (2000) to convert admittance value from milliliters to mmho at a 1000 Hz probe-tone frequency.

Given that error may arise from common clinical methods used to derive SA at high probe frequencies, we compared clinically derived measures (using $Y_a$ compensation) against mathematically derived measures that are known to be accurate. The mean and 90% range for SA computed from $+250Y_a$ is lower and narrower than for SA computed from positively compensated rectangular components; however, the mean and 90% range for SA computed from $-300Y_a$ is more comparable to SA computed from negatively compensated rectangular components. This observation means that SA values derived from $-300Y_a$ may not result in a significant mathematical error. This may not be the case for the adult population. To date, no published study has compared the test performance of these two measures in confirmed cases of middle ear problems.

**EXPERIMENT 2**

**Introduction**

In experiment 2, we examined NICU infants with risk factors linked to hearing loss (a) to determine whether 1 kHz tympanograms provide a more consistent pattern than do standard 226 Hz tympanograms in infants who passed hearing screening protocols, and (b) to investigate tympanometric patterns in babies who failed TEOAE screening criterion. ABR and TEOAE were performed to separate those with likely normal hearing status from those with possible hearing loss. Moreover, the distribution of the Vanhuyse patterns were examined at 226, 675, and
1000 Hz in NICU babies and adults who passed the screening criterion so we could better understand the mechano-acoustical properties of the normal middle ear in this group. To our knowledge, no published paper has investigated the Vanhuyse model in interpretation of the tympanograms in NICU babies.

Method

Subjects

Experiment 2 consisted of 65 ears of 33 pre-term infants in an NICU with an average GA at the time of testing of 37.8 weeks (GA range: 32–51 weeks) recruited from Children’s and Women’s Health Centre of British Columbia (C&W) in Vancouver. Also included in this experiment for comparative purposes were 47 ears of 26 healthy Caucasian adults (18–32 years of age) recruited from the University of British Columbia.

Inclusion Criteria

All NICU babies were screened in the NICU ward using both an AABR and EOAE when they were stable, as determined by an NICU nurse (not earlier than 3 weeks before discharge). For EOAE, 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 (SNR of 3 dB at 1 and 1.5 kHz, and 6 dB at 2, 3, and 4 kHz). For AABL, a pass consisted of meeting the Bio-logic ABAer passing algorithm at 35 dB nHL using earmuffs. Among the 33 NICU babies tested, 54 ears met both inclusion criteria, and 11 ears did not.

All adult subjects had (a) to present pure-tone audiometric thresholds of better than 25 dB HL at octave frequencies between 250 and 8000 Hz and air-bone gaps of ≤10 dB between 250 and 4000 Hz, (b) to report no history of head trauma or middle ear disease, (c) to present no gross eardrum abnormalities or excessive cerumen as documented by otoscopic examination, and (d) to pass a TEOAE screening.

Instrumentation

Tympanometry was conducted using a commercially available middle ear analyzer (Grason-Stadler TympStar Version 2) for both NICU and adult groups. The TympStar was calibrated daily in the calibration cavity provided by the manufacturer. The TympStar was also calibrated to ANSI (1987) standards to verify probe-tone frequencies and intensity before the commencement of the project. AABR was performed using the Bio-logic 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.

Procedure

All NICU babies were tested in NICU nurseries before discharge. The NICU babies were tested either in their incubator or crib or when held by one of the parents or by our research assistant (depending on the condition of the babies). Although testing in the NICU nursery was challenging and at times quite noisy, it did not affect the tympanometric recordings. Seal was easily achieved in most NICU babies. All systems were placed on a moving cart for ease of transportation and testing. All NICU babies were first tested by AABR and TEOAE.

Commencing the test with either AABR or TEOAE depended on the condition of the baby, and no specific order was chosen. Tympanometry was always performed following the TEOAE test. First, a 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. Then, depending on the child’s condition, B_a and G_a tympanograms were obtained sequentially at three probe-tone frequencies of 226 Hz, 630 Hz, and 1 kHz using a positive-to-negative sweep pressure recording. B_b and G_b were successfully recorded at three probe-tone frequencies of 226 Hz, 630 Hz, and 1 kHz in 33 ears of 17 NICU babies who passed both AABR and TEOAEs. Y tympanograms at 226 Hz and 1 kHz were printed, and B_a and G_a tympanograms at 226 Hz, 630 Hz, and 1 kHz were exported to a laptop using custom-made software developed in our lab. Tympanometry protocols for the adult group were conducted using an approach similar to that for the NICU babies (same pump speed and pressure direction).

