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Assessing auditory function in neonates using ipsilateral suppression of transient evoked otoacoustic emissions

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Abstract

The present study investigated suppression of transient evoked otoacoustic emissions (TEOAEs) in neonates with an ipsilateral noise suppressor method using a forward masking paradigm. Participants were 26 full-term neonates (36-42 weeks gestational age) with a mean gestational age of 39.7 weeks (SD = 1.4 weeks) and mean chronological age of 1.96 days (SD = 0.8 day). Their mean birth weight was 3.4 kg (SD = 0.5 kg). Only one ear in each neonate was tested. The TEOAE spectra obtained were analysed using the Kresge EchoMaster program comparing assessments with and without noise suppressor. The results show a prevalence of suppression in 85% of the neonates when suppression in at least one frequency band was counted. The mean suppression effect was small (< 0.5 dB) across all frequency bands from 1 to 4 kHz and time windows from 8 to 18 msec, with large variations in suppression amplitude (SD = 1.4-2.4 dB). Three different patterns of suppression were found, with 91% and 9% of neonates demonstrating suppression effects in the 1-3 kHz and 3.5-4 kHz frequency ranges, respectively. A significant negative correlation was found between suppression amplitude and birth weight. The suppression amplitude was negatively correlated to ambient noise, although the correlation was not significant at the 0.05 level. The presence of robust spontaneous otoacoustic emissions (SOAEs) could influence TEOAE suppression amplitude, resulting in reverse suppression. The present study found that males showed greater suppression in left ears and females showed greater suppression in right ears. However, this finding should be interpreted with caution in view of the small sample size of the study. Further research using a large sample size is required to confirm these findings and establish normative data for the neonatal population.

Key words

Transient evoked otoacoustic emissions, Ipsilateral suppression, Neonates, Newborn, Efferent System, Medial olivocochlear bundle

Abbreviations

OAEs: Otoacoustic emissions
TEOAEs: Transient evoked otoacoustic emissions
OHC: Outer hair cell
IHC: Inner hair cell
MOC: Medial olivocochlear system
SOAEs: Spontaneous otoacoustic emissions
APD: Auditory processing disorder

ASR: Acoustic stapedial reflexes
HFT: High frequency tympanometry
SPL: Sound pressure level
HL: Hearing Level
SNR: Signal-to-noise ratio
pSPL: Peak equivalent SPL
SD: Standard deviation

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INTRODUCTION

Otoacoustic emissions (OAEs), discovered by Kemp (1978), are sounds produced by the cochlea. Emissions are measurable in the ear canal using a sensitive microphone. In processing incoming sound, the cochlea amplifies the sound through the motility of the outer hair cells (OHCs). In this process, the sensory organ acts as a cochlear amplifier. Transient evoked otoacoustic emissions (TEOAEs) are one of the most common ways of assessing the function of the OHCs of the cochlea in neonates and young children. TEOAEs are evoked by a transient stimulus such as a click and can give frequency specific information of the function of the cochlea (Kemp, 2002). Emissions can be evoked or spontaneous (SOAEs). If SOAEs are present when assessing TEOAEs the amplitude recorded in the ear canal will partly be affected (Kemp, 2002). The presence of TEOAEs and SOAEs suggests normal auditory function up to the level of the cochlea (Kemp, 2002; Hall, 2000a).

The presence of TEOAEs also enables assessment of the function of structures up to higher auditory levels. The amplitude of TEOAEs decreases when an additional sound is presented to the same (ipsilateral) ear, opposite (contralateral) ear or both ears (binaural) (Kemp, 2002; Hall, 2000b). This phenomenon, known as suppression of TEOAEs, occurs when the gain of the cochlear amplifier is reduced under the influence of the efferent auditory system (Guinan, 2006). When the cochlea receives an ipsilateral suppressing signal (e.g., wideband noise), the auditory nerve fibres will fire and innervate reflex interneurons in the posteroventral cochlear nucleus. These neurons cross the brainstem to innervate medial olivocochlear (MOC) neurons on the contralateral side. Contralateral MOC neurons will then project over to the ipsilateral side in the brainstem through the crossed and uncrossed olivocochlear bundle to complete the pathway of the ipsilateral MOC reflex (Guinan, 2006). The MOC reflex decreases the gain of the cochlear amplifier by mechanical inhibition. This inhibition is strongest at low to moderate suppressor levels and will progressively become smaller with higher suppressor levels (Cooper and Guinan, 2006). Hence, the suppression of TEOAEs offers a non-intrusive method of studying the function of the MOC system (Collet, 1993).

The extent to which the TEOAE amplitude is suppressed depends on the method of suppression. Berlin, Hood, Hurley, Wen and Kemp (1995) studied the suppression of TEOAEs in seven normally hearing adults using bilateral, ipsilateral and contralateral noise stimulation. They showed a bilateral suppression of between 1.5 and 2 dB, while contralateral and ipsilateral suppression amplitudes are respectively smaller. Hood, Berlin, Bordelon and Rose (2003) compared the suppression of TEOAEs in ten normally hearing adults. Their findings showed average suppression amplitudes of 4.4-4.6 dB using binaural stimulation, 2.2-2.7 dB using ipsilateral stimulation and 1.4-1.7 dB using contralateral stimulation. These results are in agreement with that of Berlin et al. (1995) that the suppression of OAEs by binaural stimulation is greater than that by contralateral stimulation.

The TEOAE suppression also changes among individuals. Tavartkiladze, Frolenkov, Kruglov and Artamasov (1994) investigated the suppression of TEOAEs by ipsilateral stimulation in five normally hearing adults and found that suppression varied greatly between individuals. This result is in agreement with Berlin et al.'s (1995) finding that normally hearing adults' exhibit different degrees of TEOAE suppression. Khalfa and Collet (1996), after examining the contralateral suppression effects of TEOAEs in 44 normally hearing adults, found that right ears demonstrated greater suppression than left ears. The authors proposed that the MOC system of right ears was more effective in suppressing TEOAEs than left ears.

