INTERPRETATION OF DISTORTION PRODUCT OTOACOUSTIC EMISSIONS AT HIGHER FREQUENCIES

Makram Zebian[1,2], Johannes Hensel[1], Thomas Fedtke[1], Sven Vollbort[1]

[1] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2] International Graduate School of Metrology, Braunschweig, Germany

Corresponding author: Makram Zebian, Department 1.6 – Sound, Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany, Tel.: +49 531 592 1435, e-mail: makram.zebian@ptb.de

Results reported in this study have been partially presented at the 2011 EFAS conference: Zebian M, Hensel J, Fedtke T. Interpretation of distortion product otoacoustic emissions at higher frequencies. In 10th European Federation of Audiology Societies Congress – EFAS; 2011 June 22–25; Warsaw, Poland.

Abstract

Background: If calibration errors are excluded, the detection of distortion product otoacoustic emissions (DPOAE) reveals a healthy cochlear function. While the commonly used in-the-ear calibration provides an efficient way to adjust the stimulus levels for each test ear, it fails at higher frequencies due to standing waves within the ear canal. Slight unintentional changes in the probe position might lead to calibration errors, affecting the DPOAE results.

Material and methods: In this study, we made use of this "drawback" by deliberately varying the probe position within the ear canal and analysing the DPOAEs for two insertion depths: "intermediate" and "shallow". We performed DPOAE measurements up to a stimulus frequency of 12 kHz in four human test subjects.

Results: Varying the probe insertion depth had a marginal effect (<2 dB) on the DPOAE levels below 4 kHz. However, above this frequency, the probe insertion depth variation led to the absence of detectable DPOAEs at some frequencies, or yielded ambiguous DPOAE levels (> 20 dB) for some subjects above 10 kHz.

Conclusions: We suggest accepting DPOAEs as valid indicators for cochlear function, if detected for at least one insertion depth below 8 kHz. For higher frequencies, DPOAEs are accepted only if the stimulus frequencies are not in the vicinity of any notch frequency in the ear canal transfer function. The deliberate variation of the probe insertion depth within the ear canal provides a simple way to increase the reliability of the DPOAE pass/refer results.

Key words: otoacoustic emissions • in-the-ear calibration • insertion depth • DPOAE probe

Background

The healthy ear responds to an appropriate dual-tone stimulus by producing a distortion product otoacoustic emission (DPOAE) [1]. The stimuli are presented by the two loudspeakers incorporated within the DPOAE probe, and the DPOAEs are measured by the probe microphone. DPOAEs are best detected when both the stimulus frequencies and levels are adjusted according to well-specified criteria [2]. The stimuli are commonly calibrated "in-the-ear" by adjusting their sound pressure level (SPL) via the DPOAE probe microphone [3]. Although this in-the-ear calibration strategy provides an efficient way to adjust the stimulus levels for each test subject, it becomes inaccurate above about 3 kHz due to standing waves within the ear canal [3]. At a standing-wave minimum, the probe microphone may underestimate the eardrum SPL by more than 20 dB [4]. Note that a standing-wave minimum in the earphone-to-ear-canal transfer function is expressed as a spectral notch at the quarter-wavelength frequency f_q. At f_q, the in-the-ear calibration procedure increases the voltage amplitude at the receiver input in order to attain the desired SPL at the probe microphone. Since DPOAEs are sensitive to small changes in the relation between the stimulus levels [2], slight variations of the probe position in the ear canal have so far been considered to be a major drawback [5]. In this study, we make use of this "drawback" by deliberately varying the probe insertion depth within the ear canal and measuring DPOAEs for two insertion depths.

Material and methods

Four otologically normal test subjects TS (2 female and 2 male) aged between 23 and 25 years (mean: 24.3 years) took part in this study.

