Does over-exposure modify the fine structure of distortion product otoacoustic emissions?

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Over-exposure to high levels of sounds can reduce the hearing sensitivity, which can be measured as a reduction of otoacoustic emission (OAE) levels. In the present study it is investigated, whether an acoustical over-exposure not only causes a reduction of distortion product otoacoustic emission (DPOAE) level, but whether it also causes a modification of its typical fine structure (quasi-periodic variations across frequency). DPOAE fine structures are determined in 16 normal-hearing humans using a high frequency-resolution and primary levels of L1/L2=65/45 dB. DPOAEs are measured both before and after the subjects are exposed to a moderate narrow-band sound exposure, which causes a temporary change in the state of hearing. Immediately after the exposure the DPOAE levels are reduced. This level reduction recovers to the initial levels within 20 minutes. For some subjects, the DPOAE fine structure pattern is more pronounced after the exposure, whereas for other subjects the fine structure pattern is less pronounced or not altered. A shift of DPOAE fine structure in frequency could not be observed for any of the subjects after the exposure. The results do not indicate that there is a clear trend of DPOAE fine structure pattern as a result of the exposure.

1 Introduction

The healthy human ear does not only receive sounds, but is also able to produce low-level sounds. These sounds are called otoacoustic emissions (OAEs) and can be recorded with a sensitive microphone placed in the ear canal. OAEs are assumed to be a by-product of some active process in the inner ear, which is responsible, amongst others, for our good sensitivity to low-level sounds. The presence of OAEs is associated with a good state of hearing; reduced OAE levels can be associated with hearing-loss. Acoustic over-exposures, that have given rise to a temporary reduced sensitivity of the auditory system has also shown to reduce OAE levels.

Different types of OAEs exist, depending on the type of stimulus used. Distortion product otoacoustic emission (DPOAE) is the response of the inner ear to two pure-tone stimuli (the primaries f1 and f2). Because of nonlinear interaction of the two tones in the cochlea, the primaries evoke a series of combination tones, the most prominent being at the frequency 2f1-f2. For the measurement of DPOAE over a particular frequency range the frequencies of the primaries are varied simultaneously while keeping their frequency ratio constant.

In the literature it is suggested that OAEs are a sensitive measure to detect early noise-induced hearing damage and can possibly detect a hearing loss earlier than conventional methods. [1] suggested that the DPOAE fine structure possibly contains more information about the state of hearing than the DPOAE level alone.

The DPOAE fine structure is obtained when the measurement is performed with sufficiently high frequency-resolution. Then the DPOAE shows quasi-periodic variations across frequency, characterized by a periodic structure of maxima and minima with depth of notches of up to 20 dB and a periodicity of 3/32 octaves (e.g. [2]). According to the two-source model (e.g. [3]), DPOAE fine structure is caused by constructive and destructive interference of the distortion component close to f2 and the reflection component at 2f1-f2. The most pronounced fine structure is expected, when the two components have similar amplitudes. If one component has higher amplitude than the other, then a reduction of the higher-amplitude component will result in an increase of fine structure, and a reduction of the lower-amplitude component will result in a decrease of DPOAE fine structure.

In the literature there are some indications that the presence of DPOAE fine structure might be a property of the healthy ear. A reduction of DPOAE fine structure could be observed in a subject with sudden hearing loss [1], after aspirin consumption [4] and after acoustic over-exposure [5]. [1] determined DPOAE fine structures for subjects with mild to moderate cochlear hearing losses with certain shapes of hearing loss. If the primaries were located in a region of normal or near-normal hearing, but DP frequencies were located in a region of raised thresholds, the distortion product 2f1-f2 was still observable, but the DPOAE fine structure disappeared.

In the present study DPOAE fine structures are determined in relatively large number of normal-hearing humans. DPOAE fine structures are obtained both before and after the subjects have been exposed to an intense, narrow-band sound. It is analyzed, whether the fine structure pattern is temporarily altered after the over-exposure.

2 Materials and methods

The hearing of all subjects was screened using pure tone audiometry. DPOAE fine structures were obtained both before and after the subjects were exposed. During the entire test the subjects were seated in a double-walled, sound-isolated audiometry chamber at the Department of Acoustics, Aalborg University. That room complies with the background noise requirements stated in ISO 8253-1:1989.