The suppression of TEOAEs may be affected by the maturation of the efferent systems. Morlet, Hamburger, Kuint, Ari-even, Roth, Gartner, Muchnik, Collet and Hildesheimer (2003) investigated MOC function in infants at risk for efferent system and/or brainstem dysfunction. Contralateral

suppression of TEOAEs was measured in 22 full-term neonates and 24 pre-term neonates. Suppression was observed at almost all frequencies for the two groups. The mean suppression amplitude for the pre-term group was 1.13 dB, while the mean for the full-term group was 1.81 dB. Eight neonates had suppression amplitude greater than 2 dB. Of the eight neonates, seven were full-term neonates. These findings revealed a significant increase of suppression amplitude in the full-term group, indicating a possible maturation effect.

A similar study of TEOAE suppression by Gkoritsa, Tsakanikos, Korres, Dellagrammaticas, Apostolopoulos and Ferekidis (2006) was performed on 27 premature and 43 full-term neonates. A linear click was used and a 65-75 dB SPL broadband noise was presented to the contralateral ear. The results showed that 22 % of the pre-term and 52.4 % of the full-term neonates had a suppression of greater than 1 dB. They also found that right ears produced greater suppression than left ears, which appeared to be more pronounced in full-term neonates. These findings suggested a trend of increasing TEOAE suppression with age.

Gkoritsa et al. (2007a, 2007b) provided further evidence of the maturation effect. In their study, they compared TEOAE suppression among four groups: 42 pre-term neonates, 39 full-term neonates, ten children and 18 adults. Linear clicks were used while a 40 dB sensation level broadband noise was presented to the contralateral ear. Both ears were tested. They observed that the adult group had the greatest suppression effect. They also found a significant difference in suppression amplitude between pre-term and full-term neonates with a mean of 0.51 dB and 0.91 dB, respectively. However, no significant difference in suppression between ears was found in full-term neonates, but similar to the findings of Gkoritsa et al. (2006) a tendency of larger mean suppression in right ears was observed.

The characteristics of contralateral suppression of TEOAEs in 120 full-term neonates were investigated by Durante and Carvallo (2002). The results showed a prevalence of the presence of suppression of 88.5 %. If the suppression effect in at least one frequency band was counted, a prevalence of 96 % was found. This study also showed that males had significantly greater mean suppression amplitude than females (3.28 versus 2.32 dB).

Assessment of the MOC system function, using the TEOAE suppression technique, has led to wide clinical applications. For example, suppression of TEOAEs is reduced in patients with auditory neuropathy and auditory processing disorders (APD) (Hood et al., 2003; Collet, 1993). Yalcinkaya, Yilmaz and Muluk (2009) found that the suppression of TEOAEs in 12 children with APD was significantly smaller than that of the control group. The suppression was more pronounced between 1 and 2 kHz. In a similar study Muchnik et al. (2004) showed that 15 children between 8 and 13 years with APD had reduced contralateral TEOAE suppression. They suggested that suppression of TEOAEs should be included in a test battery to test children at risk for APD.

While the majority of research on the suppression of TEOAEs was mainly conducted using contralateral stimulation, research on the ipsilateral suppression effects has received relatively little attention. In fact there are advantages for using the ipsilateral over contralateral or binaural stimulation methods in studying the suppression of OAEs, especially in neonates. Ipsilateral stimulation produces greater suppression of TEOAEs than that produced by contralateral stimulation (Berlin et al., 1995). Ipsilateral stimulation also makes testing easier because the chance of keeping a good probe seal in one ear is high. Furthermore, the interpretation of results is straight forward and does not dependent on the hearing status of the contralateral ear. Hence, ipsilateral suppression of TEOAEs holds promise as a useful clinical tool to evaluate the function of the MOC system.

In summary, the above studies show a high prevalence of suppression of OAEs in individuals with normal auditory function. Most studies have used the contralateral suppression of TEOAEs procedure, although this procedure has been found to produce smaller suppression amplitude than that produced by ipsilateral or binaural stimulation. It is possible that suppression of TEOAEs by contralateral stimulation may be considered as absent because of the small suppression effect. It is postulated that the prevalence of suppression of TEOAEs by ipsilateral stimulation in the general population is higher than that reported in previous studies. While some studies reported greater suppression in males than in females (e.g., Durante and Carvallo, 2002) the gender effect needs to be investigated further using a technique which produces larger suppression values. While a few studies have investigated the ear asymmetry effect their results are not consistent (Gkoritsa et al., 2006; Gkoritsa et al., 2007). There is some evidence of the maturation of the MOC system around the time of birth. One important finding is that full-term babies have greater suppression amplitude than pre-term babies. However, the prevalence of the suppression of TEOAEs in full-term babies varied, depending on the method and criteria used to define suppression. The aim of this present study was to investigate the characteristics of ipsilateral suppression of TEOAEs in full-term neonates, with a view to determine the prevalence of suppression and possible gender and ear asymmetry effects in this age group.

METHOD

Ethical clearance and recruitment of participants

This study has been cleared by the Behavioural and Social Sciences Ethical Review Committee of the University of Queensland and the Darling Downs-West Moreton Health Service District Human Research Ethics Committee. Participation was voluntary and parents were free to withdraw their child from the study at any time. All results and information obtained from the parents were treated with strict confidence. Testing of the child would commence with written parental consent.

On the day of test, the research team (one audiologist and two audiology master students), would receive a list of babies in the maternity ward. Those babies, who had passed the automatic auditory brainstem response (aABR) test administrated by Queensland Health nurses, were selected at random for participation. Their parents were approached and informed verbally about the aim of the study and the test procedures involved. They were given an information sheet and a consent form to complete.

Participants

Initially, 45 full term neonates were recruited from the maternity ward at Ipswich General Hospital, Queensland, Australia. To ensure that neonates did not have significant conductive or sensorineural hearing impairment, all neonates were required to have passed the Healthy Hearing screening using aABR before recruitment. All neonates were required to pass a TEOAE test (Quickscreen mode) to ensure they had adequate emissions for the TEOAE suppression test. They were also required to have normal middle ear function as evidenced by passing a high frequency (1000 Hz) tympanometry test and acoustic stapedial reflex test.