DPOAE measurements were carried out for stimulus frequencies f_2 in the range from 900 Hz to 12 kHz (f_1=f_2/1.2), using the Etymotic Research ER-10C probe. The stimulus SPLs were adjusted by means of the probe microphone, using the in-the-ear calibration [3] and the stimulus paradigm: $L_1(f_1)$=65 dB and $L_2(f_2)$=55 dB. DPOAEs ($f_{DP}=2f_1-f_2$) were accepted as valid when a signal-to-noise ratio of 6 dB was exceeded.

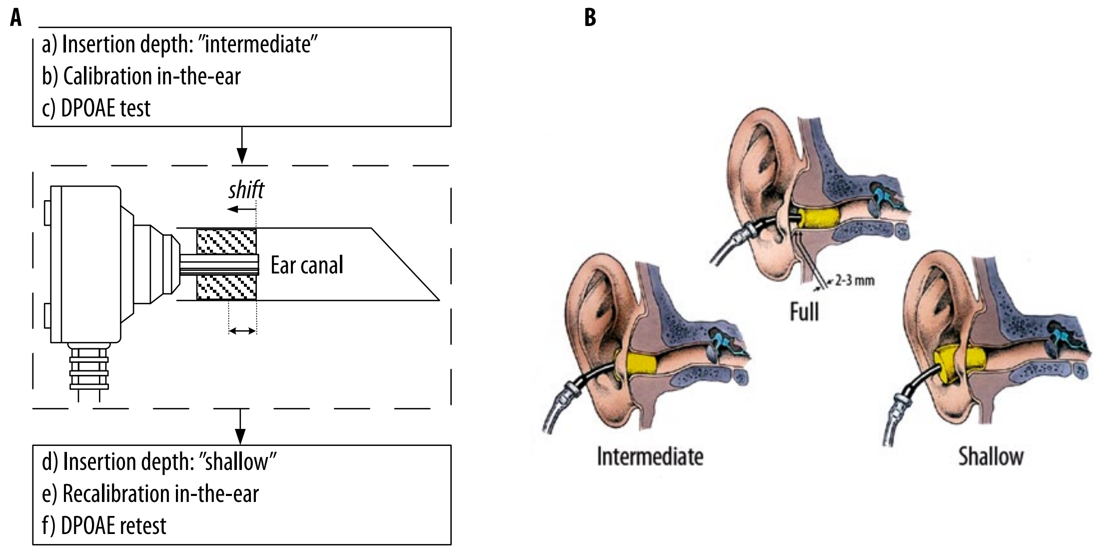

Figure 1. (**A**): Procedure for recording DPOAEs for two probe insertion depths. Step 1: "intermediate" insertion depth (a) of the probe was achieved, followed by the in-the-ear calibration (b) and the measurement of DPOAEs (c). Step 2: Probe was pulled out a distance s = 4 mm (d). Both in-the-ear calibration (e) and DPOAE measurements (f) were repeated. (**B**): Illustration of three eartip insertion depths (Courtesy of Elliot H. Berger, 3M, all rights reserved).

First, the probe was inserted into the ear canal ("intermediate" position, Figure 1). In-the-ear calibration was performed prior to the DPOAE measurements. Then, the probe eartip was pulled out a distance s=4 mm ("shallow" position), and stimulus calibration as well as DPOAE measurements were repeated.

Results and discussion

Figure 2 shows the DPgrams (L_{DP} over f_2) of the four participating test subjects, obtained at both the "intermediate" and the "shallow" insertion depth. A lack of a detected DPOAE at a certain frequency is indicated by the omission of the corresponding data point. The difference in DPOAE levels between the two insertion depths is denoted by asterisks (a-b).

The DPgrams show the expected high inter-subject variability in the DPOAE results [4]. Nevertheless, the difference between the DPgrams obtained for the two insertion depths shows similar characteristics for all subjects. At stimulus frequencies f_2<4 kHz, differences less than 2 dB were observed in the DPOAE levels between the two insertion depths (asterisks). Only subject TS_1 had a difference of 3.3 dB at 2 kHz.

