Original Article

High Frequency Tympanometry (1000 Hz) in Young Infants and Its Comparison With Otoacoustic Emissions, Otomicroscopy and 226 Hz Tympanometry

Eduardo A. Mena-Domínguez, a José I. Benito-Orejas, a,* Beatriz Ramírez-Cano, a Darío Morais-Pérez, a M. Fe Muñoz-Moreno b

a Servicio ORL y PCF, Hospital Clínico Universitario de Valladolid, Valladolid, Spain
b Unidad de Apoyo a la Investigación, Hospital Clínico Universitario de Valladolid, Valladolid, Spain

Keywords
Child; Hearing loss; Otitis media; Acoustic impedance tests; Otoscopy; Microscopy

Abstract

Introduction and objective: In the first 6 months of life, 226 Hz tympanometry is considered an ineffective procedure for the diagnosis of otitis media with effusion. With the introduction of universal hearing screening, the use of high frequency 1000 Hz (1 kHz) tympanometry has been recommended. To optimise the diagnosis of neonatal hearing loss, we present this comparison, from the clinical point of view, of the results of 226 Hz and 1 kHz tympanometry in infants.

Materials and methods: We designed a prospective study of 100 children under 9 months of age proceeding from our hearing screening programme. We compare the result of tympanometry with binocular microscopy and transient evoked otoacoustic emissions.

Results: The application of transient otoacoustic emissions, otomicroscopy and 226 Hz and 1 kHz tympanometry has shown its usefulness in the management of otitis media with effusion of young infants, with a similar effectiveness between the 4 tests.

Conclusion: The joint use of otomicroscopy, transient otoacoustic emissions and 226 Hz and 1 kHz tympanometry, has allowed us to diagnose otitis media with effusion in young infants more accurately than each test separately. We recommend initial use of 1 kHz tympanometry, at least in children younger than 7 months, but in the presence of hearing loss or an unclear result, 226 Hz tympanometry is a good diagnostic complement.

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* Corresponding author.
E-mail address: jibenito@ono.com (J.I. Benito-Orejas).

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Tympanometry and the scheme. In babies of ears, the study of hearing loss involves assessment of the middle ear. This is more important in childhood due to the high prevalence of serous otitis media (SOM), especially during the first year of life, when more than 50% of babies suffer the condition. Tympanometry is the standard procedure to establish the dynamic characteristics of the middle ear. It is based on measuring acoustic admittance of the middle ear (resulting from its 2 components: susceptibility and conductance), according to the air pressure changes in the external auditory canal. The resulting graph is termed a tympanogram. Acoustic susceptibility depends on the mass and rigidity of the system. The use of a frequency of 226 Hz as the test tone has been demonstrated to be effective in identifying SOM and other middle ear disorders in children of preschool and school age (82%-89% specificity and 95%-100% sensitivity), and therefore has now become a routine clinical test. However, it becomes less reliable in babies under 7-9 months. Paradise et al. were one of the first to doubt the efficacy of conventional tympanometry in 1976, when they found that a major proportion of ears of babies under 7 months and SOM (confirmed by pneumatic otoscopy and myringotomy) presented normal tympanograms. These findings were subsequently corroborated by other researchers. It was also confirmed that a test tone of 226 Hz in this age range can produce flat tympanograms (type B, false positives) in children with normal ears, in a percentage that varies between 40% and 90%. These discoveries appear to speak volumes in demonstrating the inefficacy of conventional tympanometry in month-old infants. However in addition, the use of 226 Hz tympanometry at this age produces a high proportion of curves with multiple peaks, which are unclassifiable within the Liden and Jerger scheme. The need arises with the rapid implementation of universal neonatal hearing screening programmes to assess hearing in the first months of life. From 4 to 5 children per 1000 newborns present brainstem auditory evoked potential (BAEP) thresholds of 50-70 dB nHL, confirming temporary conductive hearing loss in 77%. In order to be able to differentiate this from sensorineural hearing loss, we need make an assessment of the conductive component of hearing in newborn infants. So-called "high frequency tympanometry" (HFT), at 1000 Hz (1 kHz) started to be developed between the sixties and eighties, and entered clinical practice after the first equipment was marketed in 2000. Research seems to demonstrate greater validity than low frequency tympanometry (226 Hz) in diagnosing SOM in babies under 7-9 months. Based on this and other studies, the Joint Committee on Infant Hearing (JCICH, 2007) and in Spain, the Comisión para la Detección Precoz de la Hipoacusia (Committee for the Early Detection of Hearing Loss) (CODEPEH, 2010) recommend using HFT (1 kHz) to assess the middle ear in babies. The inability of 226 Hz tympanometry to establish a solution in babies is put down to anatomical differences of their outer and middle ear compared to adults and at the specific resonance frequency of the tympanic membrane. In order to be able to validate the results of HFT, we need to compare them with a gold standard. Myringotomy would be the ideal procedure, but this is an invasive method which can only be justified for specific indications, and therefore other examinations are used. Obtaining otoacoustic emissions (OAE), because efficient sound transmission...
that the middle ear is normal. It has been established that of babies that pass the acoustic otoacoustic emission test, 93% have a normal tympanogram, and if they refer, it is pathological in 74%, with sensitivity and specificity levels varying between 57%–91% and 50%–95%, respectively. Otomicroscopy is another procedure that has been endorsed for years in the diagnosis of SOM, with total precision rates of 95%, exceeding tympanometry and pneumatic otoscopy and is also a current gold standard. It should be considered that HFT, transient otoacoustic emissions (TOEA) and stapes reflex would be a good combination to detect middle ear dysfunction. Computed tomography has even been used, which demonstrates a good correlation with 1 kHz tympanometry (98%), very superior to that found with 226 Hz tympanometry.