2.1 Subjects

Eight male and eight female subjects between 20 and 29 years of age (mean age = 23.75), with hearing levels better than 20 dB HL in the frequency range from 250 Hz to 4 kHz, participated in the experiment. One ear of each subject was chosen randomly.

2.2 Measurement equipment

The pure-tone audiometry was performed with a custom-built audiometer, using Sennheiser HDA 200 headphones and the ascending method that complies with the norms for automatic audiometries (ISO 8253-1:1989). The system was calibrated using the B&K type 4153 artificial ear according to IEC 60318-3:1998. Hearing thresholds were measured in 1/2 octaves from 250 Hz to 4 kHz.

2f1-f2 DPOAEs were measured using the ILO96 Research system from Otodynamics. DPOAEs were measured in the frequency range of 903 Hz < f2 < 2295 Hz with f2/ f1=1.22

and fixed primary levels of L1/L2 = 65/45 dB. Prior to each measurement a checkfit procedure is performed, where two broadband click stimuli are alternately delivered by the two output transducers. The checkfit result is stored in an array and used during data collection to balance and normalize the two stimuli levels. All spectrum analyses are performed by the system. An FFT with a frequency resolution of 12.2 Hz is performed. The noise is estimated from the ten Fourier components nearest to but not including the 2f1- f2 frequency. The noise is represented as all levels within two standard deviations of the background noise, i.e. the limits of the 95 % confidence region. All measurements are saved as spreadsheet files and further analyzed.

2.3 DPOAE measurement parameters

The choice of DPOAE frequency range is based on the results from a previous experiment [6]: A narrow-band exposure causes a reduction of DPOAE level in the frequency range covering 0.5–1.5 octaves above the exposure frequency. The frequency range for the present study was chosen in a way that both the primary frequency f2 and the DP frequency 2f1- f2 cover the frequency region of the exposure frequency and 1/2 octave above the exposure frequency.

For the DPOAE measurement, moderate primary levels of L1/L2 =65/45 dB are used (see [6] for details for the choice of primaries). High-level primaries have shown to be less sensitive in detecting noise-induced changes in the DPOAE, whereas low-level primaries result in DPOAE levels with lower SNR.

DPOAE fine structure was measured using the frequency resolution "micro". It presents 17 primary tones within 200 Hz intervals for f2 < 3 kHz. The primary tones are swept discretely through 17 frequencies, starting at the lowest frequency. To cover the full frequency range, seven DPOAEs in different frequency ranges are measured (see also Fig. 1).

The probe was not removed between these measurements. Each pair of primary tones is averaged in the time domain (32 subaverages for the pre-exposure measurements and 16 subaverages for the post-exposure measurements), corresponding to approximately 3 and 1.5 sec measurement time for one pair of frequencies, respectively.

2.4 Exposure

The subject was exposed at one ear only to a 1 kHz tone, lasting for 3 min at an equivalent threshold sound pressure level (ETSPL) of 105.5 dB. The exposure was delivered by Sennheiser HDA 200 headphones at 100 dB above threshold (according to ISO 389-8:2004), corresponding to a free-field related A-weighted equivalent continuous sound pressure level of $L_{FF,H,Aeq}$ =108.0 dB (according to ISO 11904-1:2002). The exposure corresponds to an exposure level normalized to an 8 hour working day of $L_{Ex,8h}$=85.9 dB (according to ISO 1999:1990). The subjects listened shortly to the exposure before the experiment. They were instructed to remove the headphones if they felt any discomfort. None did.

