Objectives: Otoacoustic emission (OAE) testing is now a standard component of the diagnostic audiology protocol for infants and toddlers and is an excellent tool for detecting moderate-to-profound cochlear hearing loss. Detection of hearing loss is especially important in infants and toddlers. Unfortunately, middle-ear dysfunction has a high incidence in this age range and can confound interpretation of OAEs. The goal of the study was to determine how transient-evoked otoacoustic emission (TEOAE) and noise levels were different when tympanometric peak pressures (TPP) measured from tympanograms were normal versus negative in the same individual. Another goal was to determine how TEOAE screening pass rates using a priori pass criteria were affected on days when TPP was negative.

Design: TEOAE and noise levels were collected in 18 cases under 2 conditions: on a day when the tympanogram TPP was normal and on a day when the tympanogram TPP was negative. Data were collected from 11 children aged 3 to 39 mo, some of whom were tested more than once. Paired t tests were performed to determine whether there were changes in overall TEOAE and noise levels and TEOAE and noise levels analyzed into half-octave bands. A one-way ANOVA was performed on differences across half-octave bands to determine whether TPP affected TEOAE levels for some frequency bands more than others. Equality-of-proportion Z tests were run to determine whether there were significant differences in the percentage of “passes” on days when TPP was negative and TPP was normal.

Results: Mean TEOAE level was lower when TPP was negative, but noise levels did not change between the 2 conditions. Mean TEOAE levels were lower for all frequency bands from 1000 to 4000 Hz and no significant differences were found among the mean reduction across frequency bands. There were no significant differences in the percentage of passes between TEOAEs collected on days when TPP was normal and when TPP was negative.

Conclusions: Mean data indicated that when tympanograms had negative TPP, TEOAE level was lower by approximately 4 dB across all frequency bands. However, this affected the pass rate in only 5% to 6% of cases. Although the number of participants in the current study was small, the data suggest that it is possible to measure TEOAEs in children with negative TPP. If emission-to-noise ratio is used to identify hearing loss in mid-to-high frequency bands, the majority of children will still have TEOAEs that meet clinical criteria, this providing the clinician with important information about cochlear status.

INTRODUCTION

Otoacoustic emission (OAE) testing is now a standard component of the diagnostic audiology protocol for infants and toddlers. OAEs are generated by outer hair cells, the same structures that are thought to be responsible for the cochlear amplifier. OAEs are an essential tool in the pediatric test battery because they detect most cochlear hearing loss (e.g., Gorga, et al., 1999; Norton, et al., 2000; Prieve, et al., 1993), can be measured quickly and noninvasively and do not require a behavioral response from the child. The presence or absence of OAEs aids in site-of-lesion testing, which ultimately affects (re)habilitation decisions. One drawback to OAE testing is that changes in middle ear transmission alter OAE levels, confounding the interpretation of cochlear status.

The effect of middle ear transmission on OAEs has been studied in several ways. In early studies, negative and positive pressure was introduced into the ear canals of normally hearing ears of adults with normal middle ear function. Negative and positive pressure decreased overall transient-evoked otoacoustic emission (TEOAE) levels (Naeve, et al., 1992; Robinson & Haughton, 1991; Veuillet, et al., 1992) by an average of 4 to 5 dB. In 1 study, TEOAE levels decreased by similar amounts when negative and positive pressure were applied to the ear canal (Naeve, et al., 1992); however, other reports indicated that negative pressure reduced TEOAE levels more than did positive pressure (Robinson & Haugh-
tion. Marshall et al. (1997) studied TEOAEs in 1 adult and found that levels were reduced when TPP was negative relative to when TPP was normal. In an attempt to compensate for negative middle ear pressure that could affect OAE level, researchers have applied pressure to the external ear that matched the TPP (Hof et al., 2005a,b; Marshall et al., 1997; Trine et al., 1993). Matching ear canal pressure to TPP increased overall TEOAE amplitude in most cases. In the 1 adult participant followed by Marshall et al. (1997) who had fluctuating TPP, application of pressure to the ear canal that matched that of the TPP increased TEOAE levels. However, for frequencies less than 2000 Hz, TEOAE levels measured with pressure compensation exceeded those when TPP was normal. Hof et al. (2005a) studied a group of children and applied pressure to the external ear to match that of the TPP. They found that compensation increased TEOAE level in frequency bands of 1, 2, and 3 kHz in 80% of cases. At 4000 Hz, 58% if the cases showed increased level but 42% demonstrated decreased TEOAE levels. In another study, Hof et al. (2005b) applied 12 different a priori “pass” criteria that included overall correlation between waveforms and various TEOAE-to-noise ratios to TEOAEs measured when TPP was negative and then again using ear-canal pressure compensation. The percentage of ears passing criteria increased by 18% to 26% when pressure applied to the ear canal matched TPP. These studies suggest that application of pressure into the ear canal to match that of the TPP generally increases TEOAE level, however, not in every case across frequency, and sometimes, compensation produced higher-than-normal TEOAE levels in some bands. In addition, the mechanism for changes in TEOAE levels with compensation is not known.

