Educational Module
Oto-Acoustic Emission

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Germany
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Our educational modules are made for providing information on how the hearing organ works and which test procedures are used to test the functionality of the sound processing elements along the auditory pathway.

With that knowledge the user of our devices should be prepared to use our test modules efficiently.
Physiological tests

Tympanometry → Otoacoustic Emissions → Evoked Potentials

external/middle ear → Cochlea → neural pathway

acoustically → acoustically → acoustically
REFERRED
acoustically → acoustically → electrically
Physiological tests

Physiological test procedures reflect the mechanical and neural function of the auditory system. Therefore, physiological tests are used for reliably detecting the site of impairment along the auditory pathway. Tympanometry (Tymp), oto-acoustic emission (OAE) and auditory evoked potential (AEP) are able to differentiate between middle-ear, cochlear, and neural disorders. In case of Tymp and OAE, both, stimulus and response are acoustic signals. In contrast, in case of AEP there is an acoustical input-signal and an electrical output-signal.

In view of an adequate therapy of a hearing impairment, it is important to known which stage of the auditory pathway is concerned. Tymp, OAE, and AEP allow for selectively assessing middle-ear, sensory (cochlear) and neural disorders. Behavioural testing is less reliable. This is true, especially, in infants and other non-cooperative patients, where psycho-acoustical tests cannot reliably be performed.
We have seven educational modules

1 Sound - Physiology/Pathophysiology of Hearing
2 Tympanometry
3 Oto-Acoustic Emission (OAE)
4 Auditory Evoked Potentials (AEP)
5 Hearing Screening (newborn, pre-school/school children, elderly)
6 Tracking
7 Occupational medicine
TEOAE-test modules

**TEOAE – Transient Evoked Otoacoustic Emissions**

for checking basic outer hair cell functionality

**TEOAE-Quick** with **fixed** stop criterion in different frequency bands

**TEOAE Diagnostic** with **user-defined** stop criterion in different frequency bands
DPOAE-test modules

**DPOAE – Distortion Product Otoacoustic Emissions**
for frequency specific checking of outer hair cell functionality

- **DPOAE-Quick/Diagnostic** using one/multiple user defined level(s)
- **DPOAE-Threshold** for hearing threshold estimation using automatically controlled stimulus levels
- **DPHIERES – High Resolution DPOAE** for assessing fine-structure cochlear impairment using user-defined frequency step size
- **FMDPOAE - Frequency Modulated DPOAE** for improving hearing threshold estimation
Oto-Acoustic Emission (OAE)

*Discovered by David Kemp in 1978*

The discovery of oto-acoustic emissions (OAEs) by David Kemp in 1978 has produced a fast, powerful, and versatile tool for diagnosing cochlear integrity. OAE measurements are today a standard part of the audiometric test battery. OAEs are elicited and measured by means of electro-acoustic transducers (loudspeaker and microphone) within an ear probe placed in the outer ear canal. There are spontaneous (SOAEs) and evoked OAEs (EOAEs). EOAEs are the by-product of the non-linear sound amplification process in the cochlea. OAEs are low-level sound emissions generated by the outer hair cells (OHCs) within the cochlea. OAE levels depend on the number of functioning outer hair cells given a normal middle-ear function. OAE levels depend on the ear canal volume. Because of the smaller ear canal volume, OAE amplitude in newborns and infants is higher compared to that in adults. Thus, OAEs are easier to measure and thus provide a suited tool for newborn-hearing screening and follow-up diagnostics.
Transient Evoked Oto-Acoustic Emission (TEOAE)

- Ear canal
- TEOAE
- Sound probe
- Frequency [kHz]
- Distance from apex [mm]
- Sensory cell rows
- Basilar membrane
- Tectorial membrane
- IHC
- OHC motility
- Cochlear amplifier
- Afferent NF
Transient Evoked Oto-Acoustic Emission (TEOAE)

