High-Frequency (1000 Hz) Tympanometry in Normal Neonates

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Abstract
The characteristics of high frequency (1000 Hz) acoustic admittance results obtained from normal neonates were described in this study. Participants were 170 healthy neonates (96 boys and 74 girls) aged between 1 and 6 days (mean = 3.26 days, SD = 0.92). Transient evoked otoacoustic emissions (TEOAES), and 226 Hz and 1000 Hz probe tone tympanograms were obtained from the participants using a Madsen Capella OAE/middle ear analyser. The results showed that of the 170 neonates, 34 were not successfully tested in both ears, 14 failed the TEOAE screen in one or both ears, and 122 (70 boys, 52 girls) passed the TEOAE screen in both ears and also maintained an acceptable probe seal during tympanometry. The 1000 Hz tympanometric data for the 122 neonates (244 ears) showed a single-peaked tympanogram in 225 ears (92.2 %), a flat-sloping tympanogram in 14 ears (5.7 %), a double-peaked tympanogram in 3 ears (1.2 %) and other unusual shapes in 2 ears (0.8 %). There was a significant ear effect, with right ears showing significantly higher mean peak compensated static admittance and tympanometric width, but lower mean acoustic admittance at -200 daPa and gradient than left ears. No significant gender effects or its interaction with ear were found. The normative tympanometric data derived from this cohort may serve as a guide for detecting middle ear dysfunction in neonates.

Key Words: High frequency tympanometry, acoustic admittance, middle ear, neonate, neonatal hearing screening.

Abbreviations: ABR = auditory brainstem response; ANOVA = analysis of variance; dB peSPL = decibel peak equivalent sound pressure level; f = frequency of probe tone; OAE = otoacoustic emissions; PCA = Principal Components Analysis; Pec = ear canal pressure; TEOAE = transient evoked otoacoustic emissions; TW = tympanometric width; SPL = sound pressure level; V = volume of calibration cavity; Y = acoustic admittance; Y200 = acoustic admittance at -200 daPa; Ypc = peak compensated static admittance.

Sumario
El estudio describe las características de la admittance acústica de alta frecuencia (1000 Hz) obtenida en neonatos normales. Los participantes fueron 170 neonatos saludables (26 niños y 74 niñas) con edades entre 1 y 6 días (media de 3.26, SD = 0.92). Se obtuvieron emisiones otoacústicas evocadas por transientes (TEOAES) y timpanogramas realizados con una sonda de prueba de 226 Hz y 1000 Hz usando una unidad Madsen Capella con un analizador de oído medio y EOA. Los resultados mostraron que de los 170 neonatos, 34 no pudieron ser evaluados en ambos oídos, 14 fallaron la prueba de TEOAE en uno o en ambos oídos, y 122 (70 niños y 52 niñas) pasaron el tamizaje de TEOAE en ambos oídos y también mantuvieron un nivel de sello aceptable en la sonda de timpanometría. La información timpanométrica a 1000 Hz para los 122 neonatos (244 oídos) mostró un timpanograma de pico único en 225 oídos (32.2%), un timpanograma plano con pendi-
ente en 14 oídos (5.7%), un timpanograma de doble pico en 3 oídos (1.2%), y otras formas inusuales en 2 oídos (0.8%). Existió un significativo efecto de oído, con los oídos derechos mostrando picos medios compensados de admittance estática y anchos timpanométricos significativamente mayores, aunque gradiencias y admittencias acústicas promedio menores a +200 daPa, en oídos izquierdos. No se encontró un significativo efecto de género o de género por oído. La información normativa timpanométrica de esta cohorte puede servir como una guía para detectar disfunción de oído medio en neonatos.

**Palabras Clave:** Admitancia acústica, timpanometría de alta frecuencia, oído medio, tamizaje auditivo neonatal, neonato.

**Abreviaturas:** OAE = emisión otoacústica; PCA = análisis de componentes principales; Pec = presión del canal auditivo; TEOAE = emisiones otoacústicas evocadas por transientes; TW = ancho del timpanograma; Y = admittance acústica; Y200 = admittance acústica a +200 daPa; Yc = diferencia entre el pico de admittance y la admittance a -200 daPa; Ypc = pico compensado de admittance acústica.