Of the 38 neonates initially recruited, only 26 neonates (17 males and 9 females) who met the above inclusion criteria and completed all tests were included in the study.

The participants were full-term neonates (36-42 weeks gestational age) with a mean gestational age of 39.7 weeks (SD = 1.4 weeks). Their mean chronological age was 1.96 days (SD = 0.8 day). Their mean birth weight was 3.4 kg (SD = 0.5 kg). The participants had no complications during pregnancy or birth, no congenital deficits and no risk factors for hearing loss as suggested by the Joint Committee on Infant Hearing 2007 Position Statement (JCIH, 2007).

Procedure

All testing took place in a quiet non-sound-treated room near the maternity ward of the hospital. Testing was performed by an audiologist and/or two Master of audiology students. The students had completed a training program on test procedures prior to data collection.

During the assessments, the following data were collected using the individual neonate's medical records: birth weight, gestational age, gender, time and date of birth. Other data collected during the assessment were date of testing, test time, testers, ambient noise level and activity state of the neonate. The test time included the time spent in conducting the four measurements of the TEOAE suppression only. The ambient noise was monitored using a Quest 2100 sound level meter placed next to the neonate's ear during the test. The mean noise level was 36.6 dB A (SD = 3.3 dB).

Each neonate was tested while lying in a cot. Only one ear from each neonate, the ear which was most accessible, was tested. The test was paused when the neonate became restless and resumed when he/she became settled again. Neonates were excluded from the study if they had middle ear dysfunction, weak TEOAEs or could not complete all tests due to large physiological noise or being unsettled. Assessments for each neonate were conducted in the following order: visual inspection of the outer ear, TEOAE (Quickscreen), TEOAE suppression tests (four measurements), high frequency (1000 Hz) tympanometry and acoustic stapedial reflex tests. An additional test of Spontaneous OAEs was performed for neonates whose TEOAE spectrum showed a spiky OAE pattern. The outer ear was visually examined to rule out any observable abnormalities that could affect audiological test results.

TEOAE (Quickscreen) Test

Using the Quickscreen mode of a ILO292 Otodynamics Analyser (OAE system software ILO version 5.6, release Y), wideband, Gaussian shaped non-linear clicks were presented to the test ear at a pre-determined level (mean = 85 dB peak equivalent sound pressure level (pSPL), SD = 3.7 dB). Real time analysis using the Fast Fourier Transform was performed to obtain an OAE spectrum. The test was terminated when the pass criteria [signal-to-noise ratio (SNR) $\geq$ 6 dB in at least four out of five half-octave frequency bands at 1000, 1500, 2000, 3000, and 4000 Hz] were reached or until at least 50 quiet samples were collected to obtain robust OAEs (Korres, Nikolopoulos, Ferekidis, Gotzamanoglou, Georgiou, and Balatsouras, 2003; Korres, Balatsouras, Nikolopoulas, Korres, Economou, and Ferekidis, 2006).

TEOAE Suppression Tests

Four TEOAE tests without and with a noise suppressor were conducted using the Otodynamics ILO292 Analyser. To minimize carry-over effects of the suppressor noise, testing without noise and with noise was interleaved. To reduce variability in the TEOAE results across the four tests, the two

measurements without noise were averaged and compared with the average TEOAE results for the with noise suppressor condition (Hood et al., 2003).

The stimuli used were linear clicks of 80 μsec duration presented at an intensity of about 65 dB pSPL (mean = 64 dB pSPL; SD = 2.5 dB). This intensity was selected to avoid activation of the acoustic stapedial reflex, but capable of producing adequate OAEs for suppression testing (Hall, 2000c; Guinan, 2006). Linear clicks were used because the stimulus artefacts that normally interfere with the detection of OAEs would be reduced while OAEs are enhanced. The noise rejection level was set at 52.4 dB SPL to reduce noise contamination of the OAEs. The test was terminated when 100 quiet responses were collected.

Testing with the suppressor noise condition required an ipsilateral forward masking paradigm (Berlin et al., 1995; Robinette and Glattke, 2002). With this method, a suppressor wideband noise of the same intensity level as the TEOAE stimuli (Robinette and Glattke, 2002) and duration of 400 msec was presented prior to the linear click stimulus with a gap of 10 msec (Berlin et al., 1995; Hood et al., 2003). The duration of wideband noise of 400 msec was chosen to produce the greatest suppression effect (Berlin, 1996). The same mean noise rejection level of 52.4 dB was applied and the test was terminated when 100 quiet responses were collected.

The above two tests were repeated. Efforts were made to ensure that the activity state of the neonate could stay the same for the four tests. The mean test time for the four tests was 32 minutes (SD = 14 minutes).

High Frequency Tympanometry and Acoustic Stapedial Reflex Tests

After the TEOAE tests, high frequency (1 kHz) tympanometry and ipsilateral acoustic reflex assessments were performed using a Madsen Otoflex100 (Type 1012) immittance meter. Calibration was performed according to the manufacturer's instructions before testing began. A 1 kHz probe tone was delivered at 75 dB HL to the ear while the ear canal pressure was varied from 200 to -400 daPa at a pump speed of 400 daPa/sec. A pass was given if the tympanogram showed a positive peak with static admittance of at least 0.23 mmho (Mazlan et al., 2009).

The acoustic stapedial reflex test with ipsilateral stimulation was performed immediately after the tympanometry test. Reflex thresholds at 2 and 4 kHz were measured using an auto search method as described by Kei (2012). A pass was awarded if the reflex thresholds at 2 and 4 kHz were less than 90 and 85 dB HL, respectively.

