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Measuring Middle Ear Admittance in Newborns Using 1000 Hz Tympanometry: A Comparison of Methodologies

Joseph Kei*
Rafidah Mazlan*
Louise Hickson*
John Gavranich†
Ron Linning†

Abstract

The present study aimed to compare three measures to estimate middle ear admittance in neonates using 1000 Hz tympanometry. Data were obtained from 36 full-term newborns, aged between 24 and 123 hours, who passed a transient evoked otoacoustic emissions test and assessed using a Madsen Otoflex impedance meter. The results showed that the mean middle ear admittances obtained by compensating for the susceptance and conductance components at a pressure of 200 daPa and -400 daPa (Y_{CC200} = 1.00 mmho and Y_{CC-400} = 1.24 mmho, respectively) were significantly greater than that using the traditional baseline compensation method (Y_{BC} = 0.65 mmho). Although Y_{CC-400} has attained the highest mean value, it has the lowest test-retest reliability. Hence, the component compensation approach compensated at 200 daPa holds promise as an alternative method for estimating middle ear admittance in neonates. Further research to evaluate its test performance using clinical decision theory is required to determine its clinical significance.

Key Words: middle ear, admittance, susceptance, conductance, 1000 Hz tympanometry, neonates

Abbreviations: B = susceptance; B_{tm} = compensated susceptance; G = conductance; G_{tm} = compensated conductance; ICC = intra-correlation coefficient; SEM = standard error of measurement; SNR = signal-to-noise ratio; TEOAE = transient evoked otoacoustic emission; Vec = ear canal volume; Ya = uncompensated acoustic admittance; Y_{BC} = baseline compensated static admittance; Y_{CC200} = static admittance compensated for two components at 200 daPa; Y_{CC-400} = static admittance compensated for two components at -400 daPa; Yec = admittance of the ear canal; Ytm = admittance of the middle ear referenced to the lateral surface of the tympanic membrane

Sumario

El presente estudio buscó comparar tres medidas de estimar la admitancia del oído medio en neonatos, utilizando timpanometría de 1000 Hz. Los datos fueron obtenidos de 36 recién nacidos de término, con edades entre las 24 y 123 horas, quienes superaron una prueba de emisiones otoacústicas evocadas por transitorios y evaluados por medio de un impedanciómetro Madsen

*Division of Audiology, School of Health and Rehabilitation Sciences, The University of Queensland, Australia; †Ipswich General Hospital, Ipswich, Queensland, Australia

Dr. Joseph Kei, Division of Audiology, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Qld 4072, Australia; Phone: +61 7 3365 2824; Fax: +61 7 3365 1877; E-mail: k.kei@uq.edu.au

Otoflex. Los resultados demostraron que las admitancias medias del oído medio, obtenidas por compensación para los componentes de susceptancia y conductancia a la presión de 200 daPa y a – 400 daPa (Y_{CC200} = 1.00 mmho y Y_{CC-400} = 1.24 mmho, respectivamente) fueron significativamente mayores que aquellas que utilizan el método tradicional de compensación basal (Y_{BC} = 0.65 mmho). Aunque Y_{CC-400} ha obtenido los valores medios más altos, tienen la menor confiabilidad test-retest. Por lo tanto, el enfoque de compensación por componentes, compensado a 200 daPa, luce promisorio como un método alternativo para estimar la admitancia del oído medio en neonatos. Investigaciones adicionales para evaluar su desempeño usando teoría de decisión clínica se requieren para determinar su significancia clínica.

Palabras Clave: oído medio, admitancia, susceptancia, conductancia, timpanometría de 1000 Hz, neonatos

Abreviaturas: B = susceptancia; B_{tm} = susceptancia compensada; G = conductancia; G_{tm} = conductancia compensada; ICC = coeficiente de intra-correlación; SEM = error estándar de medición; SNR = tasa señal-ruido; TEOAE = emisiones otoacústicas evocadas por transitorios; Vec = volumen del canal auditivo; Ya = admitancia acústica no compensada; Y_{BC} = admitancia estática compensada basal; Y_{CC200} = admitancia estática compensada para dos componentes a 200 daPa; Y_{CC-400} = admitancia estática compensada para dos componentes a - 400 daPa; Yec = admitancia del canal auditivo; Ytm = admitancia del oído medio referida a la superficie lateral de la membrana timpánica