Current procedures used for infant hearing screening programs include otoacoustic emissions (OAEs) and auditory brainstem responses (ABR). These procedures produce a refer rate which varies from 2 to 5% (e.g., Thomson, 1997; Sinerger et al, 2000). It is possible that some of these “refer” cases may have a congenital middle ear dysfunction (transient or permanent). Recent studies have shown that a large proportion of young infants, diagnosed to have a hearing loss, have a mild to moderate conductive hearing impairment (e.g., McPherson et al, 1998). The evidence of a high proportion of infants having a conductive hearing impairment is also provided by Cone-Wesson et al (2000), who investigated the hearing of 2995 infants at 8 to 12 months using visual reinforcement audiometry and conventional tympanometry (with a probe tone of 226 Hz). They found that of the 168 infants (5.6%) who had a hearing loss in at least one ear, 85% had middle ear dysfunction. Hence, it would be an advantage to have a screening test of middle ear function for neonates who fail a hearing screen, if not for all neonates. However, such a screening test for detection of middle ear dysfunction in neonates has not been widely performed.

The use of conventional tympanometry to detect middle ear dysfunction for infants aged less than seven months may produce erroneous test outcomes, despite its successful application to adults and children (Beery et al, 1975; Paradise et al, 1976; Shurin et al, 1976; Shurin et al, 1977; Weatherby and Bennett, 1980; Sprague et al, 1985; Hunter and Margolis, 1992; Keefe et al, 1993; Williams et al, 1995; Keefe and Levi, 1996; McKinley et al, 1997; Meyer et al, 1997; Rhodes et al, 1999). It has been shown to have poor sensitivity (a high false negative rate) (Paradise et al, 1976; Shurin et al, 1976; Hunter and Margolis, 1992; Meyer et al, 1997). For instance, researchers have obtained Type A tympanograms (normal static compliance and normal middle ear pressure), based on the Liden/Herger classification system (Liden, 1969; Jerger, 1970), coexisting with confirmed middle ear effusion. The conventional low-frequency probe tone tympanometry can also produce Type B tympanograms (no change in static compliance with pressure variation) in normal middle ears (Keefe et al, 1993; Keefe and Levi, 1996). Further, it has produced different shaped tympanograms (such as double-peaked) in infants compared to adults and older children (Keith, 1973; Sprague et al, 1985; Holte et al, 1991).

The above spurious results may be accounted for by the differences in acoustic energy transmission through the middle ear between neonates and adults, although the exact cause for the differences remain unclear. Research findings indicate that a neonate’s middle ear is mass-dominated, in contrast to the stiffness-dominated middle ear system of adults (Holte et al, 1991; Keefe and Levi, 1996; Meyer et al, 1997). For this reason, conventional tympanometry, which is useful for assessing middle ear function in stiffness-dominated systems, is not suitable for use with neonates. Hence, the search for an effective screening test of middle ear function for neonates is necessary.

Apart from the measurement of acoustic reflectance and admittance to determine the middle ear status of neonates (Keefe et al,
2000), the use of tympanometry with a higher probe tone frequency (>226 Hz) has been advocated (Holte et al., 1991; Purdy and Williams, 2000). The use of a higher frequency probe tone (such as 668, 800, 1000 Hz) has been shown to be more sensitive to middle ear effusion in infants than the conventional probe tone (Marchant et al., 1986; Williams et al., 1995; Meyer et al., 1997). In particular, Williams et al. (1995) studied 26 infants under 4 months of age, and found that peak susceptibility at 1000 Hz provided the best agreement with otomicroscopy and pneumatic otoscopy. While Sprague et al. (1985), and Weatherby and Bennett (1980) reported less complex patterns in infant tympanograms using higher frequency probe tones, McKinley et al. (1997) found that more than half of the 55 neonatal ears studied exhibited susceptibility and conductance tympanograms that could not be classified using the Vanhuyse multi-component tympanogram models (Vanhuyse et al., 1975). However, the above findings are not conclusive in view of the small sample size of the studies. The present study aimed to describe the characteristics of high frequency (1000 Hz) acoustic admittance results in normal neonates and establish normative data for this population.