By using otomicroscopy and TOAE we attempted to establish the validity of 1 kHz tympanometry compared to that of 226 Hz in children aged under 9 months.

Finally, for HFT to be used as a clinical tool it is necessary for its results to be reproducible, and although scanty, the few research studies on reproducibility demonstrate this to be the case.

Material and Methods

A prospective study was undertaken over one year on 100 children (200 ears) aged under 9 months after universal screening for different reasons (Table 1).

<table>
<thead>
<tr>
<th>Participants (n=100)</th>
<th>59 males</th>
<th>41 females</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (&lt;9 months)</td>
<td>38 (0–3 months)</td>
<td>45 (3–6 months)</td>
</tr>
<tr>
<td>Reason for consultation</td>
<td>65 due to hearing loss risk factors</td>
<td>22 because hearing screening outcome was “refer”</td>
</tr>
<tr>
<td>Number of tests undertaken</td>
<td>Otomicroscopy (178/200: 89%)</td>
<td>TOAE (190/200: 95%)</td>
</tr>
<tr>
<td>Normal and pathological ears</td>
<td>Percentage of normal ears (157/171): 92%</td>
<td>Percentage of pathological ears (SOM) (14/171): 8%</td>
</tr>
</tbody>
</table>

Table 1 Characteristics of the Children and the Tests Undertaken.

TOAE: transient otoacoustic emissions; SOM: secretory otitis media.

Procedure

Generally the tympanometry test was performed in the children’s mother’s arms and in a quiet room, in one or other ear, randomly applying the tone test at 226 Hz or 1 kHz. This examination was undertaken by experts in impedance audiometry, generally nurses. If there were artefacts or inadequate sealing of the probe, the test was repeated. Before or afterwards, depending on the case, an automated TOAE test was performed in each ear by the same staff.

The child was then taken to a different room where, lying on a stretcher held by their parent or guardian, an ENT specialist in paediatric otology examined both ears with a binocular microscope after cleaning the EAC of wax and epithelial debris.

The tympanometer used was AT235h by Interacoustic® Pty Ltd, Denmark and the TOEA were performed with a portable screening audiometer by Otometrics®, MADSEN AccuScreen. Both pieces of equipment were calibrated according to the manufacturers’ instructions. The pressures applied with the tympanometer varied from +300 to −300 daPa.

We classified the otomicroscopy as normal, SOM and other (acute otitis media, tympanic retraction, myringosclerosis, perforation, etc., or not specified).