To summarize the literature, application of negative pressure to the ear canal of normal middle ear reduces OAEs. Individual cases indicate that TEOAEs decrease when tympanograms have negative TPP. Application of pressure in the ear canal to match that of the TPP generally increases TEOAE level for some frequencies, but not in every case. Additionally, data from Marshall et al. (1997) suggest that TEOAE levels could be erroneously inflated for mid-frequencies. Because it is uncertain how the application of pressure to the ear canal affects OAEs, especially in pediatric patients, a more basic approach to understanding the relationship between negative TPP and OAEs is needed. The design of the current study was to measure changes in TEOAEs in the same child on a day when TPP was normal and again on a day when TPP was negative. The purpose of the current study was to determine whether TEOAE levels in infants and toddlers were reduced when they had tympano-
grams with negative TPP. Based on previous literature, it was hypothesized that there would be frequency-dependent changes and that the magnitude of TEOAE level reduction would be systematically related to the magnitude of change in TPP. A second goal was to explore whether there was a linear relationship between the change in TPP and change in TEOAE level. The final goal was to examine whether negative TPP affected the pass rates using common a priori criteria.

**Materials and Methods**

The data presented in this article are part of a larger investigation of changes in TEOAE with development in human infants. In the larger study, TEOAEs and tympanometry were measured at regular intervals in 19 infants who were studied longitudinally from 4 wk to approximately 2 yr of age. Throughout the course of the experiment most of the infants who participated in this study contracted otitis media with effusion at least once and were under the care of a physician during the illness. Data were collected on some days during the recovery from otitis media with effusion when the child had measured negative TPP. These data along with data collected while TPP was normal, are presented below.

**Subjects**

A total of 11 children aged 3 to 39 mo of age (16.8 and 15.4 mo mean age during abnormal and normal tympanogram testing, respectively) participated in the current study. Eighteen cases (from the 11 subjects) are included in the data set. A case is defined as a unique pair of measurements that included data from 2 days; 1 when the child had normal TPP and 1 when the child had negative TPP. Thus, for a child to be included in the final data set more than once, each case had a different set of both normal and abnormal tympanograms. Six of the 11 children participated in this experiment for more than 1 case. Five of these 8 children participated twice (2 separate cases; a total of 4 tympanograms—2 normal and 2 abnormal), and 1 child participated 3 times (3 separate cases; a total of 6 tympanograms—3 normal and 3 abnormal). All these children had minimal response levels at 15 dB HL to 1000, 2000, and 4000 Hz pure-tone stimuli measured using automated visual response audiometry (Intelligent VRA) multiple times between 9 mo and 2 yr of age. None of the children had ever had pressure ventilating tubes in the eardrums, nor was there parental report of tympanic membrane perforations.

**Transient-Evoked Otoacoustic Emissions**

TEOAEs were measured using the ILO92 system (Otodynamics, Hatfield, UK) version 5 software. The probe design was the same as that used for adults, however, the electronics were housed in a smaller casing (what Otodynamics referred to as a “kid probe”). This probe contained both a speaker and a microphone. The probe fit was evaluated by visually ensuring the spectrum of the click measured in the ear was relatively flat from 500 to 4000 Hz and that “ringing” of the stimulus did not exceed 2 ms. Click stimuli were calibrated in the ear to 80 dB pSPL (±2 dB). The “nonlinear” mode of stimulus presentation and recording was used to reduce the stimulus artifact (for details, see Bray, 1989). TEOAE responses were averaged, high-pass filtered at 750 Hz and low-pass filtered at 6228 Hz using filter settings on the Otodynamics equipment. For children aged 3 to 23 mo TEOAEs were collected while the child was sleeping. For children 2 to 3 yr of age, TEOAEs were measured while the child was awake and watching a video at low volume.