Results

Figure 6 (a and b) shows the proportion of ears displaying various Vanhuyse patterns at each probe-tone frequency in healthy adults (Figure 6a) and NICU babies who passed the screening criteria (Figure 6b). The proportion of each pattern at different probe-tone frequencies for the ears of both healthy adult and NICU babies is also tabulated at the bottom of each figure. As in experiment 1, in the adult group the Vanhuyse pattern changes in an orderly fashion from 1B1G to 3B1G, and to the 3B3G pattern as probe-tone frequency increases from 226 Hz to 1000 Hz, which is consistent with the model’s prediction. The most common Vanhuyse pattern at 226 Hz in the adult group is 1B1G. As probe-tone frequency increases beyond 675 Hz, tympanograms become more complex in shape in the adult group. The predominant pattern switches from 1B1G at 226 Hz to 3B1G at 1000 Hz . NICU babies yielded a wider variety of tympanometric patterns than did adults across probe-tone frequencies.
Figure 6. Distribution of the Vanhuyse patterns at different probe-tone frequencies in adults (a) and NICU babies (b). The proportion of each pattern at different probe-tone frequencies for the ears of both healthy adult and NICU babies is also tabulated at the bottom of each figure.
In the tympanograms of the NICU babies, complex patterns, 5B3G and 3B3G, were predominant (accounting for 79% of the Vanhuyse patterns) for recordings at the standard 226 Hz probe-tone frequency, consistent with a mass-dominated middle ear system. In contrast, adults revealed predominantly 1B1G tympanograms at this probe-tone frequency, consistent with a stiffness-dominated middle ear system. For the NICU babies’ tympanograms, as probe-tone frequency increased, the proportion of 1B1G also increased, accounting for 64% of tympanometric shapes at 1000 Hz. In contrast, only 7% of adults yielded 1B1G tympanogram at this probe-tone frequency.

The proportion of single-peak Y tympanograms at 226 Hz and 1000 Hz probe-tone frequencies is shown in Figure 7 for adults and NICU babies. Similar to experiment 1, in NICU babies, tympanograms become simpler in shape as probe-tone frequency increases. This finding is the reverse of what is found in adult ears, where tympanograms become more complex as probe frequency increases. Because most tympanograms had a discernable and well-defined single peak at 1 kHz, SA was measured only at this probe frequency.

The mean, SD, and 90% range (5th–95th percentile) for the positive tail (+200 daPa), the negative tail (−400 daPa), and SA for the 1-kHz probe-tone frequency are shown in Table 2. The SA was computed from Y tympanograms at 1 kHz in NICU babies and Caucasian adults using positive- and negative-tail compensation. In cases of notched tympanograms (three ears in NICU babies), a notch value (trough) was used. The SA values obtained using both positive-tail and negative-tail compensation at 1 kHz in NICU babies were significantly ($p < 0.05$) lower than for the adult group. The fifth percentile of the 90% range can potentially be used as a pass or fail criterion for OM or absence of OAEs.

Although quantification of tympanograms by measuring SA is an important step toward defining normal variation of the tympanograms in presumably normal middle ears in newborns, the shape of the tympanogram also plays an important role in this process. Tympanograms obtained at 1 kHz in NICU babies who passed both AABR and EOAE can be classified into two types. Figure 8a and Figure 8b represent typical YBG tympanograms observed in NICU babies and adults. Type 1 (Figure 8a) represents Y tympanograms obtained at 1 kHz that are most likely bell shaped and have a single peak, very much like type A in the Jerger classification system (1977). Type 2 (Figure 8a) represents Y tympanograms that are multipeak at 1 kHz and have a shallow notch, and in which distance from the two maxima is not wide (within 120 daPa). It is worth mentioning that in Figure 8a, right panel, B went to 0 on the negative pressure side, indicating ear canal collapse, a common finding in young infants.