226 Hz tympanometry was described according to the Liden® and Jerger® standards, in type A, B and C curves. Curve A (with a clear peak between +100 and −100 daPa) is normal, flat B (with no clear peak) would be SOM. Negative curve C (with a negative peak between −100 and −300 daPa) we also consider normal.

The tympanogram obtained at 1 kHz was classified based on the modifications by Baldwin® to the method of Marchant et al.®. We drew a baseline joining the points of the curve from +300 to −300 daPa. If the curve showed a peak, regardless of its size, we drew another vertical line from the baseline to the peak. If the peak was positive.
High Frequency Tympanometry (1000 Hz) in Young Infants

Figure 1  Different 226 Hz and 1 kHz tympanogram images. 1. Normal tracings at both 226 Hz and 1 kHz. 2. The 226 Hz tympanogram presents a double peak. 3. Curve B at 226 Hz and negative peak at 1 kHz. 4. False positive at 226 Hz, with an undefined or flat curve; it is normal at 1 kHz. 5. False negative (repeated) at 226 Hz, with mobile curves, negative at 1 kHz.

(upwards from the baseline), the tympanogram was presumed normal; if it was negative (downwards) or flat, it was considered pathological. If there were 2 peaks (one positive and the other negative), the tracing was considered positive (Fig. 1).

In order to test the reliability of the interpretation, part of the tympanograms were reassessed by a second ENT specialist who was not aware of the result of the other test.

If the 226 Hz tympanogram was type A or C and the 1 kHz tympanogram showed a positive peak (both normal); the otomicroscopy, the TOAE or both being normal is sufficient to assess the middle ear as normal. The 226 Hz curve being type B and that of 1 kHz showing a negative peak or being flat (both pathological), the presence of SOM on otomicroscopy, a refer TOAE outcome (a pass being the screening) or both results, serve to diagnose the child with SOM. In the event of disparity in the result of the 226 Hz and 1 kHz tympanometries or if one of them is unclassifiable, the criteria of the otomicroscopy and of the TOAE prevail.

We made a comparative reliability study between otomicroscopy, TOAE, 226 Hz and 1 kHz tympanometries, establishing criteria of sensitivity, specificity, positive
Table 2  Results Obtained With Each of the Tests Used.

<table>
<thead>
<tr>
<th></th>
<th>True positive</th>
<th>False positive</th>
<th>False negative</th>
<th>True negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOAE (n=132)</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>120</td>
</tr>
<tr>
<td>Otomicroscopy (n=142)</td>
<td>9</td>
<td>3</td>
<td>0</td>
<td>130</td>
</tr>
<tr>
<td>226 Hz tympanometry (n=162)</td>
<td>23</td>
<td>11</td>
<td>1</td>
<td>127</td>
</tr>
<tr>
<td>1 kHz tympanometry (n=179)</td>
<td>16</td>
<td>6</td>
<td>1</td>
<td>156</td>
</tr>
</tbody>
</table>

n: number of ears; TOAE: transient otoacoustic emissions.

Table 3  Comparison of Positive and Negative Results Obtained From Each Test.

<table>
<thead>
<tr>
<th></th>
<th>TOAE</th>
<th>Otomicroscopy</th>
<th>226 Hz tympanogram</th>
<th>1 kHz tympanogram</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>False positive TOAE</td>
<td>REFER</td>
<td>Normal</td>
<td>A or C</td>
<td>Positive</td>
<td>2/132 1.5%</td>
</tr>
<tr>
<td>False negative TOAE</td>
<td>PASS</td>
<td>OMS</td>
<td>B</td>
<td>Negative or flat</td>
<td>4/132 3%</td>
</tr>
<tr>
<td>False positive otomicroscopy</td>
<td>PASS</td>
<td>OMS</td>
<td>A or C</td>
<td>Positive</td>
<td>3/142 2.1%</td>
</tr>
<tr>
<td>False negative otomicroscopy</td>
<td>REFER</td>
<td>Normal</td>
<td>B</td>
<td>Negative or flat</td>
<td>0/142 0%</td>
</tr>
<tr>
<td>False positive 226 Hz</td>
<td>PASS</td>
<td>Normal</td>
<td>B</td>
<td>Positive</td>
<td>11/162 6.8%</td>
</tr>
<tr>
<td>False negative 226 Hz</td>
<td>REFER</td>
<td>SOM</td>
<td>A</td>
<td>Negative or flat</td>
<td>1/162 0.6%</td>
</tr>
<tr>
<td>False positive 1 kHz</td>
<td>PASS</td>
<td>Normal</td>
<td>A or C</td>
<td>Negative or flat</td>
<td>6/179 3.4%</td>
</tr>
<tr>
<td>False negative 1 kHz</td>
<td>REFER</td>
<td>SOM</td>
<td>B</td>
<td>Positive</td>
<td>1/179 0.6%</td>
</tr>
</tbody>
</table>