**Tympanograms**

Two-phase tympanograms were measured using the Virtual 310 equipment in conjunction with a MacIntosh computer. As part of the longitudinal study, tympanograms were attempted using 10 different probe frequencies when the child’s middle ear pressure was normal. On days when the child had negative TPP, often only probe frequencies of 226 Hz were measured. If an infant was aged less than 6 mo, tympanograms were also measured using a 630 or 800 Hz probe tone. Tympanograms were measured using a positive (+239 daPa) to negative (−300 daPa) pressure sweep at the rate of 125 daPa/sec and probe level of 85 dB SPL. When 2 tympanograms of different frequency were measured, the lower frequency probe tone was always used first. TPP was measured from the 226 Hz tympanogram and was defined as the applied pressure in daPa at which the tympanogram exhibited the greatest magnitude in mmho. Tympanograms were always measured after TEOAEs were collected in children under 2 yr of age, and before TEOAEs were measured for children aged 2 to 3 yr.

Tympanograms were considered normal when the maximum TPP was between −50 and +60 daPa. In addition, for all tympanograms, middle ear admittance was greater than 0.2 mmho measured between the “tip” and the positive “tail” of the tympanogram for a 226 Hz probe tone. For infants 6 mo of age and younger, middle ear admittance at 630 Hz was also not less than 0.255 mmho (Calandruccio, et al., 2006).
Data Analysis

Overall TEOAE levels were calculated by the ILO software using a cross-spectrum analysis, and were reported in this study as the “overall response.” Overall noise levels reported are the “A–B” measure from the ILO software. The ILO software also provided TEOAE and noise levels were analyzed in half-octave bands centered at 1000, 1414, 2000, 2828, and 4000 Hz. Statistical analyses were conducted using both parametric and nonparametric tests. Parametric tests were conducted because the data met almost all of the assumptions underlying their use and importantly, statistical power could be calculated. Because of the small number of data sets, it was important to report whether nonsignificant effects were due to low power. Differences in overall TEOAE levels, noise levels and half-octave band levels collected when TPPs were normal and when tympanograms had negative TPP were analyzed using a Z test for the equality of 2 proportions (α = 0.05; β > 0.80). To examine possible differences in level across frequency, TEOAE levels in an individual when the TPP was negative were analyzed for significant differences using paired t tests (α = 0.05; β > 0.80). To examine possible differences in level across frequency, TEOAE levels in an individual when the TPP was negative were analyzed for significant differences using paired t tests (α = 0.05; β > 0.80). To examine possible differences in level across frequency, TEOAE levels in an individual when the TPP was negative were analyzed for significant differences using paired t tests (α = 0.05; β > 0.80).

Table 1 provides the age of each child when he/she had a normal tympanogram and an abnormal tympanogram and the TPP of the tympanograms. The difference in ages between the 2 recording sessions is shown in the next to last column. A positive number indicates that the child was younger during the testing for the abnormal tympanogram in comparison with the normal tympanogram testing. The difference in TPP between the 2 sessions is listed in

<table>
<thead>
<tr>
<th>Case</th>
<th>Subject</th>
<th>Normal tympanograms</th>
<th>Abnormal tympanograms</th>
<th>Difference in age (mo)</th>
<th>Difference in TPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Age (mo) TPP</td>
<td>Age (mo) TPP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>32.75 –10</td>
<td>25.25 –300</td>
<td>7.50</td>
<td>–290</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4.50 –14</td>
<td>6.50 –160</td>
<td>–2.00</td>
<td>–146</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3.25 45</td>
<td>4.25 –145</td>
<td>–1.00</td>
<td>–190</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4.50 20</td>
<td>3.25 –170</td>
<td>1.25</td>
<td>–190</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>13.25 –30</td>
<td>9.25 –200</td>
<td>4.00</td>
<td>–170</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>10.50 40</td>
<td>8.50 –100</td>
<td>2.00</td>
<td>–140</td>
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<td>7</td>
<td>5</td>
<td>4.75 0</td>
<td>10.75 –100</td>
<td>–6.00</td>
<td>–100</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>21.00 –50</td>
<td>12.25 –250</td>
<td>8.75</td>
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<tr>
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<td>13.25 –30</td>
<td>10.50 –220</td>
<td>2.75</td>
<td>–190</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>27.75 –40</td>
<td>34.00 –280</td>
<td>–6.25</td>
<td>–240</td>
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<td>8</td>
<td>8.50 –35</td>
<td>13.00 –150</td>
<td>–3.5</td>
<td>–115</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>39.25 –53</td>
<td>34.00 –105</td>
<td>5.25</td>
<td>–54</td>
</tr>
<tr>
<td>13</td>
<td>9</td>
<td>11.00 –40</td>
<td>9.250 –100</td>
<td>1.75</td>
<td>–60</td>
</tr>
<tr>
<td>14</td>
<td>9</td>
<td>21.50 60</td>
<td>18.50 –100</td>
<td>3.00</td>
<td>–160</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>22.75 –35</td>
<td>20.50 –225</td>
<td>2.25</td>
<td>–190</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
<td>14.75 50</td>
<td>9.00 –169</td>
<td>5.75</td>
<td>–219</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>14.5 30</td>
<td>9.250 –136</td>
<td>5.25</td>
<td>–166</td>
</tr>
<tr>
<td>18</td>
<td>11</td>
<td>33.50 0</td>
<td>39.25 –230</td>
<td>–5.75</td>
<td>–230</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>16.8 –5.0</td>
<td>15.4 –174</td>
<td>1.4</td>
<td>–169.5</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>10.9 37.1</td>
<td>10.9 64.9</td>
<td>4.6</td>
<td>60.8</td>
</tr>
</tbody>
</table>