2.5 Post-exposure measurement procedure

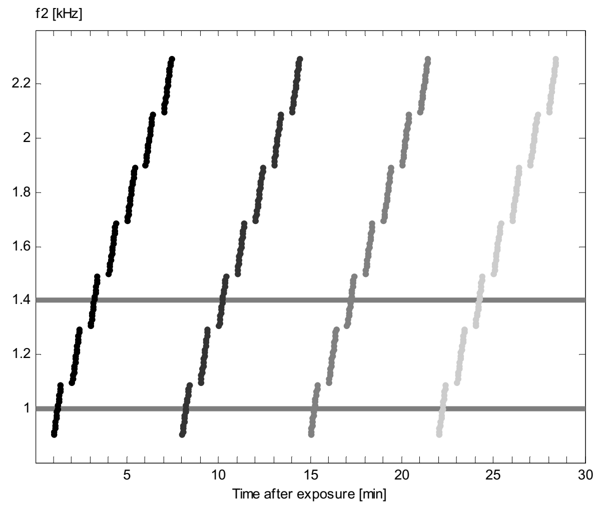


Fig.1 Time frequency distribution of post-exposure DPOAE frequencies as a function of f2. The gray bars indicate the exposure frequency and ½ octave frequency.

Fig. 1 shows the time distribution of DPOAE measurements after the exposure. The first DPOAE measurement is started 1 min after the end of the exposure. DPOAEs are measured every minute. To cover the full measured frequency range, seven DPOAEs were measured with duration of approximately seven minutes, including breakes. After the completion of one DPOAE measurement covering the full frequency range, the measurement was repeated three times, covering an observation time of 29 min.

2.6 Postprocessing of DPOAE

For further analysis, DPOAEs measured in seven different frequency regions are concatenated to one DPOAE measurement covering the full frequency range. The DPOAE fine structure maxima and minima are detected by an automatic classification algorithm, which is in detail described in [7]. The classification algorithm detects fine structure maxima and minima. Ripples are rejected, when their height (level difference between the maximum and the mean of the two minima) is less than 3 dB and when ripple maxima are less than 3 dB above the noise floor.