TOAE: transient otoacoustic emissions.

Table 4  Comparative Table of the Validity Criteria of Each Test.

<table>
<thead>
<tr>
<th></th>
<th>TOAE</th>
<th>Otomicroscopy</th>
<th>226 Hz tympanometry</th>
<th>1 kHz tympanometry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>True positives/(true positives+false negatives)</td>
<td>6/10 (60%) (31.3–83.2 CI)</td>
<td>9/9 (100%) (70.1–100 CI)</td>
<td>23/24 (96%) (79.8–99.3 CI)</td>
<td>16/17 (94%) (73–98.9 CI)</td>
</tr>
<tr>
<td><strong>Specificity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>True negatives/(true negatives+false positives)</td>
<td>120/122 (98%) (94.2–99.6 CI)</td>
<td>130/133 (98%) (93.6–99.2 CI)</td>
<td>127/138 (92%) (86.3–95.5 CI)</td>
<td>156/162 (96%) (92.2–98.3 CI)</td>
</tr>
<tr>
<td><strong>Positive predictive value (PPV)</strong></td>
<td>True positives/positive tests</td>
<td>6/8 (75%)</td>
<td>9/12 (75%)</td>
<td>23/34 (68%)</td>
</tr>
<tr>
<td><strong>Negative predictive value (NPV)</strong></td>
<td>True negatives/negative tests</td>
<td>120/124 (97%) (100%)</td>
<td>130/130 (100%)</td>
<td>127/128 (99%) (100%)</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>(True positives+true negatives)/Total</td>
<td>126/132 (95.5%)</td>
<td>139/142 (98%)</td>
<td>150/162 (93%)</td>
</tr>
<tr>
<td><strong>Unclear tympanograms</strong></td>
<td>Unclassifiable or undefined</td>
<td>4/193 (2%)</td>
<td>6/193 (3%)</td>
<td></td>
</tr>
</tbody>
</table>

Cl: confidence interval; TOAE: transient otoacoustic emissions.
predictive value (PPV), negative predictive value (NPV) and overall accuracy (true positives + true negatives/total number) (*Tables 2–4*). The positive or negative value of each of the 4 tests was obtained by comparing them with the other 3. *Table 3* shows the false positives and negatives. If one test result was pathological (refer TOAE outcome, SOM on otomicroscopy, curve B on 226 Hz tympanogram or negative/flat curve on 1 kHz tympanogram) and the results of the other 3 were normal, it was classified as a false positive. By contrast, if the result of one of the tests was normal (negative) and that of the other 3 pathological, it was classified as a false negative. In the cases of hearing loss, as we were not able to estimate the result of the TOAE, we only took into account the fact that the other 3 tests coincided.

In order to look for differences, the tympanometric data of the children aged under 3 months were compared separately (*Table 5*).

The ABSAE and TOAE, as they were automated, met the criteria of "pass" or "refer" offered by the equipment.

The data were collected on a Microsoft Access database, specific to the study, in compliance with the Data Protection Act.

In the statistical analysis, we applied Fisher’s exact test to evaluate the association of qualitative variables. The Kappa index was used to assess interobserver agreement of the tympanometric results. The calculations were made using Epidat 3.1. software. *P* values <.05 were considered statistically significant.

**Results**

The study population comprised 100 children (200 ears), 59 males and 41 females, aged between 0 and 9 months (83% were aged less than 6 months). *Table 1* specifies the characteristics, provenance and the tests undertaken.