Tympanometry is an established procedure for assessing middle ear function in humans. This procedure involves measuring the acoustic energy that is transmitted into the middle ear system while the air pressure in the ear canal is varied. The result is plotted on a tympanogram which shows a variation of acoustic admittance against ear canal pressure. This uncompensated peak acoustic admittance (Ya) is composed of two major components, namely the admittance of the ear canal (Yec) and the admittance of the middle ear referenced to the lateral surface of the tympanic membrane (Ytm). To determine the admittance of the middle ear (also called peak compensated static admittance) which is an estimate of the mobility of the tympanic membrane and the middle ear system, the admittance of the ear canal has to be subtracted from the uncompensated peak admittance as shown by the following relationship:

$$Ytm = Ya - Yec \tag{1}$$

In conventional tympanometry with a probe tone of 226 Hz, the admittance of the ear canal is numerically equal to its equivalent volume (expressed in ml) under standard atmospheric conditions at sea level and provided that the air column between the probe tip and the tympanic membrane can be modelled as pure acoustic compliance (Shanks and Lily, 1981). Hence, to determine the admittance of the middle ear, tympanometric measurements must first be compensated for ear canal volume (Vec). One method for estimating the Vec is to raise the ear canal pressure to 200 daPa and measure its equivalent volume. This measurement is based on the assumption that such positive pressure places the eardrum under sufficient tension as to drive the impedance of the middle ear toward infinity (Terkildsen and Thompsen, 1959). That is, no sound energy can be transmitted through the tympanic membrane to the middle ear. Under this high pressure, the admittance measure at the probe tip may be attributed to the ear canal alone, thus providing a good estimate of Vec. However, several studies have demonstrated that measuring the volume at 200 daPa does not provide a good estimate of the Vec (Margolis and Smith, 1977;

Vanpeperstraete, et al, 1979; Rabinowitz, 1981; Shanks and Lily, 1981; Shanks, 1984). Because of the asymmetry of admittance tympanogram, the Vec measured at 200 daPa is larger than that measured at -400 daPa. Shanks and Lily (1981), as well as other researchers, concluded that measuring Vec at -400 daPa would provide a better estimate of the volume of the ear canal than that measured at 200 daPa. In fact, the peak compensated static admittance (Ytm), compensated at the negative tail of -400 daPa, is larger than that compensated at the positive tail of 200 daPa (e.g., Margolis et al, 2003). Although compensation at the negative tail provides more accurate estimates of Vec and, hence, a larger value of Ytm, it has not been widely adopted by clinicians. In fact, estimating ear canal volume at 200 daPa has been widely promoted since 1959, and has become the norm. On practical grounds, it is not always possible to estimate volume at -400 daPa because of the possibility of a collapsed ear canal. To date, there has not been enough evidence to justify that the use of compensation at the negative tail is clinically more useful than that compensated at the positive pressure end.

Regardless of where the compensation takes place, the above method of estimating the admittance of the middle ear involves the subtraction of two *apparently* scalar quantities, namely the uncompensated peak admittance and ear canal volume (admittance at either the positive or the negative end). The ear canal volume is treated as a baseline against which the admittance of the middle ear is measured. In the present study, this method of compensation is called “baseline compensation.” In reality, the above two physical quantities are not scalar quantities. They are *vector* quantities, with each one having its susceptance (B) and conductance (G) components in the rectangular coordinate system. Each quantity has both magnitude and direction [with a phase angle given by a mathematical function, $\Phi = \tan^{-1}(B/G)$]. Hence, the admittance of the middle ear can be accurately determined only if no significant shift in phase angles occurs between the two admittance vectors representing the uncompensated peak admittance (Ya) and the admittance at either the positive or negative tail (Yec). Stated differently, the two admittance vectors cannot be subtracted *numerically* unless they have identical phase angles. When testing adults using 226 Hz tympanometry, the phase angles of Ya and Yec are close to 90^o since the susceptance (B) is much greater than the conductance (G). Hence, the phase difference between the two admittance vectors is very small and the two admittance values can be subtracted. In this manner, the error in calculating the Ytm is negligible (Shanks, 1984). However, this situation is different when a high frequency probe tone such as 1000 Hz is used with neonates where the B and G values do not hold the same relationship as in adults (Margolis and Hunter, 2000).