### Table 2

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<th>Mean</th>
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<td>2003, 32.8 GA</td>
<td>105 ears</td>
<td>1.4</td>
<td>0.30</td>
<td>0.90–1.90</td>
<td>105 ears</td>
<td>1.24</td>
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<td>0.87–1.70</td>
<td>151 ears</td>
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<td>153 ears</td>
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<td><strong>Adults in Current Study</strong></td>
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<td>18–34 yrs</td>
<td>47 ears</td>
<td>6.40</td>
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<td>4.90</td>
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<td>4.70–8.60</td>
<td>1.05</td>
<td>1.32</td>
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<td>4.70–8.60</td>
<td>1.49</td>
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![Figure 7](image-url)  
**Figure 7.** The proportion (%) of single-peak admittance (Y) tympanograms at 226 Hz and 1000 Hz probe-tone frequencies in NICU babies and adults.

Discussion

The progression of the Vanhuyse patterns in adults at different probe-tone frequencies concurs with experiment 1. The results of experiment 2 provide an important validation of the data in experiment 1 because the data in
Figure 8. Typical admittance (Y), susceptance (B), and conductance (G) tympanograms obtained at 1000 Hz probe-tone frequency in typical NICU babies (a). Type 1 is a single-peak Y tympanogram, and type 2 is a multi-peak tympanogram (the arrow points to the notch or minima). Note that in the right panel, B went to 0 on the negative pressure side, indicating ear canal collapse, a common finding in young infants. A typical YBG-tympanogram obtained at 1000 Hz probe-tone frequency in an adult (b) is also shown for comparison.
experiment 2 were obtained using different groups of adults and infants and using different instrumentation. As in experiment 1, NICU babies have a wider variety of Vanhuyse patterns than adults across probe-tone frequencies. The proportion of 1B1G and 3B1G tympanograms at 1000 Hz in NICU babies (Figure 6b) is quite different from the proportion of 1B1G and 3B1G tympanograms at 1000 Hz in 3-week-old babies (Figure 1b). The proportion of 1B1G tympanograms is almost twice as high for the NICU babies as for the 3-week-old infants, and the proportion of 3B1G is almost half of the proportion of 3B1G in the 3-week-old infants. This finding may indicate some maturational effect.

Calandruccio et al (2006) have also shown a change in distribution of Vanhuyse patterns in infants as they grow older, although the trend they reported was not similar to this study. The nature of these rapid maturational effects is not fully known; however, the NICU babies may have a more compliant ear canal wall that may behave different from the ear canal of healthy neonates in response to air pressure and probe-tone signal. As discussed previously, the vibratory motion of the ear canal wall may add to the resistive element (Holte et al, 1991), which, in turn, may contribute to the more complex patterns observed in NICU babies.

As in experiment 1, Y tympanograms obtained at a 226 Hz probe-tone frequency for NICU babies who pass screening tests are most likely irregular in shape and multipeak. In contrast, tympanograms obtained at a 1 kHz probe-tone frequency for NICU babies who passed AABR and EOAE most likely have a single peak and are well defined in shape. This observation is consistent with previous findings (Hirsch et al, 1992; Holte et al, 1991; Margolis et al, 2003; Marchant et al, 1986; Paradise et al, 1976). Thus, as in experiment 1, it is easier and more straightforward to quantify the SA from a tympanogram obtained using a 1 kHz rather than a 226 Hz probe tone.

The mean and SD of SA in the current experiment are comparable to the Margolis et al (2003) study for NICU babies (Table 2). The 5th percentile, which is often being used as a pass or refer criterion for presence of middle ear effusion, was 0.1 mmho for positive compensation and 0.53 mmho for negative compensation in the current experiment compared with 0.2 mmho for positive compensation and 0.60 mmho for negative compensation in the Margolis et al (2003) study. In the current experiment, in cases of multipeak tympanograms, the notch or minima on the admittance tympanogram was used as a peak; however, in Margolis et al (2003), the higher of the two peaks was used as a peak. This difference may explain the slightly lower values for SA in the current experiment. SA was significantly higher (p < 0.05) for adults at 1 kHz than for NICU babies for both positive and negative compensation.