**METHOD**

**Participants**

A total of 170 (96 male, 74 female) healthy neonates born at the Mater Misericordiae Hospital, Brisbane, Australia were recruited for the present study. Medical and parental permissions were obtained before testing commenced. All participants were full-term babies (38 to 42 weeks gestation) with an uneventful birth history and free from any pre-existing condition or history known to constitute an at risk criterion predisposing hearing loss. Participants were between 1 and 6 days old at the time of testing (mean = 3.26 days, SD = 0.92). Their birth weight ranged from 2512 g to 4882 g (mean = 3784 g, SD = 373).

Participants’ data were not included in the final statistical analyses if participants had a congenital defect, demonstrated one or more of the ‘at risk’ factors for hearing loss listed in the Joint Committee on Infant Hearing position statement (JCIH, 2000), or failed a screening test using transient evoked otoacoustic emissions (TEOAEs). The pass criteria for the TEOAE screening were (1) the presence of a TEOAE spectrum at least 3 dB above the noise floor and at least halfway across the test frequency bands of 2-3 kHz and 3-4 kHz as suggested by Kei et al. (1997); and (2) overall correlation greater than or equal to 50% (e.g., Shi et al., 2000). Babies who did not meet these criteria were referred to the Mater Hospital Audiology Department for diagnostic ABR test, which was performed by a clinical audiologist on the same day as the TEOAE screen. Passing a TEOAE screen suggests normal or close to normal auditory function up to the inner ear (outer hair cells) (Kemp, 1997; Taylor and Brooks, 2000).

As a result of the data exclusion, the data for 48 neonates who either failed the TEOAE screening in one or both ears, or did not complete the TEOAE and tympanometry tests in both ears, were excluded from the final statistical analysis. Hence, the tympanometry results for 122 babies (70 males and 52 females; mean age = 3.29 days, SD = 0.89) were analysed. These babies passed the TEOAE screening in both ears and also maintained an acceptable probe seal for both ears during tympanometry.

**Procedure**

Testing was performed by a clinical nurse, who was trained and had two years’ experience in the use of TEOAE and tympanometry procedures with infants. All tests were conducted in a non-sound treated room (baby’s own room) in the presence of their mother. Ambient noise levels were monitored with a sound level meter (Brüel and Kjær, type 2235). These levels ranged from 30.5 to 57 dBA. Testing was paused when noise levels exceeded 50 dBA, a level at which TEOAEs may be obscured by noise (Rhoades et al., 1998). Neonates were fed, dry, comfortable and in either a quiescent or sleeping state. The majority of babies were tested in their cribs. However, some babies required settling and were tested in the arms of their carer, usually their mother.

A visual inspection of the ear canal was conducted on each ear to assess appropriate probe size and to check for any abnormalities. Both the TEOAE and tympanometry procedures were carried out using a Madsen Capella (version 2.1) OAE/middle ear analyzer, coupled to a lap-top computer. This equipment allowed the measurement of both TEOAEs and tympanometry with the same hand held probe assembly. Specially designed neonate probe tips,
ranging in size from 3-5 mm, were used. The equipment was calibrated on a daily basis (and whenever necessary if a drift in calibration was suspected) according to the manufacturer's specifications. Briefly, the hand held probe, which delivered a pure tone of 226 Hz, was inserted into a 2 ml precision hard-walled cavity and a measurement of the equivalent volume was performed. This calibration enables the measured volume to be readjusted to 2.0 ml if it deviates from the target value.

TEOAE testing was conducted prior to tympanometry. The ear that was most easily accessible was tested first. Great care was taken to optimize probe seal. Probe fit was checked before the TEOAE test commenced. When a good probe fit was indicated, testing began. Nonlinear clicks (3 clicks of the same polarity and 1 click of opposite polarity at 3 times the amplitude of the first click) of 40 μsec pulse width were presented to the baby's ear at 80 dB peSPL. The analysis window was 3 to 20 msec. The acoustical bandwidth of the clicks was 500-4000 Hz. TEOAE recording was terminated after 1000 quiet responses (equivalent to 125 sets of 8 nonlinear clicks) had been collected. Testing was repeated when the TEOAE spectrum did not meet the criteria for a pass.