Data Analysis

The TEOAE data were analysed using the Kresge EchoMaster developed by Wen, Berlin, Hood, Jackson, and Hurley (1993). In measuring TEOAE suppression, the time window was set to 8-18 msec when optimal suppression effects occurred (Berlin, 1996). The TEOAEs collected for each test condition, without and with noise, were viewed separately and then compared. Analysis of the data would proceed if the TEOAE spectra met the following inclusion criteria: (1) SNR ≥ 1.4 dB, and (2) the correlation of TEOAE amplitude between tests was close to 0.7. During the analysis, the mean of the two measurements without noise was compared with that of the with noise condition.
The EchoMaster measures the suppression of TEOAE amplitude in the frequency and time domains. In the frequency domain, the TEOAE amplitudes at 1, 1.5, 2, 2.5, 3, 3.5, and 4 kHz were measured. Measurements outside the 1-4 kHz range were not included for analysis because

previous research findings showed limited or no suppression effects beyond this range (Hood et al., 2003). In the time domain, the TEOAE amplitudes at five different time periods (2 msec intervals centred at 9, 11, 13, 15, and 17 msec) were measured. Measurements at these time windows were included for analysis because optimal suppression effects would occur within a time window of 8-18 msec (Berlin, 1996). All data were entered into a Microsoft Excel 2010 spread sheet, which were transferred to a SPSS data sheet for statistical analysis (SPSS, ver. 20.0).

RESULTS

Of the 45 neonates initially assessed, 19 neonates were excluded from the study because six were unsettled during the TEOAE suppression tests, seven had excessive physiological noise, two did not pass the TEOAE Quickscreen test, two failed in the high frequency impedance tests, one had a large SOAE spike influencing the TEOAEs and one differed to much between suppression tests when analysed in EchoMaster. The other 26 neonates successfully completed all tests. The mean test time for the four measurements of TEOAE suppression test was 31.2 min (SD = 14.0 min; range = 13 − 75 min). Of these 26 neonates, four (two females and two males) showed no TEOAE suppression at any of the frequency bands between 1 and 4 kHz. Hence the prevalence of ipsilateral suppression of TEOAEs (in at least one frequency band between 1 and 4 kHz) was 85 %.

Table 1 depicts the descriptive data for ipsilateral suppression of TEOAEs in a sample of 22 healthy neonates with evidence of suppression. In the frequency domain, the mean suppression across all frequencies was smaller than 0.5 dB with the highest and lowest suppression value at 2 and 4 kHz, respectively. A close examination of the suppression data showed that 77% of the neonates had a suppression amplitude of ≥ 1 dB when suppression in at least one frequency band was counted. In the time window domain, the mean suppression was greater at 9-11 msec than at 13-17 msec time windows. There was a wide spread of suppression values in these variables as indicated by the large range and standard deviations (SD).

Table 1. Descriptive statistics of ipsilateral suppression of TEOAEs for 22 healthy neonates (15 M/ 7 F; 8 left/ 14 right ears) with respect to the frequency and time domains.

	Ipsilateral Suppression	N (ears)	Mean (dB)	SD	Min (dB)	Max (dB)
Frequency band	1 kHz	22	0.27	2.4	-5.5	5.4
	1.5 kHz	22	0.29	2.1	-5.2	3.9
	2 kHz	22	0.49	1.8	-2.2	4.1
	2.5 kHz	22	0.20	1.9	-2.6	4.8
	3kHz	22	0.23	1.6	-1.4	4.6
	3.5 kHz	22	0.23	1.8	-3.1	5.0
	4 kHz	22	0.05	2.4	-5.5	5.5
Time Window	9 msec	22	0.33	1.6	-3.8	3.8
	11msec	22	0.34	1.4	-2.7	3.5
	13 msec	22	0.21	1.4	-2.6	3.7
	15 msec	22	0.23	2.0	-3.7	4.0
	17 msec	22	0.21	1.5	-2.3	3.2

All variables (TEOAE suppression at various frequencies and time windows) were inspected and found to be normally distributed. An analysis of variance (ANOVA) with repeated measures was applied to the data with TEOAE suppression at various frequencies as the dependant variable, and gender and ear as independent variables. The results showed no significant frequency, gender or ear effects. But a Gender × Ear interaction was significant [$F_{(1.18)} = 6.329$, $p= 0.022$], indicating that, for males, left ears exhibited greater mean suppression than right ears (1.3 versus 0.05 dB), whereas, in females, right ears produced greater suppression than left ears (1.4 versus -0.09 dB) (see Figure 1).
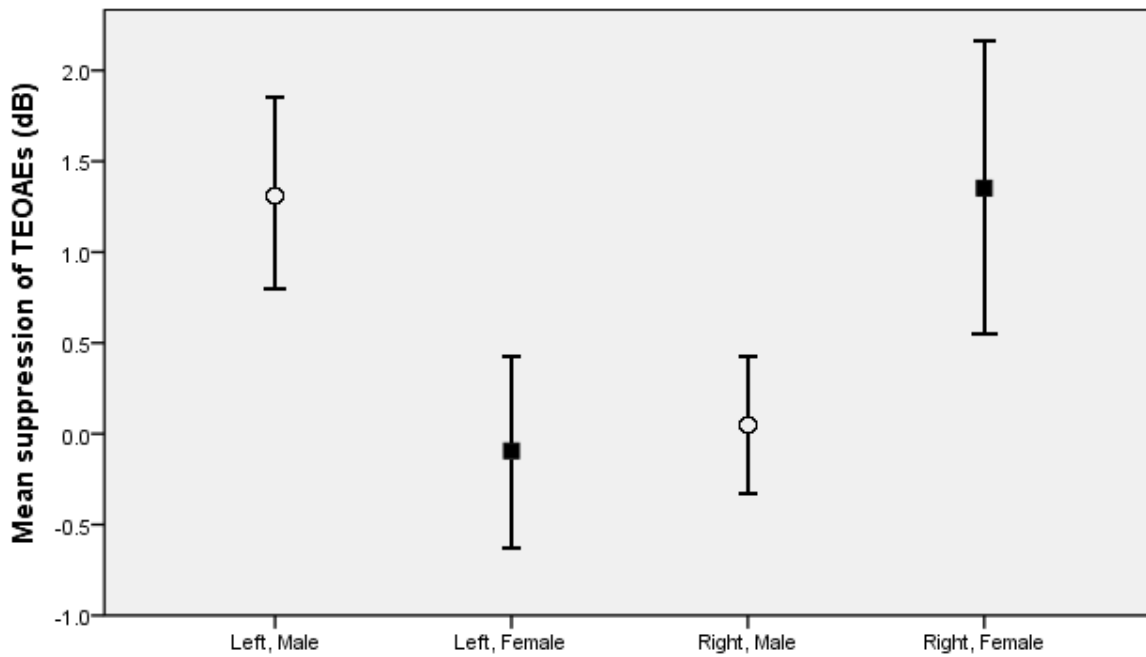
Figure 1. Plot of mean suppression of TEOAEs against left and right ears for 22 neonates (15 males and 7 females). The bars represent ± 1 SD.