The middle ear cavity undergoes a slow postnatal expansion as the temporal bone grows. Saunders et al (1993) found that this change should affect SA at different ages, which is also consistent with the Calandruccio et al (2006) findings. Some of the rapid changes during the first few weeks of life may not be accounted for by changes in the temporal bone and mastoid air cell system because they mature at a much slower pace. The NICU babies may have more-compliant ear canal walls, which may behave different from those of neonates in response to probe-tone signals. As discussed previously, the vibratory motion of the ear canal wall may add to the resistive element (Holte et al, 1991), which, in turn, may contribute to the more complex patterns observed in NICU babies.

EXPERIMENT 3

Introduction

In experiment 3, we used norms derived in experiment 2 to develop a binary classification of infant 1 kHz tympanograms into “likely normal middle ear” (hereafter, “normal”) and “likely abnormal middle ear” (hereafter, “abnormal”). This classification criterion was then applied to 1 kHz tympanograms from a group of high-risk infants who passed or failed a TEOAE screening to assess the utility of the tympanogram classification for assessing middle ear status.

Method

Subjects

Experiment 3 consisted of 81 ears of 42 infants on the high-priority hearing registry (HPHR) of Vancouver Island Health Authority (Nanaimo Central) with an average chronological age of 6 weeks (age 6 days to 23 weeks). The risk factors for HPHR babies were based on the Joint Committee on Infant Hearing (JCIH, 1991) definition of risk factors for hearing loss.

Inclusion Criteria

HPHR babies were used to test the validity of normative data established from NICU (experiment 2) and well-baby data (experiment 1); therefore, no specific inclusion criterion was used.

Instrumentation

Tympanometry was conducted using a commercially available middle ear analyzer (Grason-Stadler Incorporation–GSI 33 version 2). The GSI 33 was calibrated to ANSI (1987) standards to verify probe-tone
frequencies and intensity. TEOAEs were tested using a clinical ILO-88 Analyzer (Otodynamics Ltd., Hatfield, England) calibrated on the basis of the operations manual of the manufacturer.

**Procedure**

All HPHR babies were screened using TEOAE in Quick Screen mode on the Otodynamics ILO88 system. A pass consisted of a good emission-to-noise ratio (SNR of 3 dB) at least in three half-octave bands centered at 2, 3, and 4 kHz. Tympanometry was recorded using a 1 kHz probe-tone frequency with admittance magnitude (2 recordings attempted per ear). Ear canal pressure was swept from positive to negative at a rate of 600 daPa/sec at the tails to 200 daPa/sec around the peak. Tympanograms were classified into “normal” or “abnormal” on the basis of norm values obtained from the NICU babies in experiment 2.

Recall that normal was classified as having an SA >0.1 mmho for positive compensation with normal tympanometric shapes (Figure 8: types 1 and 2). In cases of multipeak tympanograms, the distance between the two maxima should have fallen within 120 daPa. Abnormal was defined as having an SA below 0.1 mmho for positive compensation or having a multipeak tympanogram and the distance between the two maxima exceeding 150 daPa. Tympanometric peak pressure (TPP) was not used as a criterion to classify the tympanograms because this measure by itself is not a reliable indicator of medically significant middle ear disease in older children and adults (Fiellau-Nikolajsen, 1983; Margolis & Heller, 1986; Nozza et al, 1992).

**Results**

We classified 1 kHz admittance tympanograms obtained from a cohort of HPHR neonates as normal, abnormal, or “other” and related them to the TEOAE screening outcome (pass, refer, and could not test). Table 3 shows the proportion of normal and abnormal tympanograms in this cohort. Most neonates showed a normal tympanogram, as would be expected because most infants will have a normal middle ear. Table 3 also shows the proportion of normal tympanograms among ears that passed and failed the TEOAE screening.

The majority of the neonates with normal tympanograms, 44 ears (80%), passed the TEOAE criterion. However, 9 ears (16%) with a normal tympanogram did not pass the TEOAE criterion. Of those 9 ears, 7 passed TEOAE on a second occasion shortly thereafter when checked by an audiologist. If these 7 ears are added to the 44 ears that had a normal tympanogram and passed TEOAE, then the proportion of normal tympanograms that passed TEOAE would increase to 93%. The proportion of abnormal tympanograms in ears that passed and failed the TEOAE screening is also shown in Table 3. Most of the ears (74%) showing this pattern did not pass TEOAE criterion.