In recent years, the 1000 Hz tympanometry has been trialled in neonates with healthy newborns showing single-peaked uncompensated tympanograms (Kei et al, 2003; Margolis et al, 2003; Baldwin, 2006; Calandruccio et al, 2006). However, at 1000 Hz, the vector quantities of the two admittance vectors representing the peak admittance and the admittance of the ear canal may have different phase angles (Margolis and Hunter, 2000), indicating that a significant error is likely to occur if the conventional baseline compensation approach is used to estimate the middle ear admittance in neonates. To minimize the errors involved, compensation for both components of admittance, namely the susceptance and conductance, in deriving the static admittance has been suggested (Margolis and Hunter, 2000). In this “component compensation” approach, the compensated components (B_{tm} and G_{tm}) can be obtained by subtracting the B and G values at 200 daPa from the uncompensated peak B and G values. The component compensated static admittance, Y_{CC}, can then be calculated using the following equation:

$$|Y_{CC}| = \sqrt{(B_{tm}^2 + G_{tm}^2)} \qquad (2)$$

The different methodologies in estimating the static admittance using the baseline compensation and the component compensation approaches can also be illustrated by treating the uncompensated peak admittance and admittance at 200 daPa as vectors as shown in Figure 1. In Figure 1, vectors OA and OB represent the uncompensated peak admittance (Ya) with a magnitude of 1.6 mmho and admittance at +200 daPa (Yec) with a magnitude of 1.0 mmho respectively. There is a difference in phase angles (represented by the angle, θ) between the two vectors. The baseline compensated static admittance, Y_{BC}, value is given by the difference in magnitudes between the two vectors, which is 0.6 mmho (i.e., 1.6 minus 1.0). However, the component compensated Y_{CC} value is given by the difference between the two vectors, which is BA with a magnitude of 0.9 mmho. In this example, the Y_{BC} and Y_{CC} values differ by 0.3 mmho in magnitude.

Although it has been suggested that the component compensated approach may provide a better estimate of the admittance of the middle ear in neonates when 1000 Hz tympanometry is utilized (Margolis and Hunter, 2000; Calandruccio et al, 2006), no population-based study has, to date, been reported in the literature to substantiate this claim. It is also important to find out how the admittance of the middle ear, compensated at a negative pressure of -400 daPa compares with that compensated at 200 daPa. Furthermore, the test-retest reliability of these measures of middle ear admittance in neonates has not been investigated. The aims of the study were, therefore, to compare three methods (one baseline and two component compensated approaches) for estimating the middle ear admittance in neonates using 1000 Hz tympanometry and to determine the test-retest reliability of these measures.

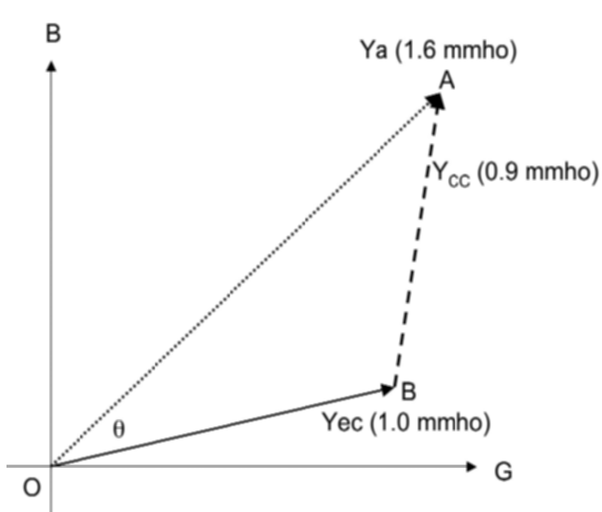

Figure 1. Graphical representation of admittance vectors **OA** and **OB**. **OA** minus **OB** equals **BA**, which represents the component compensated static admittance (Y_{CC}).

METHODS

Participants

A prerequisite for inclusion in the study was the requirement to pass an automated auditory brainstem response test which was performed by specially trained nurses employed by the Healthy Hearing Screening Program in Queensland, Australia. For inclusion in the study, the participants were also required to pass a transient evoked otoacoustic emission (TEOAE) test and were free from any pre-existing condition known to constitute an at risk criterion predisposing hearing loss (JCIH, 2000). As a result of the above inclusion criteria, 36 neonates (20 boys and 16 girls) born at the Ipswich General Hospital, Queensland, Australia participated in this study. All participants were full-term babies with mean gestational age of 39.3 weeks (SD = 1.4, range = 37 to 42) and an uneventful birth history. Their mean birth weight was 3.5 kg (SD = 0.5, range = 2.3 to 4.6). The mean chronological age was 62 hours (SD = 29, range = 24 to 163). Since only one ear from each participant was required, the most accessible ear was tested. A total of 23 left and 13 right ears were tested. Ethical approval from the hospital and parental permissions were obtained before testing commenced.