To examine the effect of time window, gender and ear on the TEOAE suppression, an ANOVA with repeated measures on time windows was fitted to the data. The results showed no significant main effects of any of the examined variables or their interactions ($p>0.05$).

To examine the relationship between birth weight and TEOAE suppression, a Pearson's correlation test was applied. Table 2 shows that a negative correlation coefficient (rho) was found between these variables at all frequencies. In particular, the correlation was significant in the frequency band between 2 and 3.5 kHz ($p < 0.05$). A significant negative correlation ($p < 0.05$) was also found at all except for the 17 msec time window.

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Table 2. Pearson's correlation coefficient (rho) between birth weight and ipsilateral suppression of TEOAEs in 22 neonates.

|	Ipsilateral Suppression	N (ears)	rho	p value (2-tailed)
Frequency band				
	1 kHz	22	-0.69	0.755
	1.5 kHz	22	-0.37	0.083
	2 kHz	22	-0.59	0.003
	2.5 kHz	22	-0.58	0.004
	3 kHz	22	-0.75	< 0.001
	3.5 kHz	22	-0.44	0.035
	4 kHz	22	-0.38	0.078
Time window				
	9 msec	22	-0.70	< 0.001
	11 msec	22	-0.54	0.009
	13 msec	22	-0.43	0.046
	15 msec	22	-0.48	0.023
	17 msec	22	-0.42	0.054

A Pearson's correlation test was applied to investigate the relationship between ear canal volume and suppression of TEOAEs, and the relationship between ear canal volume and birth weight. No significant correlations were obtained ($p > 0.05$). The Pearson's correlation test was repeated with gestational age and TEOAE suppression as variables. No significant correlations were observed ($p > 0.05$).

To examine the relationship between ambient noise and suppression of TEOAEs, a Pearson's correlation test was fitted to the data. The results showed no significant correlation between the variables. However, an insignificant negative correlation trend was observed except for the suppression at 1 kHz (see Table 3). The Pearson's correlation test was repeated with noise in ear canal and TEOAE suppression as variables. No significant correlation was observed ($p > 0.05$).

Table 3. Pearson's correlation coefficient (rho) between ambient noise and ipsilateral suppression of TEOAEs in 22 neonates.

|	Ipsilateral Suppression	N (ears)	rho	p value (2-tailed)
Frequency band				
	1 kHz	22	0.13	0.617
	1.5 kHz	22	-0.01	0.969
	2 kHz	22	-0.19	0.465
	2.5 kHz	22	-0.16	0.533
	3 kHz	22	-0.26	0.311
	3.5 kHz	22	-0.42	0.093
	4 kHz	22	-0.45	0.073
Time window				
	9 msec	22	-0.32	0.223
	11 msec	22	-0.40	0.133
	13 msec	22	-0.12	0.659
	15 msec	22	-0.08	0.764
	17 msec	22	-0.34	0.204

As mentioned earlier, there was a large variation in suppression among individuals. An examination of the data showed that the suppression of TEOAEs in neonates varied between 5.5 dB (large suppression) and -5.5 dB (reverse suppression) (see Table 1). Of the 22 neonates who demonstrated suppression effects, 20 neonates (90%) showed reverse suppression at one or more frequencies. The characteristics of the TEOAE suppression spectra were examined. Eleven of the 22 neonates demonstrated suppression over a wide frequency range. Figure 2 shows a typical suppression spectrum obtained from a 2-day-old male. Consistent suppression effects were present between 1 and 4 kHz. Nine of the 22 neonates (41 %) exhibited suppression in the low- to mid-frequencies. Figure 3 shows such pattern of suppression effects obtained from a 1-day-old male with consistent suppression between 1 and 3 kHz. The remaining two neonates demonstrated suppression effects mainly in the high frequencies. Figure 4 shows the TEOAE suppression spectrum obtained from one of the neonates showing suppression effects at 3.5-4 kHz.
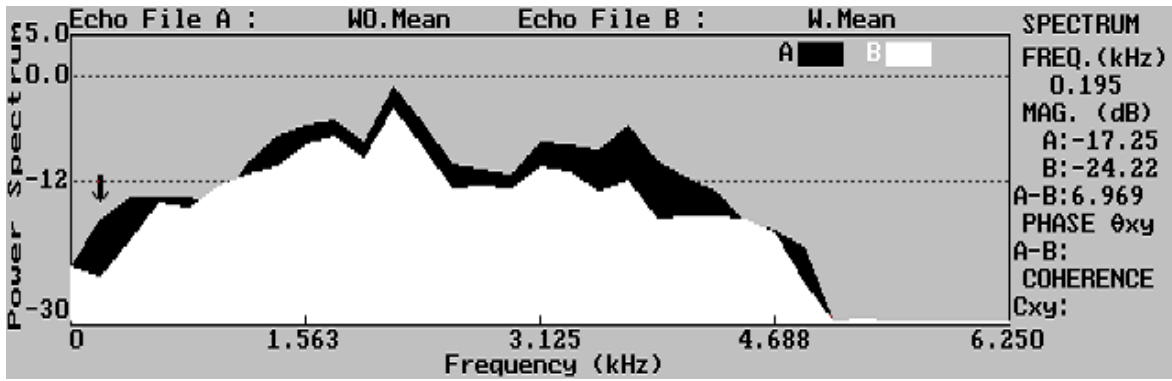
Figure 2. Ipsilateral suppression of TEOAEs in the right ear of a 2-day-old male showing a comparison between the average of two assessments without noise (A) and the average of two assessments with noise (B) analysed using the EchoMaster analysis program. The dark area represents the suppression amplitude.
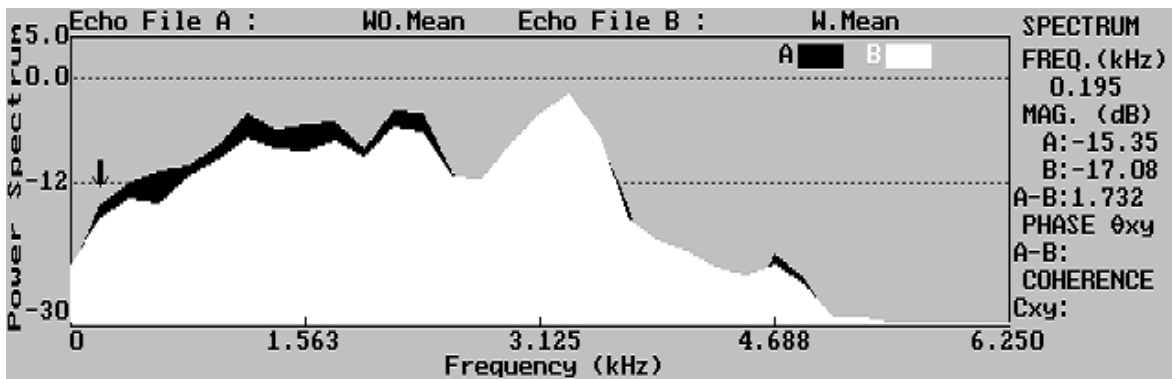