The differences in age and TPP for the 2 testing conditions are listed in the last 2 columns.
the last column. The mean ages at which the normal and abnormal tympanograms were measured were 16.8 and 15.4 mo, respectively. The mean difference in age was 1.4 mo, indicating that children were usually older when the normal tympanogram was obtained. The mean of the absolute value of age difference was 4.1 mo. Mean TPP and standard deviation for normal tympanograms ranged from 100 to 300 daPa. The mean TPP and standard deviation for the abnormal tympanograms was 174 and 64.9 daPa, respectively. The mean, paired difference between the 2 conditions was 169.0 daPa.

Figure 1 shows average overall TEOAE response levels and standard deviations when tympanograms were normal (normal TPP) and when tympanograms were abnormal (TPP was negative). Overall noise levels and standard deviations for these 2 TPP conditions are also shown. A paired t test indicated that TEOAE level was significantly higher when TPP was normal than when TPP was negative (p < 0.0005). Noise levels were not significantly different between the 2 conditions (p = 0.858).

Further analysis was done to determine whether TEOAE levels measured when TPP was negative were lower than when TPP was normal for different frequency bands. Average TEOAE and noise levels (dB SPL) in half-octave bands and their standard deviations are illustrated in Figure 2 as a function of center frequency. TEOAE levels in each half-octave band at each test frequency were significantly lower when TPP was negative based on paired t tests (p values ranging from <0.0005 to 0.011). Noise levels in each half-octave band were not significantly different when TPP was normal and when it was negative (p values ranging from 0.23 to 0.49). The same pattern of significant differences were found using nonparametric statistical tests.

To explore whether there were significant decreases in TEOAE levels across frequency, the TEOAE levels obtained when TPP was negative were subtracted from the TEOAE levels obtained when TPP was normal. Median and interquartile range differences in the TEOAE responses and standard deviations as a function of center frequency are shown in Figure 3. A repeated measures ANOVA indicated that there were no significant differences in the amount of TEOAE reduction across frequency (F = 2.24, degrees of freedom = 4.64; p = 0.90). Nonparametric tests results provided similar conclusions.

Although mean TEOAE level decreased when TPP was negative, the data were evaluated to determine whether decreases were noted for individual
Overall TEOAE levels decreased in 89% (16 of 18) of the cases. In the remaining 2 cases, overall TEOAE level when TPP was negative was within ±1 dB of when TPP was normal. Table 2 illustrates the number of ears showing decreased TEOAE level when TPP was negative (top row), the number of ears showing no change (within ±1 dB) (middle row) and the number of ears having increased TEOAE levels when TPP was negative (bottom row) for each half-octave frequency band. Across all half-octave bands combined, 80% of TEOAE levels decreased when TPP was negative. Within half-octave frequency bands, significantly more ears had lower TEOAE levels when TPP was negative than had increased TEOAE levels or no change in TEOAE levels (combined) when TPP was negative (p < 0.0005 for the 1000 Hz band, p = 0.001 for 1414, 2828, and 4000 Hz bands; p = 0.008 for band centered at 2000 Hz).