- TEOAE noise
- Evaluation window
- Recording window
- Outer hair cell response

- L (dB SPL)
- f (Hz)
- t (ms)
- p (Pa)
- Outer hair cell response

- TEOAE noise
  - Artifact: 0%
  - Stability: 100%
Transient Evoked Oto-Acoustic Emission (TEOAE)

Transient oto-acoustic emissions are elicited by transient acoustic stimuli (clicks or tone-bursts). TEOAEs represent the sum of acoustic impulse- responses of OHCs along the cochlea. At click-stimulation, almost all OHCs along the cochlear partition are set into movement. When using tone-bursts of different carrier-frequencies a specific part of OHCs along the cochlea is stimulated. Due to cochlear frequency dispersion, TEOAE components can be directly traced to a specific place. 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. As a consequence, basal responses appear at the beginning and apical responses at the end of the TEOAE time function. TEOAEs thus provide a rough frequency-specific estimation of cochlear hearing loss. TEOAE‘s sound pressure level is very low varying from about 10 to -30 dBSPL. Thus, measurement and averaging of several hundred signal-epochs are necessary for extracting TEOAE response from noise.
Transient Evoked Oto-Acoustic Emission (TEOAE)

28 years old adult, normal hearing

SNR criteria:

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<th>1</th>
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<td>26</td>
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Overall criterion: 5 / 5

Stimulus
Optimized
Level [dB peSPL]
85
Averages
533
Transient Evoked Oto-Acoustic Emission (TEOAE)

A normally hearing adults exhibits TEOAEs having high levels and a broad signal spectrum. Signal-to-Noise-Ratio (SNR) is high (more than 20 dB with the exception at 4 kHz (9 dB) in the case example). SNR criterion for accepting a response as valid was set to 9 dB.

In contrast, in a newborn at birth with a temporary sound conduction deficit due to amniotic fluid in the tympanic cavity (see case example), TEOAE components have lower levels SNRs (10, 13, 18, 17, 7 dB). However, SNR criterion is fulfilled at all test frequencies with exception at the highest test frequency (4 kHz). The reason for this is a high frequency hearing loss due to a reduced sound conduction because of the amniotic fluid.

In contrast, in a six days old newborn no TEOAEs could be measured. SNRs are below the selected criterion (< 9 dB). There was a normal tympanogram (not shown). In this case, a dysfunction of outer hair cells is most likely. TEOAEs already disappear at mild hearing losses and are therefore commonly used in hearing screening programs.
Transient Evoked Oto-Acoustic Emission (TEOAE)

2 hours old newborn, amniotic fluid in tympanic cavity

Noise: 0% Stability: 100%

SNR criteria:
- >9 dB for all frequencies
- Overall criterion: 5/5

Stimulus:
- Optimized

Level [dB peSPL]: 85

Averages: 638
Transient Evoked Oto-Acoustic Emission (TEOAE)

6 days old newborn: no TEOAE $\rightarrow$ OHC dysfunction
Distortion Product Oto-Acoustic Emission (DPOAE)

DPOAEs are cubic distortions of outer hair cells (OHC) when stimulated simultaneously by two tones $f_1$ (lower frequency) and $f_2$ (higher frequency). DPOAEs arise directly from the frequency-selective compressive nonlinearity of OHCs. The two primary tones interact in the cochlea within the region of overlap of the traveling waves of the two primary tones close to the characteristic place of $f_2$. Thus, DPOAEs can be applied as a probe for frequency-specific assessment of cochlear dysfunction at the $f_2$ place. In humans, both quadratic ($f_2-f_1$) and cubic distortion products ($2f_1-f_2$) can be detected. The cubic distortion component $2f_1-f_2$ yields the highest amplitude and is therefore primarily used for diagnostics. DPOAE amplitudes typically range from about 20 dB SPL down to about -30 dB SPL. DPOAEs are measurable at a cochlear hearing loss of up to 40 to 50 dB HL. DPOAEs provide quantitative and frequency-specific information about the range and operational characteristics of the cochlear amplifier, i.e., sensitivity, compression, and frequency selectivity of the hearing organ.
Distortion Product Oto-Acoustic Emission (DPOAE)

Diagram showing the cochlear structures, including the outer ear canal, ossicles, basilar membrane, IHC, OHC motility, and afferent NF. The diagram also includes a chart showing frequency in kHz, distance from apex in mm, and sensory cell rows.