Figure 3. Ipsilateral suppression of TEOAE in a 1-day-old male showing a comparison between the average of two assessments without noise (A) and the average of two assessments with noise (B) analysed using the EchoMaster analysis program. The dark area represents the suppression amplitude showing suppression pattern over low- to mid-frequencies.
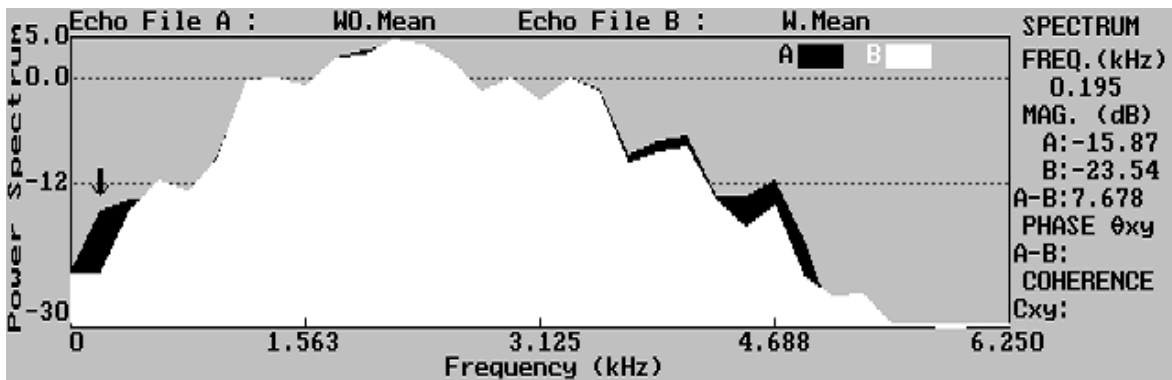

Figure 4. Ipsilateral suppression findings in a 1-day-old female showing a comparison between the average of two assessments without noise (A) and the average of two assessments with noise (B) analysed using the EchoMaster analysis program. The dark area represents the suppression amplitude showing suppression pattern over high frequencies only.