Procedure

A clinical audiologist or postgraduate audiology students, with experience in the use of TEOAE and immittance procedures with infants, performed all testing. Neonates were tested individually, in the presence of their parents, in a non-sound-treated room with a mean noise level of 36.9 dBA (ranging from 35 to 40) as measured using a CSL-254 sound level meter. These levels did not exceed 50 dBA as recommended by Rhoades et al (1998) for TEOAE testing. Neonates were fed, dry, lying comfortably in their cribs, and in a quiescent or sleeping state before testing commenced.

The baby's ear was visually inspected for any abnormality in the external ear such as abnormal shapes of the pinna before the tests began. None of the 36 participants had shown such abnormality. TEOAE testing was conducted prior to the immittance tests. The Quickscreen program of the ILO292 Otodynamics Analyser was utilized for all TEOAE testing due to its reported time efficiency and resilience to background noise in non-ideal acoustic environments (Vohr et al, 1993). Wide band, gaussian-shaped clicks of 80 ms in the non-linear mode were presented to the test ear. The mean stimulus level was 87.2 dB peak SPL (SD = 3.3, range = 81 to 93). A total of 260 quiet responses per ear were used to evoke TEOAEs. To be awarded a pass, the TEOAE spectrum demonstrated a criterion signal-to-noise ratio (SNR) of ≥3 dB at 1 and 1.5 kHz, and ≥ 6 dB at 2, 3 and 4 kHz in 4 out of 5 half-octave bands as recommended by Norton et al (2000).

A Madsen Otoflex diagnostic impedance meter was used for the high frequency tympanometry. A 1000 Hz probe tone was delivered to the ear via a probe at 75 dB SPL, the same level used by Kei et al (2003). The applied pressure to the ear canal varied from +200 to -400 daPa as recommended by Holte et al (1991) to minimize the effect of a collapsed ear canal under negative pressures. A pump speed of 400 daPa/s was used as recommended by Margolis et al (2003). Testing started once a hermetic seal was obtained. However, when a proper seal could not be achieved, the probe was held manually to ensure that a hermetic seal was obtained. An admittance tympanogram, which plots uncompensated admittance (in mmho) against ear canal pressure (in daPa), was obtained from the test ear. As well, the Otoflex plotted both baseline and component compensated tympanograms simultaneously. Like baseline compensation, the component compensation can also be performed at the negative tail (-400 daPa). Since the Otoflex diagnostic impedance meter does not have this function, this was done manually. Using the component compensation approach, the compensated components were obtained by subtracting the B and G values at -400 daPa from the uncompensated peak B and G values. The component compensated static admittance, Y_{CC-400}, was the square root of the sum of the squares of the compensated B and G values (see Equation 2).

The following test parameters were recorded for each ear: uncompensated admittance, susceptance and conductance at +200 daPa and -400 daPa, tympanometric peak pressure (usually around 0 daPa); peak compensated static admittance with baseline compensation at +200 daPa (Y_{BC}); peak compensated static admittance with component compensation at +200 daPa (Y_{CC200}); and peak compensated static admittance with component compensation at -400 daPa (Y_{CC-400}). At the end of the first test, the probe was removed, a new probe tip was fitted, and the procedures repeated.

RESULTS

Before presenting the immittance results at a group level, tympanometric data from a participant are presented to illustrate exactly what results were obtained and their relationships. These data are representative of this cohort of babies.

Representative Data

A baby girl, LL, with a gestational age of 38 weeks and a birth weight of 3.5 kg was tested 3 days after birth. She had an uneventful birth with Apgar scores of 9 and 10 at 1 and 5 minutes, respectively. She had robust TEOAEs in her right ear with an SNR of -5, 14, 17, 20 and 19 dB at 1, 1.5, 2, 3 and 4 kHz, respectively, satisfying the Norton et al (2000) criteria for a pass in the test. Figure 2 shows a plot of uncompensated admittance, susceptance and conductance values against the ear canal pressure for this baby. The conductance values were generally smaller than the susceptance values at positive ear canal pressures. However, the reverse was observed when the ear canal pressure became negative. The phase angles at 200, 0 and -400 daPa were 66.5^o, 43.4^o and 39.8^o, respectively. The finding that these phase angles are less than 90^o indicates that the admittance did not behave as a pure compliance (or susceptance). Furthermore, the phase angle varied, depending on the applied ear canal pressure. The uncompensated tympanogram obtained from this baby girl is similar to that obtained from a newborn baby in the study by Holte et al (1991), who used a probe tone of 900 Hz. The findings from this participant are typical of the results of the other participants in the present study.