Above 4 kHz, the difference between the recorded DPgrams for the two insertion depths increased, amounting to more than 10 dB at some frequencies (e.g. TS_3 at f_2=9 kHz). Moreover, we observed that for some subjects, DPOAEs were only detected for one configuration: TS_2 had DPOAEs at f_2=11 kHz only for the "intermediate" insertion; TS_4 had DPOAEs at f_2=9 kHz only for the "shallow" insertion. For f_2≤8 kHz, the presence of a DPOAE for one insertion depth and its absence for the other was considered to be an indicator of a stimulus calibration error. This presumably resulted in an unfavourable stimulus paradigm, yielding no detectable emissions in spite of a healthy cochlear function. Above 8 kHz, however, ambiguous DPOAE levels (L_{DP} >20 dB) were observed for TS_3 and TS_4. High DPOAE levels, which are not typical of human ears, may be helpful in suspecting technical distortions. In this regard, we consider, for instance, the DPOAE for TS_4 at f_2=12 kHz ("intermediate") to be a non-physiological distortion (Figure 2). Technical distortions become more likely only above about 8 kHz, where the notches are usually sharper than at lower frequencies [4]. Note that the case of unfavourable stimulus paradigms for both insertion depths cannot be ruled out. This, however, becomes unlikely if the two-step procedure is used, provided that the probe insertion depth has been sufficiently varied.

From these findings, an easy-to-use set of rules was deduced, according to which distortion products measured in human ear canals may be interpreted as physiological or technical distortions:

(i) For f_2≤8 kHz, distortion products measured for at least one insertion depth are interpreted as valid DPOAEs.
(ii) For f_2>8 kHz, distortion products present for any insertion depth are interpreted as valid DPOAEs if f_2 € [f_q–Δ/2, f_q+Δ/2], where f_q is the notch frequency and Δ is a bandwidth in Hz to be determined, and rejected otherwise.

The challenge is to determine Δ, i.e., how "far" the stimulus frequency f_2 should be away from the notch frequency f_q in order for a DPOAE to be accepted. This strongly depends on the length of the occluded ear canal l_{EC}. Varying the probe insertion depth by 4 mm does not shift the notch frequency for every subject by the same amount (Figure 3). A probe variation from 19 to 23 mm shifts f_q by 785 Hz, whereas a variation from 25 to 29 mm results in a 473-Hz shift.