One confounding factor, which could not be controlled in the present study, was the presence of spontaneous otoacoustic emissions (SOAEs) (McFadden, 1993). TEOAE suppression can be greatly affected if the SOAEs are robust in comparison to the TEOAE spectrum. Figure 5 shows the SOAE spectrum of a 2-day-old male whose data were not analysed in the present study. He exhibited a large spike of SOAE of 41.5 dB SNR at 3.1 kHz. However, his TEOAE spectrum in the without noise condition showed weak emissions except for a large spike at about 3 kHz (see Figure 6). When stimulated with the noise suppressor, the TEOAE spectrum became larger and wider. The results from the analysis in EchoMaster showed reverse suppression, found in all frequencies between 1-4 kHz. The reverse suppression was more pronounced around 3 kHz (- 5 dB) at which SOAEs were dominant.
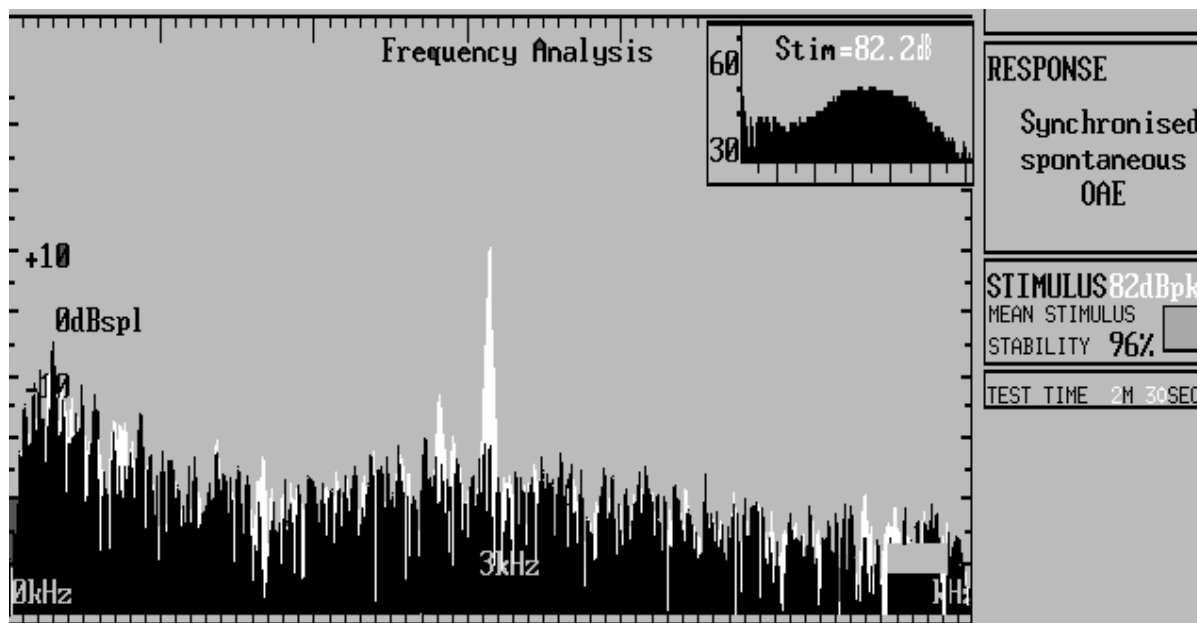
Figure 5. SOAEs from the left ear of a 2-day-old male showing large SOAE amplitude (41.5 dB SNR) at 3.1 kHz.
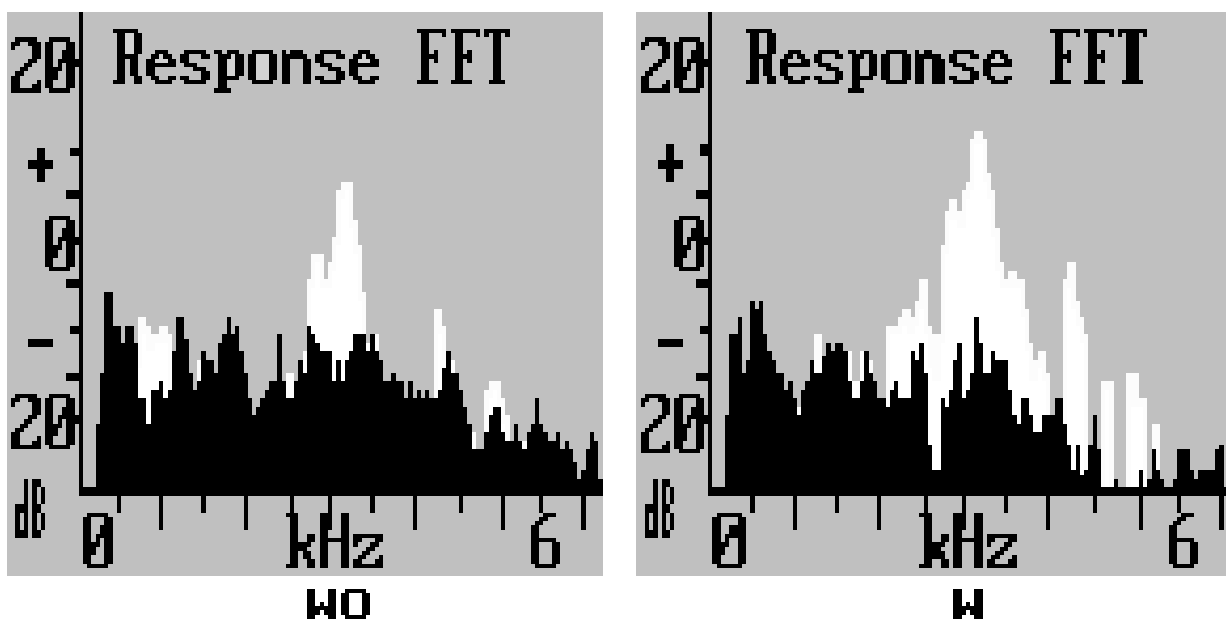
Figure 6. Raw data from the left ear of a 2-day-old male with SOAE at 3.1 kHz showing TEOAEs without noise (WO) and TEOAEs with noise (W).

DISCUSSION

In the present study, the ipsilateral suppression of TEOAEs in 26 normal hearing neonates was investigated. The results showed a prevalence of the presence of suppression (in at least one frequency band) of 85%. This prevalence is lower than 96% reported by Durante and Carvallo (2002). Despite the difference in prevalence rates between the two studies, both studies showed a high prevalence of TEOAE suppression in full-term neonates, indicating that the MOC system of a full-term neonate is functional at birth.

The present study found that the mean suppression amplitudes were smaller than 0.5 dB across all frequencies (Table 1). Furthermore, the suppression amplitude did not differ significantly across the frequencies. These mean suppression values are smaller than 0.90 dB and 0.91 found in the studies of Gkoritsa et al. (2006) and Gkoritsa et al. (2007b), respectively. The difference in findings between the present study and the Gkoritsa et al.'s (2006, 2007b) studies may be attributed to the difference in test environments. The present study tested all neonates in a quiet non-sound treated room, while Gkoritsa et al. (2007b) used a sound treated booth. Gkoritsa et al. (2006) did not use a sound treated booth. They shielded the cot with another cot, turned upside down and placed on top, to reduce the ambient noise. The present study also showed that 77% of the neonates had suppression amplitudes of ≥ 1 dB when suppression in at least one frequency band was counted. This finding is in keeping with the findings of Gkoritsa et al. (2006) and Morlet et al. (2003), who reported that 52.4% and 65.2% of full-term neonates, respectively, showed mean suppression amplitudes of ≥ 1 dB.

The present study revealed large individual differences in suppression amplitude, as indicated by large standard deviations of 1.4 to 2.4 dB and large ranges across the frequencies and time windows (see Table 1). Close examination of the data revealed positive suppression (indicative of a suppression effect) and negative suppression values (indicative of a reverse suppression effect). However, it was not possible to judge if the negative values were due to noise contamination effects, random variations of the TEOAE amplitude or a genuine reverse suppression effect in the presence of robust SOAE (see Figure 6).

