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A Review of the Effectiveness of Otoacoustic Emissions for Evaluating Hearing Status After Newborn Screening

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Objectives: The purpose of this study was to give a brief review of the effectiveness of otoacoustic emissions for getting frequency-specific information about a hearing-loss problem in newborns after hearing screening. Especially, the advantages of distortion-product otoacoustic emissions (DPOAE) over transiently evoked otoacoustic emissions (TEOAEs) are described.
Data Sources: Approximately 186 ears of 104 children aged between 76 days and 15 years and 436 ears of adults with normal hearing and sensory hearing loss.
Methods: Extrapolated DPOAE I/O-functions at frequencies between 1.5 and 6 kHz were obtained in the children for assessing the hearing loss and for differentiating between a transitory sound-conductive hearing loss and a persisting cochlear hearing loss. For getting information on the test time needed, measurements were performed in the adult patients.
Results: DPOAE thresholds derived from extrapolated DPOAE I/O-functions (DPOAE audiograms) are closely related to behavior audiometric thresholds and can be used for determining characteristic quantities of the cochlear-impaired ear. A DPOAE audiogram can be obtained in a couple of minutes. DPOAE audiograms are able to reveal a transitory sound-conductive hearing loss because of Eustachian tube dysfunction and/or amniotic fluid in the tympanic cavity or to confirm a persisting cochlear hearing loss because of outer hair cell impairment in babies with a reference result in newborn hearing screening.
Conclusion: DPOAE audiograms provide a tool for a fast automated frequency-specific and quantitative evaluation of a mild or moderate hearing in follow-up diagnosis. **Key Words:** Audiologic evaluation—Distortion product otoacoustic emissions—Newborns—Otoacoustic emissions—Transiently evoked otoacoustic emissions.

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BACKGROUND

The aim of pediatric audiologic evaluation of hearing capability in newborns who are referred from newborn hearing screening (follow-up) is to exclude a hearing deficit or to confirm and identify a hearing loss with the determination of its degree in cases where a hearing deficit cannot be excluded. Main purpose of follow-up diagnosis is to establish a working hypothesis for a successful hearing aid fitting.

Subjective tests are only able to assess disorders of sound processing as a whole. Tympanometry, otoacoustic emissions (OAEs), and auditory brain stem responses (ABRs) in combination allow for a differentiation between sound-conductive, cochlear, and neural hearing loss. Like tympanometry, OAEs are a fast and easy-to-handle method. Registration of transiently evoked otoacoustic emissions (TEOAEs) is an indispensable part of follow-up diagnosis. In cases of conspicuous TEOAEs, measurement of distortion product otoacoustic emissions (DPOAEs) has to be imperatively performed, preferably at close-to-threshold stimulus levels. In the following, an overview is given on possibilities and limitations of OAEs to determine type (site) and degree of a hearing loss. Especially, the efficacy of extrapolated DPOAE I/O-functions for getting quantitative and frequency-specific information on the hearing loss is discussed.

CAPABILITY OF TEOAES AND DPOAEs

TEOAEs represent the sum of pulse responses of outer hair cells (OHCs) along the cochlea, whereas DPOAEs arise directly from the frequency-selective compressive nonlinearity of OHC amplifiers (1,2). In principle, both DPOAEs and TEOAEs allow acquisition of frequency-specific information about a hearing loss problem.

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When stimulating the ear with a transient stimulus, almost all OHCs along the cochlear (when using a click) or a part of them (when using a tone-burst) are excited. Because of frequency dispersion in the cochlea, a specific component of the TEOAE response can be directly traced to a specific frequency component of the transient signal. As the basilar membrane at basal sites moves faster than at more apical sites, high-frequency TEOAE components stem from basal cochlear sites, whereas low-frequency TEOAE components come from more apical ones. However, because of the fact that the stimulus and the high-frequency TEOAE components superimpose (and therefore have to be cancelled during TEOAE recording), TEOAEs fail to measure cochlear function above 4 kHz (3). In contrast, DPOAEs are able to asses outer hair cell function at different sites of the cochlea separately depending on the primary-tone frequency. Stimulus (primary-tones at $f2$ and $f1$) and response ($2f1–f2$) do not superimpose Fig. 1.