Further scrutiny was given to the cases where TEOAE level had no change or increased under conditions of negative TPP. In both cases where overall TEOAE level did not change when TPP was negative, the children were older when TPP was negative. When looking at the 18 half-octave bands that were the same or higher when TPP was negative, 13 bands were when the child was older for the negative TPP. There was no consistent pattern that smaller differences in TPP between the normal and abnormal tympanograms was associated with no change or an increase in TEOAE levels.

Preceding research in ears where middle ear pressure was changed by doing the Valsalva technique suggested that there was a linear relationship between change in TPP and DPOAE level (Avan, et al., 2000). Differences in TPP and TEOAE levels in each half-octave band were compared in the present sample to determine whether a linear relationship existed. Because Avan et al. (2000) did not include any cases where TPP was at a positive pressure, separate analyses were performed for TPP of starting pressure 0 daPa or greater and when TPP was more negative than 0 daPa. Differences in TPP were calculated by subtracting the TPP on the day it was negative from the TPP on the day it was normal. Differences in TEOAE levels in the 5, half-octave bands were subtracted in a similar way. Figure 4 illustrates the data for the 1500 Hz band when normal TPP and abnormal TPP were both negative (circles) and when normal TPP was positive and abnormal TPP was negative (diamonds). The lower panel depicts data for the 2000 Hz frequency band.

### Table 2. The number of participants having decreased (top row), no change (middle row) and increased (bottom row) TEOAE levels for each half-octave frequency band on the day when TPP was negative

<table>
<thead>
<tr>
<th>Half-octave band center frequency</th>
<th>1.0 kHz</th>
<th>1.4 kHz</th>
<th>2.0 kHz</th>
<th>2.8 kHz</th>
<th>4.0 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased by more than 1 dB</td>
<td>17</td>
<td>14</td>
<td>13</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Within ±1 dB</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Increased by more than 1 dB</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
TEOAE level for individual frequencies were significant at $\alpha = 0.05$ ($p$ values ranged from 0.089 to 0.569), suggesting there was no significant relationship between the 2 measures. Analyses using Spearman-rank correlations provided similar conclusions.

Although analyzing TEOAE level changes associated with abnormal TPP is useful, most clinicians use the measures of emission-to-noise ratio (ENR), rather than absolute TEOAE level to identify hearing loss, as previous research suggests ENR identifies hearing loss with greater accuracy than OAE level (e.g., Gorga, et al., 1997; Prieve, et al., 1993). Toward this end, each TEOAE in the data set was encoded as a pass or “fail” using 2 common a priori criteria; $\geq 3$ dB or $\geq 6$ dB ENR in all 3 bands centered at 2000, 2828, and 4000 Hz. Using a 3 dB criteria, pass rates were 78% and 83% for negative TPP and normal TPP, respectively. These pass rates were not significantly different ($p = 0.674$). Using 6 dB or greater criteria in all 3 bands, pass rates were 72% and 78% for negative TPP and normal TPP, respectively. These pass rates were also not significantly different ($p = 0.707$). In order for the difference in pass rates to be significantly different ($\alpha = 0.05; \beta = 0.80$) between negative and normal TPP conditions, 504 patients using a 3 dB criterion and 280 patients using a 6 dB criterion would need to be tested.

**DISCUSSION**

In the present study, within-subject comparisons were conducted between TEOAE levels in the same child when tympanograms had normal and negative TPP. The design of the study has several strengths. First, data were collected in infants and toddlers. In these age groups, middle ear dysfunction is typically high and there is particular concern about identifying hearing loss. Second, data from each child were compared within him/herself on different days. The data probably reflect differences normally seen in other infants and young children at these ages that may routinely undergo hearing testing. In addition, no pressure was introduced into the ear canal to compensate for pressure differences across the tympanic membrane. Although this method has been used before in children (Hof, et al., 2005a,b), the underlying mechanism resulting in TEOAE level changes is unknown. There have been no studies in children comparing TEOAE levels using ear canal pressure compensation to TEOAEs when TPP is normal; therefore, it is unknown how well TEOAE levels measured with ear canal pressure compensation mimic TEOAE levels when TPP is normal. Furthermore, it is uncertain if pressures introduced into the ear canal will produce different effects depending on infant age.