We assessed the validity of the 4 tests used in the study (TOAE, otomicroscopy, 226 Hz and 1 kHz tympanometry), calculating values of sensitivity, specificity, PPV, NPV and accuracy (*Table 4*). In order to obtain positive and negative results from each test (*Table 2*) the other 3 were taken into account, as shown on *Table 3*. Agreement in 3 of the 4 tests performed gave a result of a total 157 normal ears (92%) and 14 with SOM (8%). A total of 29 ears (15%) could not be assessed either because a test was missed, there was no agreement between the tests or there was an undefined result.

226 Hz tympanometry gives the most false positives and TOAE the fewest (*Table 3*). However, the TOAE gave the highest number of false negatives, which was insignificant on otomicroscopy. The percentage of false negatives from both tympanometries (226 Hz and 1 kHz) is similar. The most accurate tests for differentiating a normal ear from an ear with SOM would be otomicroscopy (98%) and 1 kHz tympanometry (96%) (*Table 4*). However, because the values are so close, no test in particular stands out.

Five percent of the tympanometry tracings were unclassifiable (*Table 4*).

We undertook a one-off study of babies aged less than 3 months (76 ears) in order to assess whether the characteristics of the middle ear at this early age changed our general results (*Table 5*). We obtained an increased number of false positives with 226 Hz (from 3.3% to 8.3%) and a reduction in false positives with 1 kHz (from 2.5% to 1.4%), which in neither case constituted a statistically significant difference.

The degree of agreement for the 2 testers who classified the tympanometric tracings of 226 Hz and 1 kHz was 0.95 (95% CI: 0.86–1.00), indicating a good statistically significant agreement (*P*<.001).

**Discussion**

In children and adults, conventional tympanometry with a 226 Hz probe tone gives accurate results on middle ear function. However, it is considered that HFT with a 1000 Hz probe tone is more accurate in babies aged under 7 months,\(^{15–18,19}\) as corroborated by our results (*Table 4*), within the upper range of those published.\(^{19–22,24}\)

Nevertheless, and despite the evidence, 1 kHz tympanometry is still not generally used clinically, probably due to the difficulties involved in interpreting these tympanograms and due to the controversy with regard to the age group in which they are used.\(^{18,20}\)

To date we have no general protocollled agreement for analysing results,\(^{13}\) and although 1 kHz tympanometry is used in hearing clinics worldwide,\(^{18}\) there are quantitative variations between the different studies in its use.\(^{18,19,21,22,27}\) Firstly, there is no standard calibration procedure for the 1000 Hz probe, and if the calibration is not valid all the measurements will be inaccurate.\(^{12,15}\) Furthermore, variability is also a function of the characteristics of each team (those of Resende et al.\(^{38}\) and Sood et al.\(^{39}\) are similar to ours), of the study population and of the methodology used.

It is assumed that the anatomical differences between the ear of a baby and that of an adult account for the

<table>
<thead>
<tr>
<th>Age (number of children)</th>
<th>False positives 226 Hz</th>
<th>False positives 1 kHz</th>
<th>False negatives 226 Hz</th>
<th>False negatives 1 kHz</th>
<th>Unclear</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–9 months (n=193)</td>
<td>6.8%</td>
<td>3.4%</td>
<td>0.6%</td>
<td>0.6%</td>
<td>5.2%</td>
</tr>
<tr>
<td>0–3 months n=72)</td>
<td>8.3%</td>
<td>1.4%</td>
<td>0%</td>
<td>0%</td>
<td>2.8%</td>
</tr>
<tr>
<td>3–9 months (n=121)</td>
<td>3.3%</td>
<td>2.5%</td>
<td>0.8%</td>
<td>0.8%</td>
<td>5%</td>
</tr>
</tbody>
</table>

n: number of ears.
acoustic variations that will determine a different tympanometric response. These disparities will affect impedance and the ear’s resonance frequency. The acoustic compliance of a baby’s middle ear is less than that of an adult and resistance is greater. This is why, the middle ear develops from a system that is mass dominated to one where rigidity prevails. The time of transition between the mass-dominated to the stiffness-dominated effect in the middle ear of babies has not been exactly established, although it is presumed to be complete at about 7–8 months. Hoffman et al. consider it appropriate to use 1 kHz tympanometry up to the age of 9 months. Alaerts et al. conclude that 1 Hz should be used at <3 months; 226 Hz at >9 months, and both at between 3 and 9 months (starting with 1 kHz, using 226 Hz if the curve is undefined).