There are some limitations when performing OAE measurements. Electric microphone noise, physiologic noise (breathing, blood flow), and external acoustic noise do not allow reliable measurements below 1 kHz. Because of the limited frequency range of the sound probe's electro-acoustic transducers, high-frequency OAE measurements are difficult without using specialized devices. Moreover, at high frequencies (>6 kHz), standing waves in the outer ear canal make a defined primary-tone setting for eliciting DPOAEs difficult to obtain. For more detailed information on OAE generation, stimulus setting, OAE recording, and clinical applications, see (4).

TONOTOPIC ASSESSMENT OF HEARING LOSS

OAEs are a fast measure to confirm normal middle ear and cochlear function. This is the case if OAEs are present over a wide frequency range. In case of missing OAEs, middle ear or cochlear (OHC) pathology is likely. OAEs then should be followed by tympanometry. If the tympanogram is abnormal, a sound-conductive hearing loss is likely. If the tympanogram is normal and OAEs are abnormal or absent, then a cochlear disorder is likely.

If both tympanogram and OAEs are normal, ABRs are needed to reveal whether there is a cochlear (inner hair cell) or neural pathology. For example, in auditory neuropathy, where synchronization of neural activity is malfunctioning (either because of inner hair cell synaptic or neural dysfunction), normal OAEs and abnormal ABRs occur (5,6).

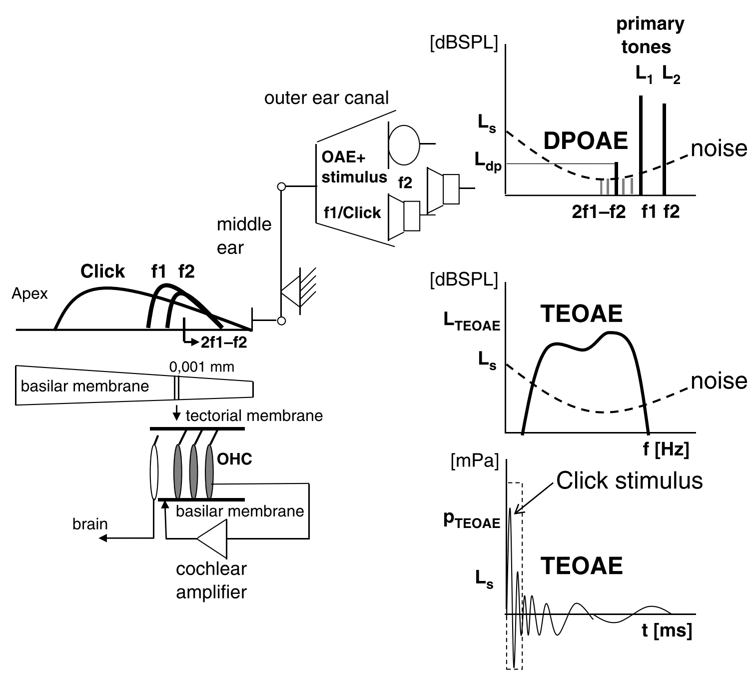

FIG. 1. Schematic drawing to show how TEOAEs and DPOAEs are evoked within the cochlea and subsequently measured in the outer ear canal. The sound probe consists of a microphone for measuring the acoustic response signal and either one loudspeaker for applying a click stimulus (TEOAE) or of 2 loudspeakers for applying 2 independently generated primary tones with frequencies f_1 and f_2 and levels L_1 and L_2. OAEs are a by-product of nonlinear sound amplification within the cochlea because of outer hair cell (OHC) motility. TEOAEs represent OHC pulse responses along the basilar membrane. Basal high-frequency responses appear at the beginning, and apical low-frequency responses appear at the end of the TEOAE time function. Stimulus and high-frequency TEOAE responses superimpose and are therefore removed from the microphone signal. Noise is lowest at mid frequencies. Therefore, TEOAEs fail to obtain information on cochlear function at high and low frequencies. DPOAEs are generated within the region of overlap of the traveling waves of the 2 primary tones close to the f_2 place. Thus, DPOAE provide information on cochlear function at a distinct place.

QUANTITATIVE EVALUATION OF HEARING LOSS

Especially for hearing aid adjustment in infants, a quantitative evaluation of the hearing loss is necessary. When elicited by high stimulus levels (which is common in clinical practice), TEOAEs are absent at a cochlear hearing loss exceeding 20 dB HL, whereas DPOAEs are absent only at a cochlear hearing loss exceeding 40 to 50 dB HL. Thus, when using TEOAEs and DPOAEs elicited at high stimulus levels only, a rough estimate of the hearing loss is possible. For example, when TEOAEs are absent and DPOAEs are present, then the hearing loss is suggested to be not more than 30 dB HL.