Tympanograms were recorded with probe tone frequencies of 226 Hz and 1000 Hz in a balanced order for each ear. The applied pressure varied from +200 to -200 daPa at a pump speed of 50 daPa/sec. The 226 Hz and 1000 Hz probe tones were delivered to the ear at 85 dBSPL and 75 dBSPL respectively. Both the 226 Hz and 1000 Hz tympanograms were recorded twice to confirm reliability. In version 2.1 of the Capella OAE/middle ear analyzer, the test parameters (e.g., acoustic admittance Y) of tympanograms for both 226 Hz and 1000 Hz were measured in ml. At 226 Hz, the admittance of an air-filled enclosure is equal to its volume, provided that the cavity dimensions are within certain limits and the atmospheric conditions are not extreme. In other words, the admittance of a 2 ml volume is 2 mmho. However, the admittance at other probe tone frequencies is a function of the volume of calibration cavity (V) and probe tone frequency (f), represented mathematically by $Y = Vf^2/226$ (Margolis and Hunter, 2000). Hence, the admittance values (in mmho) for the 1000 Hz probe tone were calculated by multiplying the displayed values (in ml) by a factor of 8.85.

Measures of 6 test parameters: peak compensated static admittance ($Y_{pc}$, the difference between the peak admittance and the admittance at +200 daPa), admittance at +200 daPa ($Y_{200}$), downward admittance ($Y_d$, the difference between the peak admittance and the admittance at -200 daPa), ear canal pressure ($P_{ec}$), tympanometric width ($TW$, the pressure difference between the two points on the curve at which the admittance is half the peak admittance) and gradient (the peak admittance minus the admittance where width = 100 daPa, divided by the peak admittance) were recorded for each high frequency (1000 Hz) tympanogram.

## RESULTS

Tympanometry findings obtained from the 170 babies (340 ears) revealed that a proper seal for tympanometry to produce a repeatable tympanogram was secured for only 299 ears (87.9 %). Examination of the raw data of 1000 Hz tympanograms for the 122 healthy neonates revealed a single-peeked tympanogram (Type 1) in 225 ears (92.2 %)(see Figure 1), a flat sloping tympanogram (Type 2) in 14 ears (5.7 %)(see Figure 2), a double-peeked tympanogram (Type 3) in 3 ears (1.2 %)(see Figure 3), and other unclassified tympanograms in 2 ears (0.8 %)(see Figure 4). As shown in Figure 1, the Type 1 tympanogram consists of a single peak with maximum admittance value occurring at a pressure of about 0

![Figure 1](image)

**Figure 1** Type 1 tympanogram as demonstrated by the tympanogram (with a probe tone of 1000 Hz) for the left ear of a 5-day-old baby boy (BE) who passed TEOAE screening. The 1000 Hz tympanogram shows a single peak with $Y_{pc} = 1.15$ mmho, $Y_{200} = 3.45$ mmho, $P_{ec} = 2$ daPa, $TW = 110$ daPa, and gradient = 0.46. The Type 1 tympanogram was found in 225 out of 244 ears from 122 healthy neonates.
The maximum acoustic admittance appeared to occur at an ear canal pressure of \(-72\) daPa. The 1000 Hz tympanometric data, with the 5 test parameters (Pec, Ypc, Yd, TW and gradient), for the 122 neonates were subjected to a Principal Components Analysis (PCA), with a view to discover which test parameters form coherent subsets (factors) that are relatively independent of one another (Tabachnick and Fidell, 1996). The results revealed two independent factors, namely the Pec and TW, accounting for 56% and 44% of the variances respectively. The Pec was found to be the test parameter, which accounted for most of the subject differences, and that Ypc, Yd and gradient could not be used as a surrogate for Pec.