Recording TEOAEs from infants and children with normally varying TPP also has drawbacks. First and foremost, TPP is not an exact measure of middle ear pressure, merely an indication that negative pressure exists. Additionally, the same TPP measured in 2 individuals could reflect different middle ear pressures (Elner, et al., 1971; Renvall & Holmquist, 1976). Comparing within an individual may have “normalized” the differences in TPP to some extent to allow for better comparison, however, this has not been tested. A second drawback of this study is that the TPP of the “normal” and “negative” tympanograms could not be controlled, so systematic changes in TEOAE level for given TPPs are not known. For mean data, changes in TEOAEs were averaged across a relatively wide range of TPP differences. Although this may not seem ideal, there were no significant correlations between changes in TPP and TEOAE level to suggest that averages were inappropriate. Another limitation of this study is that DPOAEs were not recorded in addition to TEOAEs. Additional research is needed to study changes in DPOAE levels with changes in TPP. Finally, the total number of subjects who participated in the study was small due to the time-consuming longitudinal design.

Results from this study indicated that average overall TEOAE levels in infants and children aged 4 mo to approximately 3 yr were lower when their TPP was negative compared with when their TPP is normal. The mean reduction in TEOAE level was approximately 4 dB whereas the mean difference in TPP between normal and abnormal tympanograms was $-169.0$ daPa. The amount of average reduction seen in the current study was within $\pm 1$ dB to the average amount reported by Veuillet et al. (1992), Naeve et al. (1992), and Robinson and Houghton (1991) when negative pressures of $-180$ daPa (Veuillet, et al., 1992) and $-200$ daPa (Naeve, et al., 1992; Robertson & Houghton, 1991) were introduced into the ear canals of normally hearing adults.

Reductions in average TEOAE level were observed across the entire frequency range from 1000 to 4000 Hz. Moreover, the average TEOAE level difference between days when TPP was normal and TEOAE was negative was not significantly different across the half-octave frequency bands centered at 1000, 1414, 2000, 2828, and 4000 Hz. It was hypothesized that there would be greater reduction in TEOAE for the lower than for the higher frequency bands, but this was not the case. Previous research that involved application of pressure to ear canals of persons with normal middle ear function indicated that TEOAEs were reduced for frequencies 2000 Hz
and lower but no changes or slight increases were observed in the 4000 Hz band (Naeve, et al., 1992; Veuillet, et al., 1992). Essentially no or small changes in TEOAE level around 4000 Hz have been reported, both for an adult case of negative TPP (Marshall, et al., 1997) and when pressure was introduced into the ear canal to compensate for negative TPP (Hof, et al., 2005; Trine, et al., 1993). Data from the current study are more consistent with Zhang and Abbas (1997), who found that DPOAE levels were reduced for both high and low frequencies in guinea pigs where middle ear pressure was manipulated.

A consistent relationship between changes in TEOAE level and TPP would allow for a correction factor to be applied to the TEOAE level when a child had a negative TPP. However, the lack of correlation between changes in TEOAEs and differences in TPPs indicated that this was not possible. The lack of a relationship between negative TPP and a “passing” TEOAE ENR was also noted by Koike and Wetmore (1999). Trine et al. (1993) found that TEOAE level increase due to ear canal pressure compensation was also not related to TPP. For example, in 3 subjects with TPP of −100 daPa, TEOAEs increased from 2.2 to 6.8 dB, when pressures of −100 daPa were applied to the ear canal. One person with a negative TPP of −300 daPa had only a 2 dB increase in TEOAE level when equal pressure was applied to the external ear.

In the presence of negative TPP, mean overall TEOAE levels decreased and TEOAE levels in half-octave bands decreased in most cases; however, in some cases, TEOAE levels were higher when the child had negative TPP. In 10% of cases, TEOAE levels (90 levels total; 5 frequency bands, 18 cases) increased when TPP was negative. Another 10% of cases showed no change in TEOAE level when TPP was negative (±1 dB). These results were contrary to expectations. Hof et al. (2005a) found that compensation for negative TPP through applied pressure to the ear canal sometimes decreased TEOAE levels rather than increasing them. The percentages were also fairly high, ranging from approximately 22% at 1000, 2000, and 3000 Hz to as much as 42% at 4000 Hz. In the current study, significantly more levels decreased with negative TPP than increased or stayed the same.