Despite the large variation in suppression amplitudes, the present study identified three patterns of TEOAE suppression spectrum in the sample of neonates. The spectrum with suppression across a wide frequency range was the most common pattern found in 50 % of neonates (see Figure 2). The second most common pattern was the spectrum with suppression of TEOAEs in the 1-3 kHz frequency band. This pattern was found in 41 % of neonates (see Figure 3). The third pattern, found in 9% of neonates, showed suppression only in the high frequencies (3.5-4 kHz) (see Figure 4). This may explain why the mean suppression amplitude at 4 kHz was negligibly small (see Table 1). The existence of different patterns of suppression spectra indicates the need to examine suppression effects at all frequencies from 1 to 4 kHz. , these three patterns were not reported in previous studies. For example, Morlet et al. (2003) reported suppression effects at almost all frequencies between 0.5 and 6 kHz. They also showed an increase in suppression amplitudes between 2 and 3 kHz. Hence, the predominance of suppression of TEOAEs from low- to mid- frequencies found in the Morlet et al. (2003) study is in line with the findings of the present study.

The other objective of the present study was to investigate the characteristics of the TEOAE suppression with respect to gender or ear effects. The present study did not find any significant gender or ear effects. However, a Gender × Ear interaction reached significance (p = 0.022). This interaction indicates that the left ears of males showed greater suppression than right ears, while the reverse is evident for females (see Figure 1). Given the small sample size of the study, generalisation of this result to the neonatal population is not recommended. In the literature, the

findings related to gender and ear differences were consistent. For instance, Durante and Carvallo (2002) found that males have larger suppression than females and Gkoritsa et al. (2006, 2007b) demonstrated that right ears produced greater suppression than left ears.

The present study found a significant negative correlation ($p < 0.05$) between the birth weight of neonates and suppression of TEOAEs at 2-3.5 kHz. This significant relationship was also evident between birth weight and suppression at most time windows except for the 17 msec time window. These findings indicate greater suppression in full-term neonates with smaller birth weight. The reason is not clear. Perhaps, larger neonates have a larger ear canal which affects the amplitude of the TEOAEs. Further investigation to examine the relationship between ear canal volume and suppression of TEOAEs did not find any significant correlations ($p > 0.05$). A Pearson's correlation test, applied to the ear canal volume and birth weight data, showed no significant correlations ($p > 0.05$). Another possible cause for this negative correlation between birth weight and suppression could be related to the middle ear transmission mechanics of the neonates with different birth weights. In the present study, all neonates were found to have normal middle ear function as they passed the HFT and ASR tests and the stimuli used do not activate the acoustic reflex. However, there are individual differences in middle ear transmission characteristics as revealed by the reflectance/absorbance at the ear drum in healthy neonates (Keefe, 1994).

The present study investigated if the suppression of TEOAEs was influenced by maturation effects. A Pearson's correlation test applied to the gestational age and suppression data showed no significant correlations ($p > 0.05$). This is an expected result given the small range of gestational age in this sample of neonates. However, this finding is not in line with the results of Morlet et al. (2003) that observed a weak but present correlation between gestational age and suppression amplitudes.

One of the confounding variables in investigating TEOAE suppression in the present study was noise. The present study found a trend of decreasing suppression amplitude with increasing ambient noise, although the negative correlations did not reach significance ($p > 0.05$). As the TEOAE suppression tests were conducted in a room with no special sound treatment, the ambient noise level could not be effectively controlled. It ranged from 33.4 to 46 dB A. This finding is expected given that increased ambient noise would raise the noise floor in the recordings which resulted in reduced SNR in the measurement. To control for this confounding variable, it would be ideal to conduct testing in a sound treated booth. However, this is not always possible given the limited space for research in a busy hospital setting.

The other influential confounding variable affecting TEOAE measurements was the physiological noise produced by the neonates. High ambient noise levels were observed in neonates with heavy breathing, jaw and head movements and suckling and swallowing activities. Neonates who were fed just before testing were found to have heavy breathing and suckling activities which increased the noise level beyond the pre-determined noise rejection level of 52.4 dB SPL. This confounding variable of physiologic noise was controlled in the present study by testing neonates while they were asleep. However, it was not always possible to maintain this sleeping state in view of the long testing time (mean = 31.2 min) required for the four suppression tests. When the activity state of the neonate changed from one test to the other, the physiologic noise changed accordingly. To minimise the physiologic noise effect, the neonates who showed different activity states across the four tests were not included in the present study.

Another variable which may affect the results of the assessment was the probe seal. Testing with a poor or unstable probe seal would result in variable stimulus and noise levels which had a profound effect on the quality of the TEOAE suppression results. In the present study, very effort was made

to ensure a tight seal during testing. However, this was not always possible due to the movement of the neonates even during natural sleep. In the event of losing the probe seal, the test was paused, and then resumed when the probe seal was restored. Even with this procedure in place, there is no guarantee that the same seal effect was maintained.

Among all the variables which may affect TEOAE testing, the presence of SOAEs has been a perplexing variable especially when the TEOAEs were not as robust as the SOAEs. In the example shown in Figure 5, the SOAEs with a particularly strong emission at 3 kHz could easily be misconstrued as TEOAEs especially when the TEOAEs were weak. In reality, the TEOAE spectrum obtained without the noise suppressor was dominated by the SOAE spikes. When stimulated by the linear clicks and noise suppressor at 65 dB pSPL, the SOAE spikes appeared to have increased slightly both in amplitude and width. This inflation of SOAEs could be interpreted as a reverse (negative) suppression effect. It is not possible to determine the extent of the inflated SOAEs influence on the TEOAE suppression results in the present study. Nevertheless, McFadden (1993) suggested that greater suppression effects could be observed when SOAEs were small. Further research is warranted to examine the effect of SOAEs on TEOAE suppression.

Summary
The present study found a prevalence of ipsilateral suppression of TEOAEs in 85% of healthy neonates. The mean suppression amplitudes were less than 0.5 dB with large variations among the participants. Three different patterns of the TEOAE suppression spectra were identified, with 91% of neonates demonstrating suppression effects in the 1-3 kHz and 9% in the 3.5-4 kHz frequency range. The suppression amplitude decreased with increasing birth weight. A trend of decreasing suppression amplitude with increasing ambient noise was observed, although the correlation was not significant. Reverse suppression effects were observed in a neonate with robust SOAEs. The present study showed that the left ears of males produced greater suppression than right ears, while the right ears of females produced greater suppression than left ears. Further research using a large sample size is needed to substantiate the above findings with a view to establish normative data for the neonatal population.

ACKNOWLEDGEMENTS

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