Figure 9 shows the average number of frequencies in which each type of tympanogram (normal and abnormal) meets an emission-to-noise ratio of at least 3 dB.

**Discussion**

Normal tympanograms at 1 kHz were most likely associated with normal TEOAE results. The proportion of normal tympanograms associated with normal TEOAE was very high (44 out of 53 ears). Abnormal tympanograms were most likely associated with abnormal TEOAE results. The proportion of abnormal tympanograms associated with normal TEOAE results was very low (7 out of 27 ears). It should be noted that though presence of TEOAE is a good indication of a normal middle ear condition (Kei et al, 2003; Margolis et al, 2003), it cannot completely rule out the absence of effusion in the middle ear (Taylor and Brooks, 2000). The type of effusion found in the middle ear appears to be the controlling factor for the presence or absence of effusion.
emissions (Koivunen et al, 2000). In general, it seems that the norm established for the 1 kHz probe-tone frequency for the admittance tympanogram in NICU babies may be a useful index for detecting an abnormal middle ear in neonates.

Case Studies: Predict Screening Outcome from 1 kHz Tympanograms

Among the NICU babies, 11 ears failed the EOAE screening. Some of these infants who failed the screening are reviewed in the following cases. Case 4 is a special case in which the presence of fluid in the middle ear was later confirmed by a myringotomy. The following cases illustrate the potential value of tympanometric shape in the assessment of the middle ear in NICU babies.

Case 1 (Figure 10) was born at 27 weeks GA and was tested using AABR at 39.5 weeks GA and using TEAOE at 40 weeks GA. She referred on AABR for the left ear and passed for the right ear and failed in both ears for TEAOEs. The fact that she passed AABR and referred for TEAOE in the right ear most likely indicates the presence of middle ear pathology in this ear. She later passed second stage AABR in both ears close to discharge from the hospital (47 weeks GA). At 40 weeks GA, tympanograms at 226 Hz in both ears were multipeak. SA at 1 kHz was below the NICU cutoff of 0.1 mmho (computed from the positive tail) and 0.53 mmho (computed from the negative tail) in both ears. The tympanogram at 1 kHz was flat in the right ear, and it seemed to have widened and become multipeak in the left ear. The arrows show the two maxima and one minimum on the left tympanogram. The distance (in daPa) between the two maxima (between the far right and left arrows) is noticeably very wide, and the notch is below the positive tail. If the higher of the two peaks would have been used as a peak, SA computed from the negative tail would have fallen within the normal range.

Case 2 at 40 weeks GA (Figure 11) and case 3 at 38 weeks GA (Figure 12) are interesting because only the left ear failed AABR and EOAE. In both cases, the left ear passed AABR in the second stage. In both cases, the right ear tympanograms are bell shaped and have a single peak at a 1 kHz probe-tone frequency. SA in the right ear is also within normal range at 1 kHz in both cases. In both cases, the left ear tympanogram at 1 kHz is widened and multipeak. The notch is below the positive and negative tails, which makes SA below the NICU cutoff of 0.1 mmho (computed from the positive tail) and 0.53 mmho (computed from the negative tail) in both ears. In both cases, the tympanograms at 1 kHz measures suggest a normal middle ear in the right ear and a middle ear problem in the left ear.

Case 4 (Figure 13) is a female with Downs syndrome who was screened at 13 weeks corrected gestational age (CGA). She was rescreened at 16 and 23 weeks CGA. She did not meet passing criteria for TEOAE on all three occasions. Tympanograms obtained at 1 kHz at the corrected ages of 16 weeks and 23 weeks are shown. Tympanograms at 16 weeks of age in both ears are widened and multipeak. The notch is below the positive and negative tail, which makes SA below the NICU cutoff of 0.1 mmho (computed from the positive tail) and 0.53 mmho (computed from the negative tail) in both ears. Tympanograms obtained at the corrected age of 23 weeks are almost flat at 1 kHz. The corresponding 226 Hz tympanogram also shows restricted SA and abnormally wide TW. Behavioral observation audiometry (BOA) in the sound field suggested severe hearing loss. She underwent a myringotomy and tube insertion, and the presence of serous otitis media was confirmed by the surgeon. Follow-up behavioral and tonal ABR testing confirmed normal hearing in both ears.