The chart illustrates the relationship between primary tones and DPOAE (Distortion Product Oto-Acoustic Emission) with 2f1−f2, where f1 and f2 are the primary tones.

The text mentions key terms such as basilar membrane, tektorial membrane, IHC, OHC motility, and afferent NF.
Distortion Product Oto-Acoustic Emission (DPOAE)

The number of OHCs contributing to DPOAE generation depends on the size of the overlapping region, which is determined by the primary tone levels $L_1$ and $L_2$, and the frequency ratio $f_2/f_1$. A frequency ratio of about 1.2 has been found to be optimal.

A primary tone level setting, which accounts for the different compression of the primary tone traveling waves at the $f_2$ place, is the scissor paradigm (see below) DPOAE-grams plot the DPOAE level $L_{dp}$ as a function of $f_2$ (the main DPOAE generation site) for a selected combination of primary-tone levels $L_1$ and $L_2$.

DPOAE-grams reflect the sensitivity of the cochlear amplifier (CA) best when recorded at close-to-threshold stimulus levels. In normal hearing (normal CA), DPOAE-grams are close to each other at high and more separated at low stimulus levels reflecting cochlear non-linear sound processing. In cochlear hearing loss ears (impaired CA), DPOAE-grams are more separated even at high stimulus levels, revealing loss of CA compression.
Distortion Product Oto-acoustic Emission (DPOAE), case examples

DP-gram → OHC-dysfunction

DP-gram → normal OHC-function
Multiple Distortion Product Oto-Acoustic Emission (Multichannel DPOAE)

DPOAE-tests are normally performed by stimulating one ear with one tone pair only. Why not apply multiple tone pair stimulation and binaural stimulation? Both will reduce test time. However, when using multiple and binaural stimulation two facts have to be taken into account. First, when using multiple stimulation, the distance between the primary tone pairs have to be huge enough to avoid overlapping of the travelling waves on the basilar membrane and with that reduction of DPOAE level. Second, stimulus protocol must ensure that there is no crosstalk at the higher stimulus levels. In a study it was evaluated under what conditions mDPOAE measurements have to be done without mutual influence of primary tone pairs in the ipsilateral and the contralateral ear. DPOAE was collected using single- and multi-frequency presentations of the primaries for both monaural and binaural conditions. The mean DPOAE levels collected with mDPOAE and binaural presentation conditions were highly reproducible when compared to those obtained with the single-frequency paradigm (Smyrzinski and Janssen, 20xx).
Multiple Distortion Product Oto Acoustic Emission (Multichannel DPOAE)

In detail, the binaural presentation of single-pair stimuli had subtle effects on DPOAE levels. The difference of 2 dB between mean DPOAE levels collected with binaural versus monaural presentations for $f_2 = 1.5$ kHz and $L_2 = 45$ dB SPL was the only one that reached statistical significance. All other data measured with the two paradigms were very consistent. Thus, the effects of contralateral inhibition created by binaural stimulations are negligible.

The effect of applying one additional pair of tones with an octave spacing on DPOAE levels was quite small, with the largest decrease of 1.3 dB for $f_2 = 4$ kHz and $L_2 = 65$ dB SPL. Slightly lower DPOAE levels obtained with the mDPOAE method than with single-pair stimulation may result from small mutual suppression of cochlear nonlinearities.