The relation between DPOAE level and auditory threshold is strongly debated. Earlier, it was common to define confidence limits to determine the degree of certainty with which any measured response could be assigned to either normal or impaired hearing (7,8) or to define a "DPOAE detection threshold" as the stimulus level at which the response equaled the noise present in the instrument (9). However, because noise superimposes, the response threshold evaluated in this way does not match the behavioral threshold.

A more reliable measure is the intersection point between the extrapolated DPOAE I/O-function and the primary-tone level axis (10,11). DPOAE data can be easily fitted by linear regression analysis in a semi-logarithmic plot, where the intersection point of the regression line with the $L2$ primary-tone level axis at $p$dp = 0 Pa can thus serve as an estimate of the DPOAE threshold (Fig. 2). The estimated DPOAE threshold is independent of noise and seems to be more closely related to behavioral threshold than the DPOAE detection threshold (10,11).

It should be emphasized that a linear dependency between the DPOAE sound pressure and the primary-tone sound pressure level is only present when using a special stimulus setting—the "scissor" paradigm (12)—which accounts for the different compression of the primary-tone traveling waves at the $f2$ place (10,12–14).

Because of the steep slope of the traveling wave toward the cochlear apex, maximum interaction site is close to the $f2$ place. Thus, OHCs at the $f2$ place contribute most to DPOAE generation. The number of OHCs contributing to DPOAE generation depends on the size of the overlapping region, which is determined by the primary-tone level setting $L1|L2$ and the frequency ratio $f2/f1$ of