3 Results

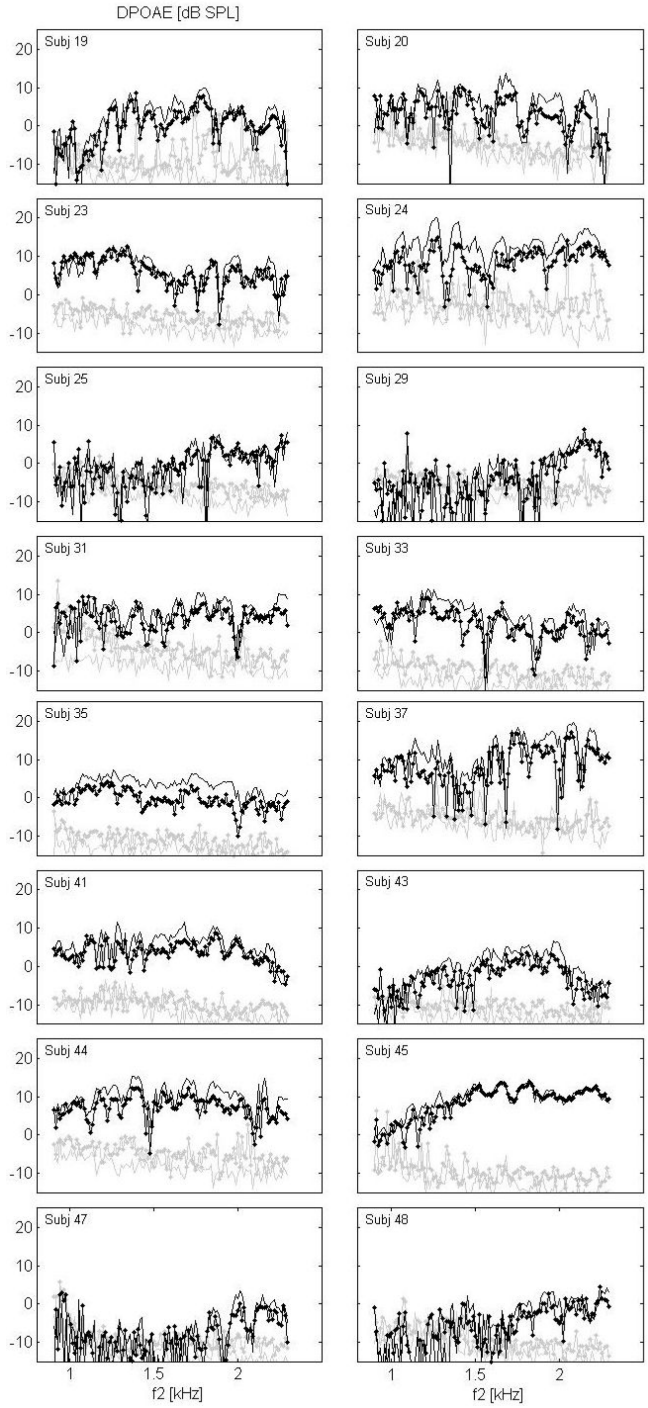


Fig.2 Individual pre-exposure DPOAE fine structures (thin, black line), postexposure (1–8 min) DPOAE fine structures (marked, black line), pre-exposure noise floors (gray line), and postexposure noise floors (marked, gray line).

The DPOAE fine structures of all individual subjects are illustrated in Fig. 2. The measurements obtained before and the first measurements after the exposure are illustrated. In addition the noise floors of these two measurements are illustrated.

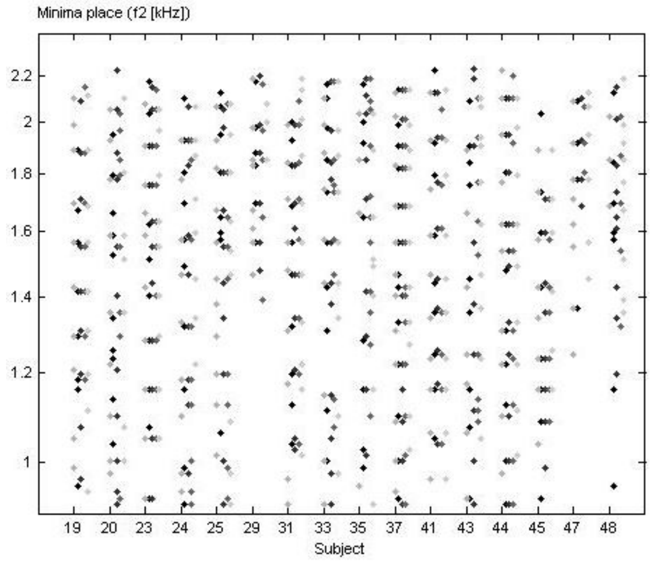
The high-resolution DPOAE measurements show a periodic pattern in frequency, known as DPOAE fine structure. For some subjects (e.g. subjects 20, 24, and 37), the DPOAE fine structure has a pronounced periodic pattern, while for other subjects (e.g. subjects 25, 29, 35, 43, and 45) this pattern is less pronounced. Subjects 25, 29, 47 and 48 have low-level DPOAEs, especially in the low-frequency range. For these subjects variations in level are presumably due to measurement uncertainties close to/ below the noise floor and not due to fine structures.

When looking at the effects of over-exposure on the DPOAE, then DPOAE levels are generally decreased after the over-exposure. There are some differences in the amount of DPOAE shift between individuals. Little DPOAE shifts can be seen for subjects with low-level DPOAEs (e.g. subjects 29, 47 and 48). The data of the present study show that the DPOAE normalizes to the initial values within 20 min after exposure (data at later recovery times are not shown in the figure).

The primary purpose of this experiment was to investigate, whether the over-exposure causes a systematic change in the periodic pattern of DPOAE fine structure. For some subjects (e.g. subjects 23, 24, 31 in the mid frequency range, 33, and 37) the levels at fine structure minima are reduced more than the levels of fine structure maxima and in this way result in a more pronounced fine structure. The DPOAE levels at minima are often below the noise floor after the exposure. For other subjects (e.g. subjects 19, 20, 31 at the higher frequency range, 43, and 44) the fine structure is less pronounced after the exposure.

Since both flattened and more pronounced fine structures could be observed for individuals after the exposure, it can be concluded that there is no clear trend in fine structure characteristics as a result of the exposure. The results indicate that DPOAE fine structures and their modifications after sound exposure are highly individual. The results do not support the idea that an unequivocal relation exists between the fine structure characteristics and the state of hearing.