In general, the mean DPOAE levels collected with mDPOAE and binaural presentation conditions were highly reproducible when compared to those obtained with the single-frequency monaural paradigm.
Monaural vs binaural presentation: Single tone-pairs
For $L_2 = 65$ dB SPL, the mean DPOAE and noise levels were almost identical for the two testing conditions.
For $L_2 = 45$ dB SPL, the mean DPOAE levels were lower, mostly at $f_2 = 1.5$ and 2 kHz, for binaural stimulation than those for monaural stimulation.
**Monaural presentation: Single tone-pairs vs mDPOAE**

For $L_2 = 65$ dB SPL, the mean DPOAEs were lower, mostly at $f_2 = 4$ and 8 kHz, for the mDPOAE condition than those for the single-pair presentation. The mDPOAE testing resulted in elevated noise levels at 4 kHz for both $L_2$ values and at 3 kHz for $L_2 = 65$ dB SPL.
Monaural single tone-pairs vs binaural mDPOAE
There was a small decrease of DPOAE levels measured with $L_2 = 45$ dB SPL, especially at 1.5, 2, and 4 kHz.
For $L_2 = 65$ dB SPL, an increase of noise levels at 3 and 4 kHz and slightly reduced DPOAEs were observed.
When the ear is stimulated by two tones simultaneously, there are two DPOAE sources, one at the f2 place and the other at the 2f1 -f2 place. Since DPOAE should serve as a probe for assessing hearing function at solely one place within the cochlea (at f2) the DPOAE source at 2f1-f2 has to be eliminated.

There are two techniques to overcome this problem. First one is to use a third tone to suppress the second source at the 2f1-f2 place. However, for doing this, there is need for a third loudspeaker within the sound-probe. A second technique is to use frequency-modulated primary tones. To do this, primary tone frequencies are varied over time, following

\[ f_1(t) = f_{1\text{norm}} + d_1(t) \quad \text{and} \quad f_2(t) = f_{2\text{norm}} + d_2(t) \]

resulting in

\[ f_{dp}(t) = 2 * f_1(t) + f_2(t). \]
Frequency Modulated Distortion Product Oto-Acoustic Emission (FM-DPOAE™)

Primary tone frequencies are shifted between ±100Hz with a modulation rate of about 1.5 Hz. Because of the associated phase shift the impact of the second source is reduced. As a consequence, DPOAE detection and hence hearing threshold estimation is significantly improved.

**FM-DPOAE™** was developed by **PATH medical** in 2012 as a means of suppressing the impact of the second DPOAE source and with that to improve reliability of DPOAE detection and hence hearing threshold estimation.

Moreover, due to frequency modulation the number of stimulated OHCs is increased resulting in a higher DPOAE level. Thus, FM-DPOAE does not need any additional stimuli and does not extend test time. Therefore, FM-DPOAE has the potential to improve both screening and diagnostic DPOAE testing performance.
The effect of second DPOAE source elimination by applying FM-DPOAE technique can be shown best, when comparing high-resolution DPOAE measurements with and without elimination of the second source.

The influence of the second DPOAE source may be observed when plotting the DPOAE level across frequency with narrow frequency spacing, i.e. $\leq 100$ Hz (DPOAE fine-structure). Due to either destructive or constructive superposition of the second source across frequency, a pattern of dips and peaks in the DPOAE fine-structure can be observed in subjects with normal or near-normal hearing.

DPOAE fine-structure gives information about the integrity of OHCs and with that about the fine-structure of behavioural pure-tone thresholds. However, due to the superposition of the second source, there is no reliable correlation between the two measures. When using FM-DPOAE technique DPOAE fine-structure is able to reveal OHC impairment in the very early stage, e.g. beginning hearing loss due to noise over-exposure or ototoxic drug administration.
High resolution Distortion Product Oto-Acoustic Emission (DPOAE)

176 measurement points between 1.5 kHz and 5 kHz, frequency spacing 100 Hz

Second source effect
Distortion Product Oto-Acoustic Emission (DPOAE), DPOAE I/O-function