Data for the 106 babies who had a Type 1 tympanogram for both ears were analysed. A factorial model that included two factors [ear (left/right) and gender (male/female)] was applied to the data with Ypc as the dependant variable. The significance of any term was assessed using the analysis of variance (ANOVA), with a significance level of 95%. This statistical procedure was repeated for other dependant variables such as Yd, \(Y_{200}\), Pec, TW and gradient. The results revealed a significant ear effect for Ypc \([F(1,104) = 4.592, p = 0.034]\), \(Y_{200}\) \([F(1,105) = 8.779, p = 0.004]\), gradient \([F(1,41) = 5.383, p = 0.025]\), and TW \([F(1,41) = 6.380, p = 0.016]\), but not for Yd or
Table 1: Normative Data for 106 Neonates (62 Boys and 44 Girls) Who Passed TEOAE Screening and Obtained Type 1 Tympanograms in Both Ears

<table>
<thead>
<tr>
<th>Variable</th>
<th>N (ears)</th>
<th>Mean</th>
<th>SD</th>
<th>5th Percentile</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Compensated Static Admittance, Ypc (mmho)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Left ear)</td>
<td>106</td>
<td>1.04</td>
<td>0.51</td>
<td>0.39</td>
<td>1.95</td>
</tr>
<tr>
<td>(Right ear)</td>
<td>106</td>
<td>1.16</td>
<td>0.58</td>
<td>0.39</td>
<td>2.28</td>
</tr>
<tr>
<td>Admittance at +200 daPa, Y200 (mmho)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Left ear)</td>
<td>106</td>
<td>3.20</td>
<td>1.11</td>
<td>1.54</td>
<td>5.09</td>
</tr>
<tr>
<td>(Right ear)</td>
<td>106</td>
<td>3.06</td>
<td>1.07</td>
<td>1.40</td>
<td>5.01</td>
</tr>
<tr>
<td>Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Left ear)</td>
<td>57</td>
<td>0.51</td>
<td>0.13</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>(Right ear)</td>
<td>62</td>
<td>0.48</td>
<td>0.13</td>
<td>0.27</td>
<td>0.75</td>
</tr>
<tr>
<td>Tympanometric Width, TW (daPa)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Left ear)</td>
<td>57</td>
<td>97.7</td>
<td>30.1</td>
<td>46.1</td>
<td>144.2</td>
</tr>
<tr>
<td>(Right ear)</td>
<td>62</td>
<td>107.6</td>
<td>28.0</td>
<td>56.6</td>
<td>154.0</td>
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<tr>
<td>Ear Canal Pressure, Pec (daPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ears combined)</td>
<td>212</td>
<td>18.3</td>
<td>41.6</td>
<td>-58.0</td>
<td>86.6</td>
</tr>
<tr>
<td>Downward Admittance, Yd (mmho)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ears combined)</td>
<td>212</td>
<td>2.13</td>
<td>0.77</td>
<td>0.13</td>
<td>3.54</td>
</tr>
</tbody>
</table>

There were no significant gender effect or ear by gender interactions for any of the variables.

Table 1 shows the normative data for neonates who passed TEOAEs and obtained Type 1 tympanograms in both ears. As shown in Table 1, right ears show significantly higher mean Ypc and TW, but lower mean Y200 and gradient than left ears. Normative data for Pec and Yd were compiled with the left and right ears combined, in view of the absence of a significant ear effect for these two variables. The 5th and 95th percentiles of each variable are also shown.

As shown in Figure 2, the Type 2 tympanogram (using a probe tone of 1000 Hz) is characterised by the decreasing acoustic admittance as pressure goes from about 0 to −200 daPa. The mean Yd for the 14 ears with this tympanogram type was 1.08 mmho (SD = 0.36). A close examination of TEOAE data for ears with a Type 2 tympanogram revealed less robust TEOAEs when compared to ears with a Type 1 tympanogram. The mean overall TEOAE-to-noise ratios for Type 1 and Type 2 tympanograms were 9.72 dB (SD=5.98) and 5.94 dB (SD=4.09) respectively. An independent samples T-test showed a significant difference in mean overall TEOAE-to-noise ratios between ears with the 2 types of tympanograms (t=2.33, df=232, p=0.02). Despite the significantly lower mean overall TEOAE-to-noise ratio, there is no clear evidence of a significant middle ear dysfunction for ears with a Type 2 tympanogram. For instance, a one-day-old baby girl (YO) who failed the TEOAE screen, had a Type 2 tympanogram in her right ear. She was referred for a diagnostic ABR test, but eventually passed the ABR test.