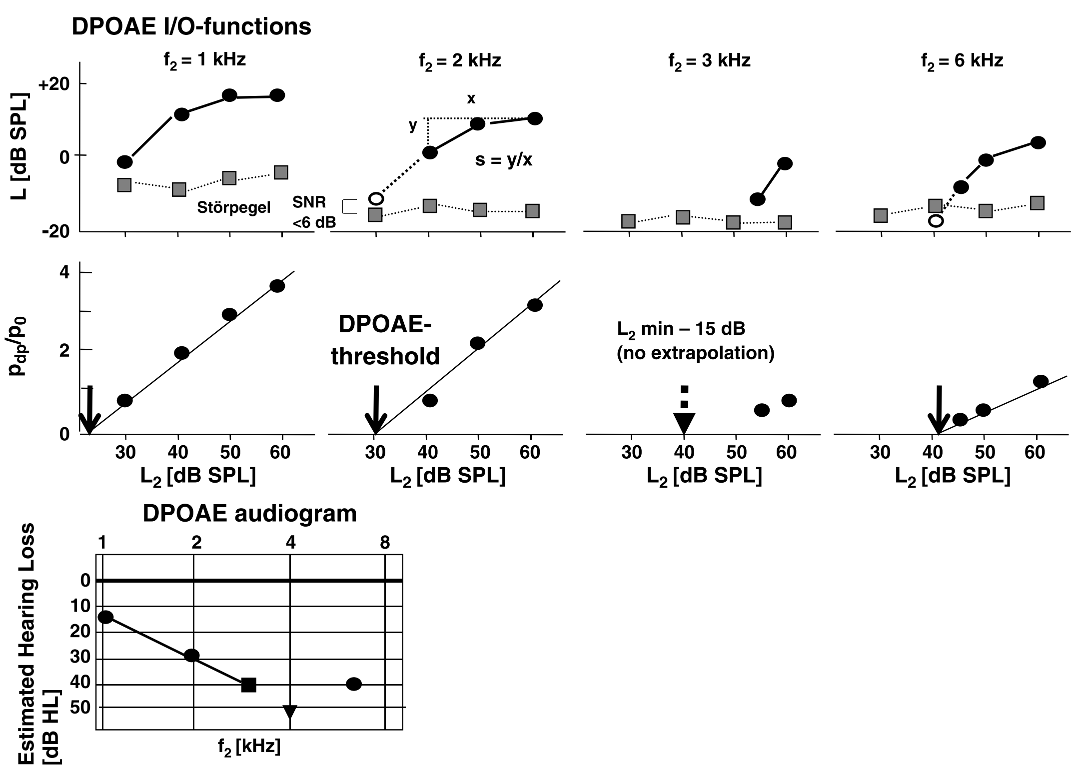

FIG. 2. Schematic drawing of how to determine DPOAE thresholds and to estimate hearing loss at different test frequencies when eliciting DPOAEs using 'scissor' stimulus setting (L1 = 65|L2 = 65, L1 = 63|L2 = 60, L1 = 61|L2 = 55 L1 = 59|L2 = 50, L1 = 57|L2 = 45, L1 = 55|L2 = 40, L1 = 53|L2 = 35, L1 = 51|L2 = 30). DPOAEs are plotted in double-logarithmic (L across L2) and semi-logarithmic (p across L2) scales. Intersection of the linear regression line with L2 axis serves as an estimate of DPOAE threshold. At test frequencies where DPOAEs are only present at 2 L2 levels or 1 L2 level, no extrapolation is performed. In this case, the estimated threshold is calculated by the lowest L2 (L2min) at which a valid DPOAE could be achieved minus 15 dB. After converting SPL in HL, a DPOAE audiogram is constructed. *Circle* means threshold estimation by means of extrapolated DPOAE I/O functions; *square* means simplified estimation L2min—15dB; *arrow* symbol means no DPOAE are measurable, and thus, the hearing loss is estimated to be higher than 50 dB HL.

the primary tones. To preserve optimum overlap of the primary-tone traveling waves at a constant frequency ratio $f2/f1 = 1.2$, the primary-tone level difference has to be increased with decreasing stimulus level, resulting in a $L1|L2$ setting described by $L1 = 0.4L2 + 39$ dBSPL (scissor paradigm). When converting DPOAE sound pressure level (SPL) to hearing loss level (HL), the estimated DPOAE thresholds can be plotted in an audiogram form (DPOAE audiogram).

DPOAE audiograms can be applied in babies with a refer result in newborn hearing screening to reveal a transitory sound-conductive hearing loss because of Eustachian tube dysfunction and/or amniotic fluid in the tympanic cavity or to confirm a persisting cochlear hearing loss in follow-up diagnosis.

One case example shall illustrate how DPOAE audiograms can reveal temporary sound-conductive disorders in the early postnatal period (Fig. 3). In a newborn with a "refer" ATEOAE screening response, the DPOAE audiogram indicated a hearing loss of more than 50 dB at 1.5, 2, 3, and 6 kHz (arrows in Fig. 3) and a 40-dB hearing loss at 4 kHz. The second measurement 12 days later revealed normal hearing function. In this baby, both a low- and a high-frequency sound-conductive hearing loss might have been present where middle ear stiffness is increased because of Eustachian tube dysfunction (low frequencies are affected), and middle ear mass is increased because of amniotic fluid (high frequencies are affected).

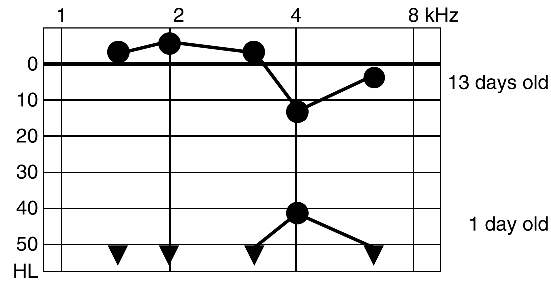

FIG. 3. DPOAE audiograms in 2 newborns (*A* and *B*) with temporary sound-conductive hearing loss. Newborn "a" with a "pass" ATEOAE screening response exhibits a low-frequency hearing loss in the first measurement (3 d after birth). In the second measurement (86 d after birth), the DPOAE audiogram indicates normal hearing. In newborn "b" with a "refer" ATEOAE screening response, no DPOAE could be measured (except at 4 kHz) in the first measurement (1 d after birth). DPOAE audiogram obtained in the second measurement (13 d after birth) indicates normal hearing.

Three case examples shall demonstrate the efficacy of DPOAE audiograms for evaluating a persisting cochlear hearing loss. Pure-tone audiogram and DPOAE audiogram obtained in a 5-year-old boy exhibit a close correspondence (Fig. 4A). This is to show that older children are able to reliably report on their hearing loss. In contrast, in the 2 younger children, there is a high discrepancy between the behavioral free-field audiogram and the DPOAE audiogram. The free-field audiogram of a 5-month-old girl