In order to study, whether the DPOAE fine structure is systematically shifted in frequency as a result of the exposure, the frequencies of ripple maxima and minima are plotted as a function of time for each individual (Fig. 3). Most ripple maxima and minima are detected at the highest frequencies, where the best SNR is achieved. The frequencies of maxima and minima for individuals are either constant over time, or there is a shift towards higher frequencies in time or a shift towards lower frequencies in time. No clear trend can be seen for a maxima or minima shift in frequency and a recovery after exposure. Small variations are presumably caused by measurement uncertainties. The data do not support the idea that the ripple pattern of DPOAE is shifted in frequency after the exposure, as it was suggested by [5].



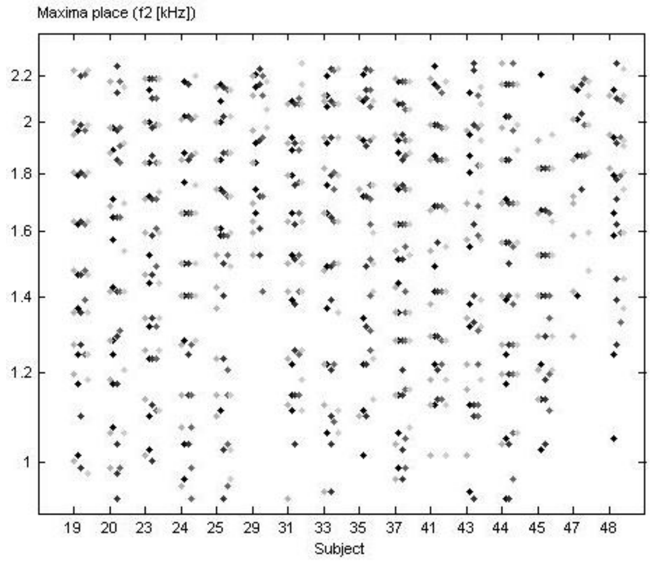


Fig.3 DPOAE fine structure maxima (top panel) and minima (bottom panel) for individual subjects as a function of time (before exposure, 1-7 min post-exposure, 8-14 min post-exposure, 15-21 min post-exposure, 22-28 min post-exposure). For gray-scale legend see Fig. 1.

4 Discussion

The exposure in the present study was a narrow-band exposure, which is expected to affect hair cells in a narrow region of the basilar membrane. According to the two-source model, the DPOAE fine structure is modified, if only one DPOAE component, i.e. either the f2 or the 2f1-f2 component, is affected. According to this theory, one might expect a systematic modification of fine structure after an equal narrow-band exposure, if both components have similar relations to each other for all subjects. Since no clear trend (either increase or decrease of fine structures) are observed in the present study, the results indicate that the relative component contributions of the pre-exposure DPOAEs might differ from subject to subject.

In the present study the data of DPOAE fine structure experiment are shown as raw data, and conclusions are drawn by visually inspecting the data. By determining frequency positions and levels at fine structure maxima and minima, the fine structure pattern can be described by the parameters ripple spacing, ripple height, and ripple prevalence, as suggested by [7]. Whether the fine structure changes systematically, e.g. flattens or becomes more pronounced after the exposure, can be determined from an analysis of ripple heights at each determination time. This analysis is, however, not trivial in the present case for two reasons: (1) The calculation of ripple parameters depends on the noise floor of the system. Since different measurement average times were used for the DPOAE fine structures obtained before and after the exposure, the noise floor differs systematically between these two measures. Additionally, an increase of noise floor with time during post-exposure has been observed in both experiments. (2) The measurement time of the DPOAE fine structure in the present study lasts seven min and is rather long. The data were always collected in a sweep starting at the lowest frequency and ending at the highest frequency; therefore, the first effects of the exposure will always be measured for the lower frequencies, while the higher frequencies would always be measured at later recovery times.

5 Conclusion

16 human subjects were exposed to a narrow-band high-level sound, which caused a temporary change in their state of hearing. This temporary change could be monitored as a DPOAE level reduction. The pattern of DPOAE fine structure was modified for individual subjects as a result of the exposure, but no clear trend of DPOAE fine structure pattern could be observed. The exposure did not cause a frequency shift of DPOAE fine structure. The results do not support the idea that the DPOAE fine structure contains more information about the state of hearing than the DPOAE level.

Acknowledgments

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