The Otoflex diagnostic impedance meter

automatically plotted two types of tympanograms: one baseline compensated for admittance at 200 daPa and the other compensated for both the conductance and susceptance components at 200 daPa. Figure 3 shows a comparison of these two admittance tympanograms. They differ in shapes and numerical values. Generally, the component compensated admittance values are greater than the baseline compensated admittance values for all ear canal pressures. As shown in Figure 3, the peak compensated static admittance values for the component compensation (Y_{CC200}) and baseline compensation (Y_{BC}) are 0.95 and 0.75 mmho, respectively. The values were derived from the maximum admittance value of the respective tympanograms. The finding that the component compensated static admittance is greater than the baseline compensated static admittance is a typical result for this cohort. The Y_{CC-400} value, calculated manually as described in the Method Section, was 1.31 mmho. This value is greater than either the Y_{CC200} or Y_{BC} value.

Group Results

Analysis of TEOAE results at the group level revealed mean SNRs to be 7.4, 16.8, 22.3, 23.4, and 22.3 dB with SDs being equal to 6.9, 6.6, 6.6, 6.2, and 7.7 dB at 1, 1.5, 2, 3 and 4 kHz, respectively. These values are comparable to that obtained by Norton et al (2000). The small SNR values at 1 and 1.5 kHz when compared to those in the higher frequencies were probably due to a higher physiologic and ambient noise level commonly observed in neonates.

In the present study, all uncompensated admittance tympanograms were single-peaked. The mean uncompensated peak admittance was found to be 1.60 mmho (SD = 0.47; range = 0.9–2.7). To examine if there is a relationship between this test parameter and other parameters of interest, a Pearson Correlation test was performed. The correlation coefficients between the uncompensated peak admittance and Y_{BC}, Y_{CC200} and Y_{CC-400} were 0.85 ($p < 0.001$; N=36), 0.84 ($p < 0.001$; N=36), and 0.85 ($p < 0.001$; N=23), respectively. The reason for the smaller sample size in the latter correlation was due to the inability to obtain valid immittance data at -400 daPa from 13 babies. In general, the correlation coefficients indicate high correlation between the uncompensated peak admittance and the three test parameters (Y_{BC}, Y_{CC200} and Y_{CC-400}).

Table 1 shows the descriptive statistics

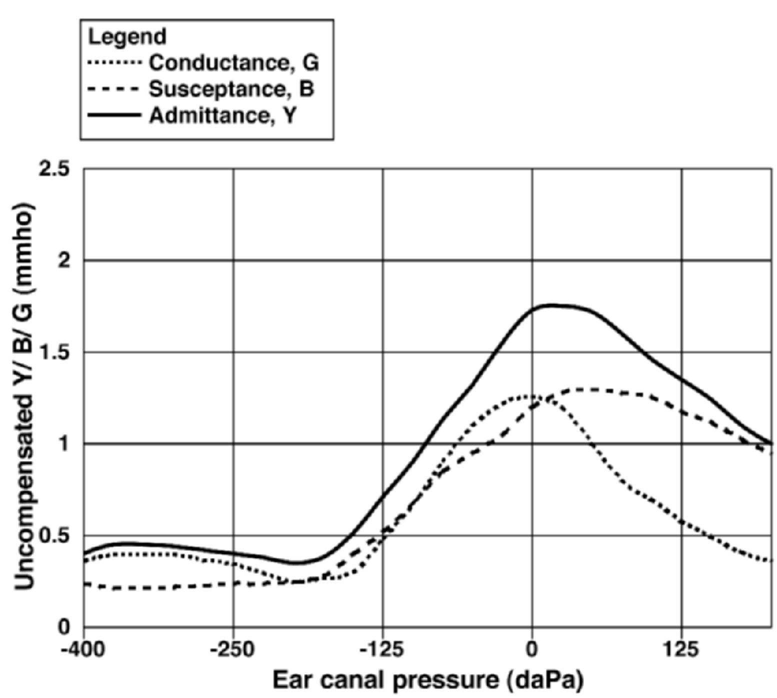

Figure 2. Plot of uncompensated admittance, susceptance and conductance values against ear canal pressure for baby girl LL, aged 3 days.