Extrapolated DPOAE I/O functions allow for assessing loss of cochlear sensitivity and compression. The number of OHCs contributing to DPOAE generation depends on the size of the overlapping region, which is determined by the primary tone levels $L_1$ and $L_2$, and the frequency ratio $f_2/f_1$. A frequency ratio of about 1.2 has been found to be optimal for yielding highest amplitudes. A primary tone level setting, which accounts for the different compression of the primary tone traveling waves at the $f_2$ place, is the scissor paradigm. Due to the steep slope of the traveling wave towards the cochlear apex, the maximum interaction site is close to the $f_2$ place in the cochlea. To preserve optimum overlap of the primary tone traveling waves at a constant frequency ratio, the primary tone level difference has to be increased with decreasing stimulus level. This results in a decrease of $L_1$ being lower than the decrease of $L_2$ (scissor paradigm: $L=0.4L_2 + 39$ dB SPL).
Distortion Product Oto-acoustic Emission (DPOAE) Threshold

Hearing threshold estimation by means of extrapolated DPOAE pressure I/O-function: intersection between L2-axis and linear regression line.
Distortion Product Oto-acoustic Emission (DPOAE) Threshold

DPOAE level I/O-functions plot the DPOAE level $L_{dp}$ as a function of primary-tone level $L_2$ for a selected $f_2$ and thus reflect cochlear amplification at the $f_2$ place. In normal hearing, in response to low-level stimuli, DPOAE level I/O-functions exhibit steep slopes, while at high stimulus levels slopes decrease, thus mirroring the strong amplification at low and decreasing amplification (saturation) at moderate sound levels. However, this is only true when a specific stimulus level setting is used which accounts for the different compression of the primary-tones at the $f_2$ place (scissor paradigm).

DPOAE pressure I/O-functions plot the DPOAE pressure $p_{dp}$ (instead of the DPOAE level $L_{dp}$) as a function of the primary-tone level $L_2$. Due to the logarithmic dependency of the DPOAE level on the primary tone level there is a linear dependency between DPOAE pressure $p_{dp}$ and primary tone level $L_2$. Thus, DPOAE data can easily be fitted by linear regression analysis. The intersection point of the linear regression line with the $L_2$-axis at $p_{dp} = 0$ Pa can then serve as an estimate of DPOAE threshold.
Distortion Product Oto-Acoustic Emission (DPOAE)

Hearing Threshold Estimation using extrapolated DPOAE I/O-functions
Distortion Product Oto-Acoustic Emission (DPOAE)

When converting DPOAE level from dB SPL to dB HL (hearing level), estimated DPOAE thresholds can be plotted in an audiogram form (DPOAE audiogram). DPOAE audiograms can be applied in babies due to Eustachian tube dysfunction and/or amniotic fluid in the tympanic cavity or to confirm a persisting cochlear hearing loss in follow-up diagnostics. In case of mild and moderate hearing loss DPOAE audiograms are an alternative method to behavioural audiometry or auditory brainstem responses (ABR, ASSR). Especially in infants where the conditioned free-field audiogram does not reliably reflect hearing threshold. DPOAE audiograms may assess cochlear hearing loss more precisely than behavioural tests. Moreover, unilateral hearing loss can be detected. DPOAE audiograms are able to quantitatively assess the hearing loss at distinct frequencies in a couple of minutes. Predicting hearing loss at five frequencies by tone burst ABR or ASSR may take half an hour and more. Thus, DPOAE audiograms can serve as a suited tool for bridging the gap between screening and behavioural testing in paediatric audiology.
Distortion Product Oto-Acoustic Emission (DPOAE)

DPOAE- Threshold Estimation → normal hearing

- Full I/O-function-based estimation for right ear
- Hearing threshold estimation based on lowest detected DPOAE (right ear in red)
- Full I/O-function-based estimation for left ear
- No DPOAE could be recorded for this frequency. Hearing threshold is probably above 50 dB (right ear in red)
- Gray symbols if some levels were skipped
Distortion Product Oto-Acoustic Emission (DPOAE)