Figure 4: Two unclassified tympanograms for a 2-day-old baby girl (LH) and a 1-day-old baby boy (NM). Baby LH's right ear displayed a relatively flat configuration with Y200 = 3.00 mmho. As the ear canal pressure decreased to −200 daPa, the acoustic admittance increased slightly. On the other hand, baby NM's left ear displayed negative acoustic admittance values as the ear canal pressure decreased from 200 to 25 daPa and from −100 to −200 daPa. The peak compensated acoustic admittance value reached its maximum of 0.35 mmho at a pressure of −72 daPa and Y200 = 3.10 mmho.
The other type of 1000 Hz tympanogram identified in the present study is the double-peaked Type 3 tympanogram (see Figure 3). The corresponding 226 Hz tympanograms for the 3 ears (from 3 babies) were also double-peaked. Further analysis of Type 3 tympanogram was not performed due to the small number of ears falling into this category. The conventional 226 Hz tympanograms for the same 122 babies were analyzed in terms of tympanogram shape (see Figure 5). There were 116 ears with a single-peaked tympanogram, 116 ears with a double-peaked tympanogram, 9 ears with a multi-peaked tympanogram, and 3 ears that did not produce a valid tympanogram.

**DISCUSSION**

One of the aims of the present study was to describe the characteristics of 1000 Hz tympanograms for neonates with normal TEOAE results. In general, passing a TEOAE screening suggests normal or close to normal auditory function up to the inner ear (outer hair cells) (Kemp, 1997). However, passing the TEOAE test, in its strictest sense, cannot serve as a "gold-standard" for normal middle ear function because TEOAEs have been found to be present in some ears with middle ear dysfunction in children and adults (Thornton et al, 1993; Driscoll et al, 2000; Taylor and Brooks, 2000). Perhaps, a "gold-standard" for confirming normal middle ear function should involve the investigation of the middle ear cavity by myringotomy (Marchant et al, 1986). Unfortunately, this procedure is invasive and can only be justified in infants with specific indications, such as prolonged middle ear effusion.

Given the above constraint, it is not surprising to find several different types of 1000 Hz tympanograms in this sample of neonates. The reasons for the various tympanogram shapes found in the present study remain unclear. Possible reasons may include normal variation that exists within the population, a slight middle ear dysfunction that did not obliterate the TEOAEs, maturational delay of the middle ear system of the neonates, the probe tone frequency not being high enough for some neonates, inadequate probe seal, and movement artifacts.

Among the different tympanogram types, the most commonly occurring type is the single-peaked tympanogram (Type 1; see Figure 1). It was found in 92.3% of ears. This type is similar to the Type A tympanograms in the conventional Liden/Jerger classification (Liden, 1969; Jerger, 1970) found in adults and older children with normal middle ear function. Although there is no one-to-one correspondence between middle ear status and tympanogram type, the Type 1 tympanogram is probably indicative of normal middle ear function in the 106 healthy neonates due to the presence of normal TEOAEs, an uneventful birth history, and no at-risk factors predisposing hearing loss. This result is consistent with the findings of other researchers who claim that single-peaked tympanograms (with high frequency probe tones) are generated in ears with normal middle ear function (Marchant et al, 1986; Sutton et al, 1996; Rhodes et al, 1999).

The Type 2 tympanogram (see Figure 2) occurred in 5.7% of ears that passed the TEOAE screen. Since ears with this type of tympanogram exhibited less robust TEOAEs, it is possible that the middle ear function of these ears may be compromised to some extent. A Type 2 tympanogram does not have a discernable peak for acoustic admittance. However, there is a decrease in acoustic admittance as pressure decreases from 0 to ~200 daPa. This "tail" of decreasing admittance with decreasing pressure, which resembles the tail in the Type 1 tympanogram, may be an ear canal effect. This effect produces a diminishing volume of the ear canal cavity under the influence of a negative ear canal pressure, in view of the non-rigid ear canal walls of a neonate.