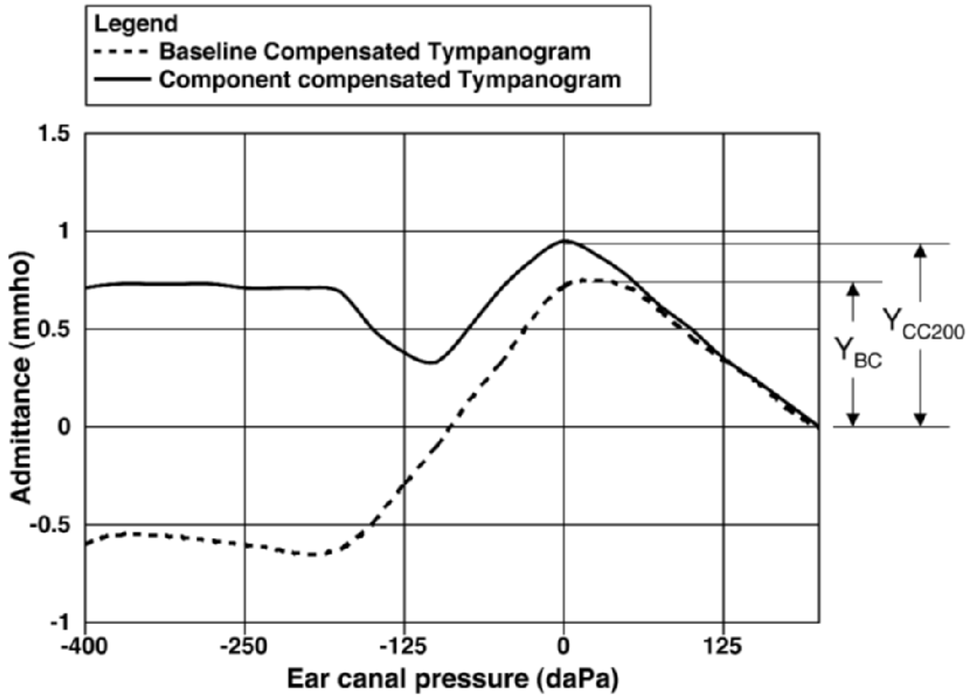

Figure 3. Plot of baseline compensated and component compensated admittance against ear canal pressure for baby girl LL, aged 3 days.

of the immittance results for 36 normal babies. Of the 36 babies, some did not complete the entire test procedure because they woke up and became restless. Hence, the numbers of ears in the statistical analyses were different depending on which test parameter was involved. As shown in Table 1, Y_{CC-400} has the highest mean value, followed by Y_{CC200} and Y_{BC}. Paired comparison t-tests were applied to the Y_{BC}, Y_{CC200} and Y_{CC-400} data obtained in the first test (Test 1). The results showed that Y_{BC} was significantly smaller than Y_{CC200} ($t = -10.04$, $df = 35$, $p < 0.0001$) and Y_{CC-400} ($t = -7.89$, $df = 22$, $p < 0.0001$). However, the difference between Y_{CC200} and Y_{CC-400} did not reach significance.

The test-retest reliability of the tympanometric measures was evaluated by calculating the single measure intra-correlation coefficients (ICC) as follows: ICC = between-participant variance ÷ total variance x 100%. The ICC value ranges from 0 to 1, indicating very low to very high test-retest reliability. In the present study, the ICC values for both Y_{CC200} and Y_{BC} were in excess of 0.88, but below 0.6 for Y_{CC-400}. Another useful measure of the reliability of a test is the standard error of measurement (SEM), which is the standard deviation of an individual's repeated measurements. Large SEM values indicate low test-retest reliability. In the present study, Y_{CC-400} had the largest SEM (0.33 mmho) of the three measures. The difference in mean values between the test and retest conditions was assessed using a paired comparison t-test. The results did not show significant differences in any of the measures at the 0.05 significance level.