DPOAE- Threshold estimation $\rightarrow$ cochlear hearing loss

**Graph:**
- **f₂ = 3000 Hz**
  - Full I/O-function-based estimation for right ear
  - Full I/O-function-based estimation for left ear
  - Hearing threshold estimation based on lowest detected DPOAE (right ear in red)
  - Gray symbols if some levels were skipped
  - No DPOAE could be recorded for this frequency. Hearing threshold is probably above 50 dB (right ear in red)

**Table:**
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<th>Frequency (Hz)</th>
<th>Thres</th>
<th>L₂ min</th>
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**Graph:**
- DPOAE Threshold
- FM multi
Distortion Product Oto-Acoustic Emission (DPOAE)

DPOAE- Threshold estimation

6 months old infant

3 months old infant

hereditary hearing loss

discrepancy between behavioral and physiological threshold
Distortion Product Oto-Acoustic Emission (DPOAE)

100 newborns < 2,5 days old

Estimated hearing loss dB HL

1 kHz 2 kHz 4 kHz 8 kHz

Newborn study, see T. Janssen "Otoakustische Emissionen" in: Lehnhardt/Laszig "Praxis der Audiometrie" Thieme 2009 (ISBN 078-3-13-369009-6)
Oto-Acoustic Emission
Clinical application

• Newborn hearing screening and Follow-up
• Pediatric audiology

• Clinical Diagnostics
  à Confirmation of cochlear hearing loss (topological diagnostic, report noise induced hearing loss)

• Simulation und Aggravation
  à Difference between pure-tone threshold and OAE

• Follow up: Sudden Hearing Loss and Ototoxic Medication
OHCs are reported to be impaired by sound overexposure, ototoxic drugs (e.g. therapeutic antibiotics), infections (e.g. meningitis, mumps, materno-fetal infection), and anoxia (e.g. birth trauma), or to be partly missing in genetic hearing loss. OHC impairment results in a loss of sensitivity and frequency selectivity of the hearing organ. OAEs, as a by-product of cochlear non-linear sound amplification, then appear with reduced amplitude or disappear. Since OAEs are a by-product of the non-linear sound amplification process of OHCs in the cochlea they can only serve as a measure for evaluating OHC integrity. Lesions of inner hair cells or retro-cochlear defects (e.g. neural defects, auditory processing disorders) are not detectable by means of OAE. In sound-conductive hearing-loss, both the stimulus and the response amplitude are reduced. OAEs are not present even at a mild hearing-loss. At a cochlear hearing loss exceeding 20-30 dB HL (TEOAE) or 40-50 dB HL (DPOAE) no OAEs are measurable. In these cases, tympanometry, ABR, and ASSR should be performed to determine type and degree of the hearing loss.
If there is a suspicion of a hearing disorder, OAEs should be used first. It is fast and helps to confirm normal middle-ear and cochlear function. This is the case if OAEs are present over a wide frequency range. If OAEs are absent, the presence of a middle-ear or cochlear (OHC) pathology is likely. OAEs then should be followed by tympanometry. If the tympanogram is normal and OAEs are absent, then a cochlear disorder is likely. If the tympanogram is abnormal, a sound-conductive hearing-loss is likely. If there is an indication for a hearing disorder and both the tympanogram and OAEs are normal, ABR/ASSR may reveal if there is a cochlear (inner hair cell) or neural pathology. For example, in auditory neuropathy, where synchronization of neural activity is malfunctioning (either due to inner hair cell synaptic or neural dysfunction), normal OAEs and abnormal ABRs occur.
Oto-Acoustic Emission
Clinical application

Typical clinical applications of OAEs are: hearing screening, follow-up diagnostics after newborn hearing screening, confirmation of cochlear hearing loss (together with tympanometry and ABR), quantitative evaluation of hearing loss and recruitment for providing hearing aid fitting parameters, early detection and monitoring of OHC impairment after noise over-exposure or ototoxic drug administration, topological diagnostics, as well as identifying subjects simulating a hearing loss.