In the present study, there were only three ears (1.2%) that produced a double-peaked Type 3 tympanogram using the 1000 Hz probe tone. The ear canal effect is also evident in this type of tympanogram (see Figure 3). In con-
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contrary, 47.5 % (116/244) of ears exhibited the double-peaked pattern when the 226 Hz probe tone was used (see Figure 5). These findings are in agreement with that reported by Keith (1973), Sprague et al. (1986) and Holte et al. (1991), who found that the occurrence of double-peaked tympanograms and the complexity of shapes decreased as the frequency of the probe tone was increased.

As well, two ears (0.8%) with unclassified tympanograms displayed a relatively flat configuration (see Figure 5) despite having robust TEOAEs. The reasons for these unusual tympanogram shapes remain unclear. A possible explanation for the flat configuration may be related to the sound pressure level delivered to the neonate's ear. As the probe was calibrated using a 2ml cavity, which is larger than the ear canal of infants, the sound pressure level actually presented to the ear canal would be greater than 75 dB SPL. At this level, it is possible that stapedial reflex might have been elicited, resulting in a reduced peak compensated acoustic admittance value.

The results of the PCA analysis also showed the importance of Pec, as well as TW in explaining individual differences in high frequency tympanometric measures. While Pec can be obtained easily from a tympanogram, TW is not always available, especially when the tympanogram is difficult to define (e.g., when Ypc is too small). Apart from these two measures, the other test parameters such as Ypc, Yd, Y200, and gradient may serve as clinically useful measures.

The present study revealed a significant ear effect, with right ears showing significantly higher mean Ypc and TW, but lower mean gradient and Y200 than left ears. There were no significant gender differences in any of the test parameters in the neonatal population. This is in contrast to results of conventional tympanometry obtained from the young adult population where significant differences were found between the genders, with females showing lower peak compensated static admittance and equivalent volume, but higher tympanometric width values (Roup et al., 1998).

There is a potential for high frequency tympanometry to be utilized in a neonatal hearing screening program to screen for possible middle ear dysfunction in neonates. The use of high frequency tympanometry may also serve to increase the number of infants in which a definitive audiological diagnosis is delayed due to chronic otitis media. Based on the above findings, normative data derived from the 106 neonates who passed TEOAE screening and obtained Type 1 tympanograms in both ears were tabulated (see Table 1). Should a newborn baby not display test parameter values within the 90% range (5th to 95th percentile), the clinician should be alerted to the possibility of a conductive component in his/her hearing impairment. If possible, tympanometry should be repeated to ensure the validity of the results as measurement artifacts (probe displacement or probe being blocked by the ear canal wall) might obscure the results.

The current experimental design did not permit the use of a gold standard (such as myringotomy) in the selection of neonates with perfectly normal middle ear function. The use of a "pass in TEOAE" as one of the subject selection criteria may have contributed to the presence of tympanometric types other than the Type 1 tympanogram. Nevertheless, the majority of neonate ears demonstrated a single-peaked configuration consistent with the literature.

Inadequate probe seal may affect the success rate in testing a neonate. The present study reported a success rate of getting an adequate seal for tympanometry of 87.9%, while Sutton et al. (1996) and Thornton et al. (1993) reported a success rate of 99.4% and 87% respectively. The probe tips used in the present study were specially designed neonatal probe tips. However, they were still too large for the small ear canal of the neonates.

CONCLUSION

The characteristics of high frequency tympanograms for neonates with normal TEOAE results have been described in the present study. In summary, a single-peaked high frequency (1000 Hz) tympanogram (Type 1) was found in 92.2% of neonate ears. This tympanogram type is indicative of normal middle ear function. The normative data derived from this sample of neonates may serve as a guide for detecting middle ear dysfunction in neonates. However, tympanometric types other than Type 1 cannot be regarded as normal at this stage.

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