DISCUSSION

The present study is an exploratory investigation of three methods, which may be used to estimate the middle ear admittance in neonates using 1000 Hz tympanometry. The primary aim of the present study was to compare the middle ear admittance values obtained using the conventional baseline compensation approach with that obtained using a component compensation approach, compensated at the positive and negative pressure ends. In estimating the middle ear admittance, all three methods involve subtracting the ear canal effect from the uncompensated peak admittance. While it is straightforward and methodologically sound to estimate middle ear admittance in this manner for adults and older infants, it is not clear if the same procedure can be confidently applied to newborn babies. The middle ear of a newborn baby is a mass dominated system and has a lower resonant frequency, in sharp contrast to the adult ear, which is a stiffness dominated system and has a higher resonant frequency (Holte et al, 1991). Hence, the mathematical principles underlying the tympanometric measurements in adults may not be applicable to neonates. The ear canals of neonates are distensible under applied air pressure because of the underdeveloped osseous portion of the ear canal. The neonates' ear canals do not appear to satisfy the constraints needed to model the ear canal as pure acoustic susceptance. Furthermore, the admittance of the ear canal measured at the extreme pressures may not correspond to the admittance of the ear canal under zero static pressure. Thus, compensating for the ear canal contribution by making measurements of admittance at extreme ear canal static pressures (i.e., 200 or -400 daPa) may introduce errors in estimating the static admittance.

Notwithstanding the above limitations, there is some evidence that the 1000 Hz tympanometry may be more sensitive to middle ear dysfunction in neonates than either the 226 Hz or 660 Hz tympanometry (Williams et al, 1995; Rhodes et al, 1999; Baldwin, 2006). Flat tympanograms (no measurable admittance with varying ear canal pressure) in 1000 Hz tympanometry are indicative of middle ear dysfunction in young infants less than 4 months of age (Williams et al, 1995; Margolis et al, 2003; Baldwin, 2006). In particular, Baldwin (2006) classified tympanograms obtained from 211 young infants using a shape classification method adapted from Marchant et al (1986). Normal tympanograms were characterized by a positive peak while abnormal ones were of a negative or trough configuration. Using TEOAE and auditory brainstem response results as a gold standard, Baldwin found that the sensitivity and specificity of the 1000 Hz tympanometry were 0.99 and 0.89, respectively. These encouraging findings indicate that tympanograms with a positive peak are consistent with normal middle ear function.

In the present study, all tympanograms from 36 neonates were single-peaked. The results of a Pearson Correlation test to examine the relationship between the uncompensated admittance (Ya) and compensated admittances (Y_{BC}, Y_{CC200}, and Y_{CC-400}) showed high correlation (≥ 0.84) between the uncompensated and compensated quantities. This indicates that the compensated admittance could be predicted from the uncompensated admittance to a great extent and vice versa. Hence, in the absence of a better measure of middle ear function, the compensated admittance approaches are useful measures of middle ear function in neonates.

In the present study, the mean value of the baseline compensated admittance (Y_{BC}) was 0.65 mmho, which compares favorably with the mean middle ear admittance values (0.52 - 0.58 mmho) in the Kei et al (2003) study. However, a greater mean value of 1.3 mmho was reported by Margolis et al (2003), who tested 30 full term infants at 2 to 4 weeks old. Such a discrepancy in mean admittance values may be due to procedural differences between studies such as different age groups, the

Table 1. Descriptive statistics for test and retest immittance results. The intra-correlation coefficients (ICC) with 95% confidence interval and standard error of measurement (SEM) between the test and retest measures are also shown. Y_{BC} represents the baseline compensated static admittance. Y_{CC200} and Y_{CC-400} are the static admittances component-compensated at 200 and -400 daPa respectively.

Test parameter	Test 1 Mean; SD; Range; N	Test 2 Mean; SD; Range; N	ICC; (95% C.I.)	SEM
Y_{BC} (mmho)	0.65; 0.37; 0.13-1.47; 36	0.66; 0.34; 0.20-1.50; 34	0.89 (0.79-0.94)	0.12 mmho
Y_{CC200} (mmho)	1.00; 0.46; 0.37-2.15; 36	1.02; 0.46; 0.40-2.48; 34	0.92 (0.84-0.96)	0.13 mmho
Y_{CC-400} (mmho)	1.24; 0.51; 0.36-2.38; 23	1.14; 0.45; 0.31-2.09; 18	0.58 (0.14-0.83)	0.33 mmho

use of different equipment and calibration techniques.