SUMMARY AND CONCLUSION

Evaluation of the Vanhuyse patterns and peak compensated \( \psi_{tm} \), \( R_{tm} \), and \( C_{tm} \) in well babies and Vanhuyse patterns in NICU babies at different probe-tone frequencies revealed a greater contribution of the mass and resistive elements in the middle ear system at a standard 226 Hz probe-tone frequency. In contrast, the middle ear system in adults is stiffness-dominated at this probe-tone frequency. Y tympanograms at 226 Hz are most likely multipeak in ears that passed or referred on TEOAE. They are, therefore, less specific and sensitive to presumably normal or abnormal middle ear conditions. Tympanograms obtained at 1 kHz appear to be more sensitive and specific to presumably abnormal and normal middle ear conditions. Tympanograms obtained at a 1 kHz probe-tone frequency in ears that had passed AABR and EOAE had a single peak and were bell shaped and well defined, with very few exceptions.

This finding means that quantification and interpretation of the tympanogram is more straightforward at this probe-tone frequency compared to a 226 Hz probe measure. However, it is not known whether the probe-tone frequencies above 1 kHz would do better. One of the commonly measured tympanometric variables is SA. Holte et al (1990) showed that the highly distensible ear canal of neonates had the greatest effect on the tails of the tympanograms that are used to estimate ear canal volume in measuring SA. This observation raises the questions regarding validity of correcting ear canal volume in newborns.

The analysis of the shape of tympanograms at 1 kHz may prove to be more beneficial. In ears that failed TEOAEs, tympanograms were often flat or widened and multipeak. In these cases, the distances (in daPa)
Right Ear: AABR: Pass TEOAE: Refer

![Tympanograms at 226 Hz and 1 kHz from an NICU baby who referred the left ear and passed for the right ear for AABR and failed in both ears for TEOAE.]

Left Ear: AABR: Refer TEOAE: Refer

![Tympanograms at 226 Hz and 1 kHz from an NICU baby who referred the left ear and passed for the right ear for AABR and failed in both ears for TEOAE.]

Figure 10. Tympanograms at 226 Hz and 1 kHz from an NICU baby who referred the left ear and passed for the right ear for AABR and failed in both ears for TEOAE.
Right Ear- AABR: Pass TEOAE: Pass

Left Ear- AABR: Refer TEOAE: Refer

Figure 11. Tympanograms at 226 Hz and 1 kHz from an NICU baby who referred on AABR and TEOAE for the left ear and passed on AABR and TEOAE for the right ear.
Right Ear-Pass both AABR & TEOAE

Left Ear: Fail both AABR & TEOAE

Figure 12. Tympanograms at 226 Hz and 1 kHz from an NICU baby who referred on AABR and TEOAE for the left ear and passed on AABR and TEOAE for the right ear.
Figure 13. An NICU female baby with Downs syndrome, who referred on TEOAE on several occasions. Tympanograms at 226 Hz and 1 kHz are shown for two occasions. The presence of fluid in the middle ear was confirmed by the surgeon during myringotomy.
between the two maxima in multipeak tympanograms are excessively wide and the notch is usually below both the positive and negative tails. Although the degree of widening has not been statistically quantified, the widening is large and deep and predictable when there is a middle ear problem in comparison to the multipeak tympanogram observed occasionally in normal cases. Finally, tympanometry at 1 kHz is a good predictor of the presence or absence of TEOAE.

One of the limitations 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 in 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 OAEs (Koivunen et al, 2000). Use of more objective gold standards 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 to identify the presence or absence, as well as the severity, of the conductive component in newborns and very young infants.

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NOTES

1. SP recording yields different results for tympanometric indices from sweep frequency recording. For more information, please refer to Shahnaz and Polka (1997).

2. “Other” was defined as tympanograms that could not be classified into normal or abnormal because of their being very noisy.

3. All the babies who failed TEOAE were followed up. Three babies were not followed because their families did not come to follow-up appointments; one baby died before the follow-up appointment; one child failed consistently on TEOAE follow-ups and is discussed in further detail in the case studies section (case 4). All other babies either later showed normal hearing in both ears or passed OAE screening bilaterally.
REFERENCES