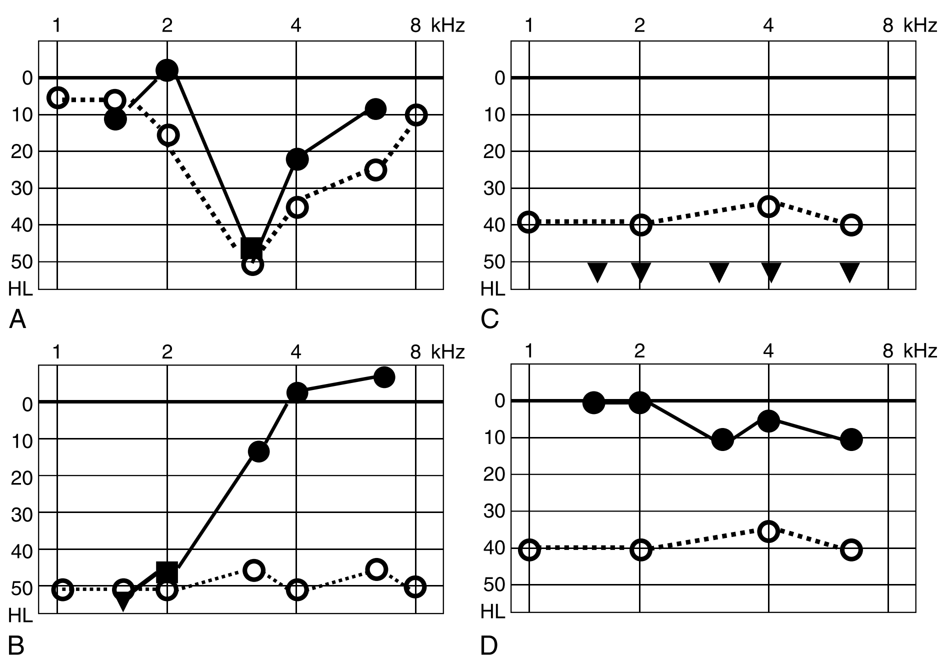

FIG. 4. Pure-tone audiograms (*open circles*) and DPOAE audiograms (*black symbols*) –6 years old boy, left ear (*A*); 5 month old girl, left ear (*B*); 3 months old girl, right (*C*) and left ear (*D*). Pure-tone audiogram and DPOAE audiogram are closely related in the 6-year-old boy. The free-field audiogram (*dotted lines*) of the 5-month-old girl indicates a hearing loss of 50 dB HL in the entire frequency range. However, the DPOAE audiogram reveals a hearing loss only in the mid and low frequency range. The free-field audiogram of the 3-month-old girl indicates a hearing loss of 40 dB HL. In the right ear, DPOAEs are not present, indicating that the hearing loss must be higher than 50 dB (*red arrows* in Fig. 4C). In the left ear, DPOAE audiogram indicates normal hearing.

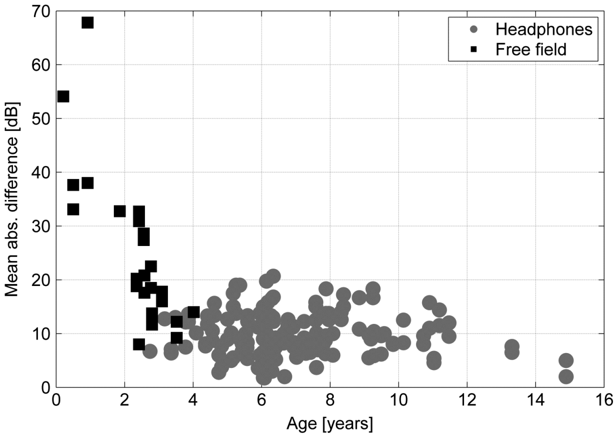

FIG. 5. Scatter plot of the difference between behaviora1and estimated threshold from DPOAE I/O-functions across age obtained in 186 ears of 104 children aged between 76 days and 15 years. *Squares* represent free-field, and *circles* represent head-phone thresholds. Difference between behavioral and estimated thresholds decreases with increasing age.

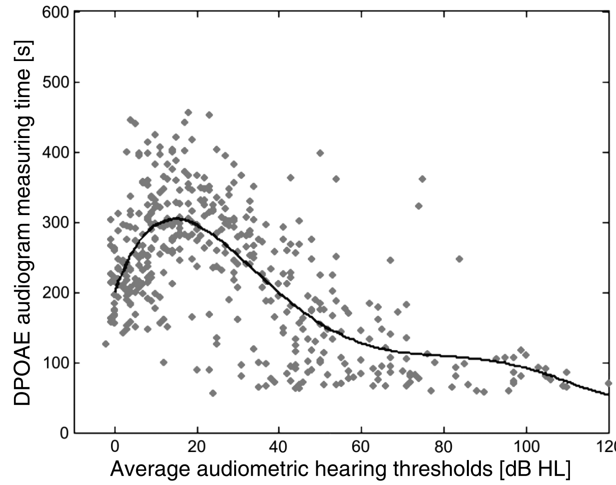

FIG. 6. Scatter plot of measuring time for getting a DPOAE audiogram at frequencies f2 = 1.5, 2, 3, 4, and 6 kHz across average audiometric hearing thresholds. Data are from 436 ears of patients with cochlear hearing loss.