As mentioned earlier, the Y_{BC} value was calculated when compensation was performed at a pressure of 200 daPa. In the present study, the values using the component compensated approach were calculated at both the positive and negative pressure ends. The representative data from Baby LL, revealed a Y_{CC-400} value of 1.31 mmho which is greater than either the Y_{CC200} (0.95 mmho) or Y_{BC} (0.75 mmho) values. This pattern of results was replicated at the group level where the mean Y_{CC-400} attained the highest value (1.24 mmho), followed by the mean Y_{CC200} (1.00 mmho) and mean Y_{BC} (0.65 mmho) values. The mean Y_{CC200} compares reasonably well with the median middle ear admittance of 1.07 mmho obtained from 4-10 week-old infants in the Calandruccio et al (2006) study, despite the difference in age of participants and equipment between the two studies. In essence, the middle ear admittance values calculated using the component compensated approaches were found to be significantly greater than that using the baseline compensated approach. Given these results, the component compensated approaches hold promise as an alternative method for estimating middle ear admittance in neonates. The larger mean Y_{CC} values may, therefore, permit a better separation of abnormal tympanograms from the normal ones. Hence, very shallow or flat tympanograms may be identified more easily than that using the conventional baseline approach.

The present study did not attempt to justify that one method was better than another. Rather, it has outlined three different mathematical approaches to estimate the middle ear admittance in neonates. None of the three approaches has assumed that the newborn ear canal can be modeled as pure acoustic susceptance. It is clear that the inability to accurately measure the ear canal effect in newborn babies is a confounding variable which needs to be addressed in future research. Although the component compensation approaches are more mathematically accurate because they take into account the phase differences between two vector quantities, this does not necessarily mean that the component compensation approaches are better than the baseline compensation approach. Further evidence, based on sensitivity and specificity measures of the three approaches, is required to justify their use in clinics. Another aim of the present study was to investigate the test-retest reliability of the tympanometric test parameters. The results from the present study showed that both the Y_{CC200} and Y_{BC} measures demonstrated very good test-retest reliability, indicating that these two measures are highly repeatable on retest. However, the test-retest reliability for Y_{CC-400} was only moderate with an ICC value of 0.58 and SEM value of 0.33 mmho. The reasons for the lower test-retest reliability measures of the Y_{CC-400} remain unclear. Possible reasons may include a smaller sample size than that used in the other two measures (23 versus 36 ears), and greater variability of admittance values observed at the negative pressure end (-400 daPa). The greater variability of the admittance as the ear canal pressure was approaching -400 daPa might be caused by the inability of the equipment to secure a tight seal in the participant's ear canal. The Otoflex impedance meter incorporates very small pressure pumps that abort if a slight pressure leak is detected. The problem may also be caused by collapsed ear canal or sealing against the ear canal wall at extreme negative pressures. Further investigation is warranted to determine the possible factors that affect the reliability of the Y_{CC-400} measure.

In the current experimental design, all babies were required to pass a TEOAE test, which was conducted in a quiet room with ambient noise ranging between 35 and 40 dBA. Testing babies while they were asleep also minimized the physiologic noise from babies, hence reducing the false positive rate of the TEOAE test due to excessive noise. However, as pointed out by Kei et al (2003) and Margolis et al. (2003), passing a TEOAE test does not guarantee normal middle ear functioning in all cases. Another limitation of the present study was the difficulty in obtaining and maintaining an appropriate probe seal for the tympanometry test. In most cases, the probe had to be held manually. The instability of the tester's hand might have contributed to unwanted artifacts, thus affecting the accuracy in determining the tympanometric measures and increasing the variability of the admittance data. To minimize measurement errors, improvement in instrumentation is required to quickly achieve a hermetic seal in a baby's ear canal and speed up the testing.

In summary, the mean middle ear admittances obtained using the component compensation methods were significantly greater than that using the baseline compensation method. Theoretically, the larger mean admittance values may allow a better separation of abnormal tympanograms from the normal ones. Although the Y_{CC-400} has attained a higher mean value than Y_{CC200}, it has the lowest test-retest reliability as determined by a low intra-correlation coefficient of 0.58 and a high standard error of measurement of 0.33 mmho. Hence, the component compensation approach compensated at 200 daPa holds promise as an alternative method for estimating middle ear admittance in neonates. Further investigation, based on the test performance of this approach using clinical decision theory, is required before it can be effectively applied in clinics.

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