One factor that could have slightly confounded the results is that TEOAE levels were measured not only when TPP was different, but also when the age of the child was different. TEOAE levels decrease with maturation in children (e.g., Prieve, et al., 1997). The exact time-course of changes has not been extensively studied. Preliminary analyses of longitudinally measured TEOAEs suggest that general patterns exist, but according to Prieve & Fitzgerald (Reference Note 1) the exact course cannot be predicted based on chronological age. Ultimately, it is probably the maturation of the ear canal and middle ear that are responsible for changes of TEOAEs with development. The length and diameter of the ear canal increase with development, resulting in larger ear canal volumes (e.g., Keefe, et al., 1994). In newborns, the immaturity of the middle ear reduces the sound getting into the cochlea and the small ear canal volume enhances the OAE levels measured in the ear canal (Abdala & Keefe, 2006; Keefe & Abdala, 2007). In the current study, paired data sets were chosen with the smallest age difference possible between the two. The mean difference between normal and negative TPP data sets was 1.4 mo (meaning the tympanogram with normal TPP and TEOAE were collected at an older age) with only 3 comparisons exceeding 6 mo. The data for the negative TPP condition were collected at an older age for less than half of the cases (6 of 18). In 12 of 18 cases, the normal tympanogram and TEOAE was collected at an older age, meaning that TEOAE levels could be slightly lower for the case with the normal tympanogram than the younger age (had there been normal TPP) because the child was older. If there were decreases in TEOAE levels as a result of maturation, this would result in mean TEOAE reduction between conditions when TPP was normal and negative being underestimated. Despite the majority of children being older for the normal TPP condition, mean TEOAE levels were significantly higher when they had normal TPP than when they had negative TPP, suggesting that slight changes in TEOAE level because of age were not as dramatic as those because of differences in TPP. It should be noted, however, that in all the cases where higher TEOAE levels were obtained when the tympanogram had negative TPP, the TEOAEs and the tympanogram with a normal TPP was collected when the child was older. It is possible that maturational changes contributed to the increased level for the negative TPP condition noted in those 9 of 90 cases.

Despite the fact that TEOAE level was lower when TPP was negative, pass rates using common a priori criteria were different by 5% to 6%. On one hand, this could be a significant difference in a clinic where large volumes of patients are tested. On the other hand, the prevalence of hearing loss is probably high for children being seen in an audiology clinic and they will be undergoing a diagnostic test battery, so auditory status will not be determined solely by "passing" TEOAE criteria. The changes in pass rates in the present study are less than that reported by Hof et al. (2005b), who reported in-
creases in pass rates of 18% to 26% when pressure was applied to the ear canal to equal TPP. It is difficult to know whether the results from the current study are significantly different than that from Hof et al. (2005b) because of the small number of participants. In addition, there are several differences between the 2 studies. First, the mean age of participants in the Hof et al. study was 4 yr, whereas the mean age in current study was 17 mo (normal tympanograms). Because TEOAE level decreases with maturation, it is possible that the TEOAE levels recorded by Hof et al. (2005b) were lower, and thus negative middle ear pressure could reduce the levels enough so that the ENR ratio was also smaller. Second, the criterion for a pass was different for the 2 studies. Although Hof et al. (2005b) computed pass rates using 12 different pass criteria, each one also included the overall correlation between waveforms. In the current study, we considered ENR in only 3 higher frequency bands. Overall reproducibility is not widely used as a screening criterion because the measure is dominated by low-frequency noise. The small change in pass rates between days when TPP was normal and TPP was negative found in the current study could have been due to the high TEOAE level in infants and toddlers. Even though there was a reduction in overall TEOAE level, the levels are still high enough to be sufficiently above noise floor in most patients. Thus, the ENRs still met pass criteria. Another difference is that the number of children in this study was smaller than that of the other studies and the data were collected as part of a larger research study.

Conclusions

Mean TEOAE levels decreased in infants and children when they had tympanograms with negative TPP. The mean reduction in TEOAE level was similar across frequency bands from 1000 to 4000 Hz. Despite these reductions, most participants still passed a TEOAE screening using common criteria. Although the number of participants was small in this study, the results suggest that negative TPP should not preclude clinicians from testing TEOAEs in a diagnostic setting. If ENR ratio is used to make decisions about cochlear hearing loss, a high percentage may still pass TEOAE criteria, providing the clinician with valuable information about cochlear status.

Acknowledgments

The authors are grateful to Lisa Lahtinen for her assistance.

This work was supported by Grant R29 DC20285 from the National Institute on Deafness and Other Communication Disorders.

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Received May 18, 2007; accepted November 26, 2007.

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**REFERENCE NOTE**