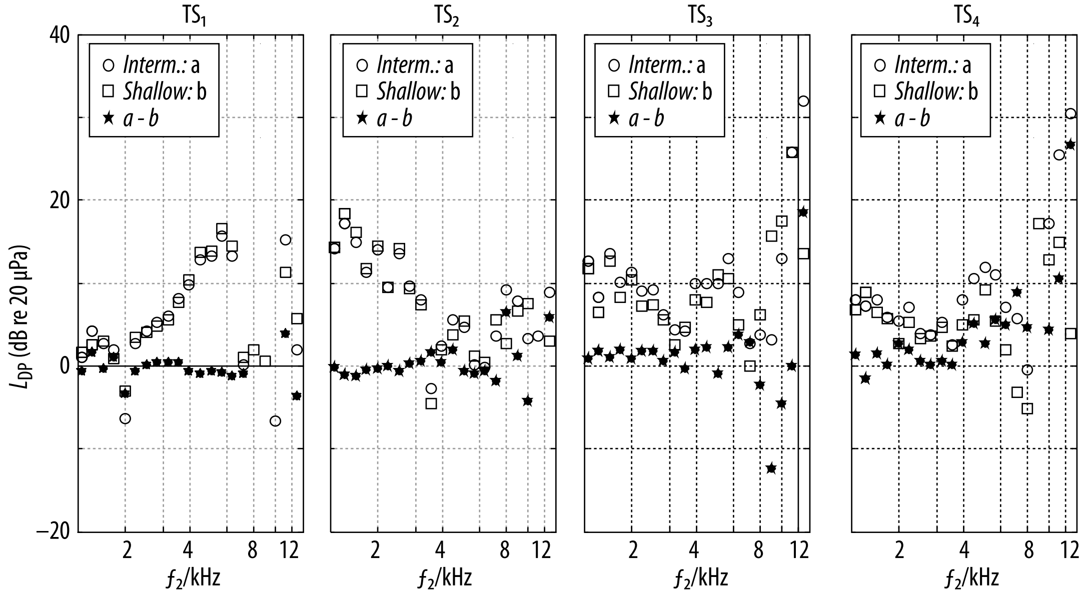

Figure 2. Each panel shows the DPgrams of one test subject TS_i (i = 1 … 4), measured for both the "intermediate" insertion depth (a) and the "shallow" insertion depth (b). Difference: a-b.

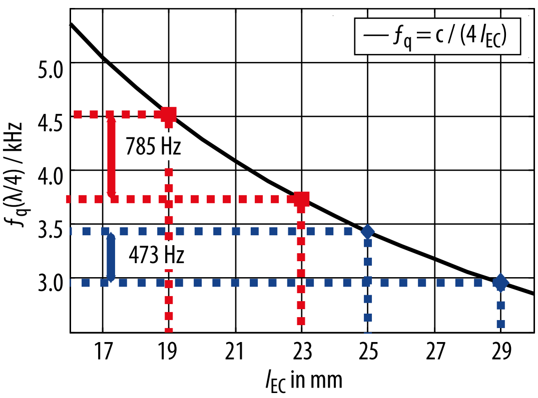

Figure 3. Analytical consideration: Quarter-wave frequency f_q plotted over the occluded ear canal length l_{EC}. Wavelength λ, sound speed c.

Even small and unintentional probe variations caused, for example, by swallowing or jaw movement are known to affect the DPOAE levels. We expect s=4 mm to be sufficient to achieve the required change in the notch frequency and consequently in the DPOAE level. This however, requires further investigations, for instance, analysing the DPOAE levels for three probe insertion depths ("shallow", "intermediate", "full") as illustrated in Figure 1. Furthermore, additional studies to assess the validity of this procedure on hearing-impaired subjects might be beneficial.

Conclusions

The deliberate variation of the probe insertion depth within the ear canal can be beneficial when assessing whether a measured distortion product in the ear canal truly represents a DPOAE generated by the cochlea. Performing two measurements with different insertion depths yields two DPOAE results at each frequency. Using the proposed rules, we consider the detected DPOAEs to be more reliable. The proposed procedure is easy to perform and does not require any further instrumentation or tedious measurements at the eardrum.

Acknowledgements

This study was kindly supported by the Deutsche Forschungsgemeinschaft, "FE 1192/1-1".

References:

1. Kemp DT: Evidence of mechanical nonlinearity and frequency selective wave amplification in the cochlea. Arch Otorhinolaryngol, 1979; 224: 37–45
2. Gaskill S, Brown AM: The behavior of the acoustic disortion product, $2f_1$-f_2, from the human ear and its relation to auditory sensitivity. J Acoust Soc Am, 1990; 88: 821–39
3. Whitehead ML, Stagner BB, Lonsbury-Martin BL, Martin GK: Effects of ear-canal standing waves on measurements of distortion-product otoacoustic emissions. J Acoust Soc Am, 1995; 98: 3200–14
4. Dreisbach LE, Siegel JH: Distortion-product otoacoustic emissions measured at high frequencies in humans. J Acoust Soc Am, 2001; 110: 2456–69
5. Scheperle RA, Neely ST, Kopun JG, Gorga MP: Influence of *in situ*, sound-level calibration on distortion-product otoacoustic emission variability. J Acoust Soc Am, 2008; 124: 288–300