(Fig. 4B) indicates a hearing loss of 50 dB HL in the entire frequency range. However, the DPOAE audiogram reveals a hearing loss only in the mid and low frequency region. Figure 4C shows the free-field audiogram and the DPOAE audiograms of the left and the right ear of a 3-month-old girl. The free-field audiogram indicates a hearing loss of 40 dB HL. In the right ear, DPOAEs are absent, indicating that the hearing loss must be higher than 50 dB (arrows in Fig. 4C). In the left ear, DPOAE audiogram reveals normal hearing.

Figure 5 shows the difference between behavioral pure-tone thresholds and estimated DPOAE thresholds across age obtained in 186 ears of 104 children aged between 76 days and 15 years. Red circles represent conditioned free-field pure-tone thresholds, and blue circles represent head-phone pure-tone thresholds. The difference between behavioral and estimated threshold is high in the first year of life ranging between 32 and 68 dB. Within the period of the second and third year of life, the difference decreases rapidly. In children older than 3 years, the difference remains nearly constant being about 10 dB on average. The difference of 10 dB indicates that the physiologic measure is more sensitive than the behavioral threshold. This may be due to the fact that the stimulus level at which the child is able to respond has to be a certain degree higher than the real hearing threshold level.

DPOAE audiograms can be obtained by means of an automated measuring procedure with simple handling and short measuring time. The time for getting a DPOAE audiogram, which predicts hearing threshold at 1.5, 2, 3, 4, and 6 kHz is shown in Figure 6. Data are from 436 ears of adults with normal hearing and sensory hearing loss. Measuring time is plotted over the average behavioral pure-tone threshold obtained from the clinical audiogram of each individual. At normal hearing (<10 dB HL), a DPOAE audiogram can be obtained in 2 or 3 minutes. At slight hearing losses (10–20 dB), measuring time is longest (up to 7.5 min) because DPOAE amplitude is low but DPOAEs are present at almost all primary tone levels. The higher the hearing loss, the lower is the number of primary tone levels at which a valid DPOAE can be measured. Consequently, the shorter is the measuring time. Thus, measuring time decreases rapidly at a hearing loss higher than 20 dB HL, about 3 minutes at an average pure-tone hearing loss of 40 dB HL, and about 2 minutes at an average pure-tone hearing loss of 60 dB HL.

CONCLUSION

A reliable diagnosis of a hearing deficit in newborns referred from newborn hearing-screening is only ensured if as many as possible objective audiometric tests are performed: tympanometry for evaluating middle ear status, otoacoustic emissions for assessing the function of cochlear amplification, and auditory evoked potentials for assessing synaptic and neural functionality. TEOAEs more qualitatively assess cochlear function and are therefore more suited for topologic diagnostics. DPOAEs—especially DPOAE audiograms—provide more quantitative information about the hearing loss.

DPOAE audiograms are able to assess cochlear hearing loss more precisely than behavioral tests in infants where the conditioned free-field audiogram does not reflect the real threshold. Moreover, unilateral hearing loss can be detected. DPOAE audiograms can reveal a transitory sound-conductive hearing loss in the early postnatal period. DPOAE audiograms are an alternative method to tone-burst or chirp evoked ABRs or auditory steady-state responses (ASSRs) in case of a mild or moderate hearing loss. Test time for establishing a DPOAE audiogram takes only a couple of minutes. Thus, DPOAE audiograms have an essential advantage over ABRs or ASSRs. DPOAE audiograms can help to establish a working hypothesis for a more successful hearing aid fitting.

Because DPOAEs only reflect outer hair cell functionality, they are not present at frequencies where the hearing loss is higher than 50 dB HL. However, the incidence of a hearing loss higher than 50 dB in children with a hearing problem is low. Thus, in most of the children with hearing problems, DPOAEs are measurable at least at high stimulus levels. In cases where DPOAEs are not measurable, ASSRs have to be measured for getting frequency-specific information on the hearing loss in the entire range of hearing.

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