In our results we observe that in children under 3 months false positives increase with 226 Hz tympanometry (from 3.3% to 8.3%), and reduce when 1 kHz is used (from 2.5% to 1.4%) (Table 5). Although this disparity is not statistically significant, it shows a clear trend. Although it is certain that the percentage of false positives that we obtained with low frequency tympanometry was very much lower than that reported in other studies (8.3% of false positives compared to 40% and even 90%). As we have explained, these differences might depend on the study population (well/unwell children) and probably on analogy of the results with an appropriate standard to assess the presence of SOM. Coinciding with other authors, we found a good correlation between 1 Hz tympanometry and using otomicroscopy and TOAE, whose overall reliability increases when they are used together. We recorded TOAE in ears where otomicroscopy showed the presence of fluid in the middle ear and conversely, the absence of OAE does not rule out the possibility of SOM, because incorrect placement of the probe, poor test conditions or sensorineural hearing loss might be the cause.

Another problem in using HFT was finding our own classification technique, since using the traditional system of Liden and Jerger yielded a high rate of false positives and a high percentage of unclassifiable tympanograms. There are 3 procedures for interpreting HFT. The first is to examine the morphology alone (Baldwin’s technique, adapted from a system of Marchant et al., which identifies positive or negative peaks around a baseline, without considering their height or the number of peaks); this is our chosen procedure. The second method is to analyse the shape and the peak obtained after baseline compensated static admittance (compensates magnitude). And finally the third procedure which in addition to configuration, studies component compensated static admittance. In order to perform these types of compensation, specific tympanometry equipment is required, but to date no procedure has been demonstrated to be better than another in diagnosing SOM in babies. A particular feature of Baldwin’s morphological method is that it is not exclusively subjective (like Liden and Jerger’s methods), based on the experience of the person interpreting it, but it introduces a rule whereby, for example, any positive peak indicates normality, regardless of its size. Applying this methodology, Baldwin establishes a sensitivity and specificity in diagnosing SOM for HFT of 99% and 89%, respectively (this is 94% and 96% in this study). Five percent of the tracings were difficult to classify in normal ears and 0.6% in ears with SOM (in these cases this being when the other tests assessing the status of the middle ear have resulted definitive). The degree of agreement between 2 testers in analysing the tympanometric tracings that we obtained using these procedures was very high (95%).

Using healthy children and children with SOM in our study, chosen at random, enabled us to establish the sensitivity and specificity of the tests. The sensitivity values are very similar between 226 Hz and 1 kHz tympanometry, probably because there were few pathological cases (out of 14 ears with SOM only one false negative was detected with both 226 Hz and 1 kHz). However the difference in false positives is reflected in the specificity, which is greater with HFT (96%) than with conventional tympanometry (92%).

The drop in PPV, both for 226 Hz (68%) and for 1 kHz (73%), coincides with that of other authors, this is explained because not all tympanometric changes are due to SOM, and other middle ear disorders (adhesions, fibrosis…) may alter tympanometry.

The percentage of complete 1 Hz tympanometries (subtracting those that were not performed and unclassifiable) obtained in a clinical environment in babies up to the age of 9 months was 95% (between 87% and 99%). To summarise our experience, 1 kHz tympanometry is an effective complementary test in assessing the middle ear of babies, together with TOAE and otomicroscopy. When 1 kHz tympanometry does not give a clear result, as well as repeating it, we consider it appropriate, in line with Alaerts et al., to obtain a 26 Hz tympanogram because it might be helpful, given the accuracy that we achieved in our patients.

Conclusion

We recommend using 1 kHz tympanometry in children aged under 9 months, together with otomicroscopy and TOAE, to diagnose SOM. In the differential diagnosis of hearing loss in the infant population or when the 1 kHz tympanogram is unclear or impossible to obtain, 226 Hz tympanometry can be helpful.

Conflict of Interests

The authors have no conflict of interests to declare.

References
