Objective assessment of auditory function is an important topic in research and clinical practice. Particularly, assessment of the compressive nonlinearity provides useful information about the inner ear. One way to assess auditory processing is the measurement of the neural response elicited by acoustic stimulation via electroencephalography (EEG). Specifically, auditory-steady state responses (ASSR) receive increasing attention due to their ease of measurement and reproducibility. ASSRs have recently been used to estimate the state of the compressive nonlinearity in the peripheral auditory system. Since it is commonly assumed, that outer hair cells in the inner ear play an important role in the compressive nonlinearity, is it desirable to selectively obtain information about the inner ear, rather than the system as a whole. The common method to objectively measure inner ear activity is the measurement of distortion-product otoacoustic emissions (DPOAEs) via acoustical signals in the ear canal. The nonlinear nature of generation of the DPOAE however, complicates the interpretation of the results, especially on an individual basis. In the current study, the signal in the ear canal, present during ASSR measurements is utilized to extract sinusoidally-amplitude modulated OAEs (SAMOAEs). The hypothesis is, that the stimulus used to evoke ASSRs will cause acoustic energy to be reflected back from the inner ear into the ear canal, where it can be picked up as an OAE. This signal can provide information about a) the state of cochlear processing, and b) the contribution of cochlear compression to the compression obtained by ASSRs. Results indicate, that SAMOAEs can be extracted while measuring ASSRs using sinusoidally-amplitude modulated tones, with characteristics similar to those of stimulus-frequency otoacoustic emissions, SFOAE. A robust extraction and evaluation of SAMOAE in connection with ASSR provides additional information about the state of the peripheral auditory system without the need of additional measurement time.

1. Introduction

The compressive nonlinearity of the auditory systems is a key property to enable listeners to perceive sounds of very low intensity and at the same time to be able to perceive a large dynamic range of input intensities in the range of 120 dB. This compressive nonlinearity is very vulnerable to overstimulation, and is often reduced in listeners with a sensory-neural hearing loss. These listeners have subsequently problems with the understanding of speech in noisy environments, and have a smaller dynamic range in terms of loudness perception. In audiological practice, the estimate of the compressive nonlinearity is a promising tool to characterize the health of the auditory system, and to gain some information about the processing of sounds above threshold in quiet. In non-human mammals,
this compressive nonlinearity can be measured using a variety of invasive methods, where the cochlea is excited by an external stimulus, and the vibration of the basilar membrane is measured \[1\]. Non-invasive measurement of the compressive nonlinearity in the inner ear of human listeners is however challenging due to the inaccessibility of the cochlea. A variety of methods has been proposed to estimate this property of the inner ear using psychoacoustics \[2\] or oto-acoustic emissions. Psychoacoustical methods rely on the assumption, that the estimated compression originates predominantly from cochlear processing, even though psychoacoustical methods always evaluate the system as a whole. In addition are these methods very time consuming and hence not applicable for clinical practice. One method proposed to estimate cochlear compression is the derivative of the DPOAE growth function \[3\]. These measurements show however large variability across subjects, and only provide reliable results when averaged over a larger population of subjects. In addition does the generation of DPOAE include a nonlinear mechanism which in turn might make the interpretation of the results more complicated.

It was recently suggested \[4\], that peripheral compression can be measured using auditory-steady-state responses (ASSR). This type of auditory-evoked responses is thought to reflect the modulation of the firing rate of a neuron population, and is used in clinical applications for the estimation of hearing thresholds. For this purpose, the ASSR amplitude was measured as a function of stimulus intensity. The ASSR magnitude as a function of input intensity showed a compressive growth at low- and mid frequencies. The compression rate extracted from this data is similar to what is known from invasive measurements of basilar membrane motion and psychoacoustical data \[2\]. The ASSR is however a neural measure, presumably stemming from neural activity at either midbrain or cortical regions, depending on the modulation frequency. Hence, the results reflect compressive processing of all stages from the cochlear up to the generation site of the ASSR, and not necessarily exclusively cochlear compression.

The goal of the present study was to investigate, if the signal in the ear canal during acoustic stimulation to evoke ASSR responses can be used to obtain information about cochlear compression. The processed signals are a by-product of the stimulation procedure for ASSR and hence require no additional measurement time. Such a measure would help to separate cochlear from retro-cochlear contributions of compressive level processing in the hearing system, and might be a valuable tool for audiological practice in order to quantify the state of the system at above-threshold levels.

2. Materials and Methods

2.1 Subjects

Seven listeners with audiologically normal audiogram were included in the study. None of the listeners reported any history of hearing damage.

2.2 OAE recordings

Otoacoustic emissions were measured in the ear canal of human listeners using a microphone-probe assembly (ER10-B+, ETYMOTIC RESEARCH). The stimuli were sinusoidally-amplitude modulated tones (SAM) with a modulation depth of 85% and centre frequencies of 498 Hz, 1002 Hz, 2005 Hz and 4011 Hz modulated with frequencies of 81 Hz, 87 Hz, 93 Hz and 98 Hz, respectively. The stimuli were presented at levels between 10 dB SPL and 70 dB SPL in steps of 6 dB. The 6 dB increments for a given level were achieved by presenting the same stimulus presented via both channels of the probe assembly, compared to using only a single channel. To facilitate the comparison with stimulus-frequency OAEs (SFOAEs), SFOAEs were measured in the same listeners by replacing the SAM tones by pure tones.

The signals were generated in MATLAB, D/A converted (RME FireFace UCX), attenuated by 15 dB (TDT HB7) and presented using ER-2 (ETYMOTIC RESEARCH) insert-ear headphones cou-
pled to a ER-10B+ probe. The signal from the probe microphone was pre-amplified (+20 dB), band-
pass filtered (0.3-6 kHz) and A/D converted (RME FireFace UCX).

The stimuli were presented at levels between 10 and 70 dB SPL with increments of 6 dB. Each
condition was presented individually (single-component stimulation) and in combination (multi-frequency
stimulation).

2.3 OAE analysis

The sinusoidally-amplitude modulated OAEs (SAMOAEs) were extracted from the recorded ear
canal signal using a compression paradigm as used to extract stimulus-frequency otoacoustic emis-
sions [5]. The ear canal signals during stimulation with two Levels $L_1$ and $L_2$ were recorded. The
amplitude of the signal at level $L_1$ was linearly scaled up to the level $L_2$ and subtracted from the
recording at level $L_2$. The residual $r(t)$ was taken as the corresponding SAMOAE.

$$r(t) = p_2(t) - p_1(t) \cdot 10^{(L_2-L_1)/20}$$

3. Results and discussion

In the first experiment, SAMOAEs were measured for each of the stimulus components separately.
In the second experiment, all stimulus components were presented simultaneously.

3.1 Single-component stimulation

Figure 1 shows results of a typical subject. The SFOAE and the SAMOAEs show similar trends
as a function of the stimulus level. The curves show a slightly compressive behaviour for levels up to
40 dB SPL, before growing linearly. The carrier and the side bands show a similar growth. At levels
above 50 dB SPL, the growth continues rather linearly, and consistent across listeners and frequencies.

The similarity between the SFOAE and the SAMOAE support the applicability of the compression
method to SAM stimuli. The smooth growth and behaviour of the carrier component and the side
bands indicate the absence of any strong nonlinear interaction between each other. The notches found
in the growth function might arise due to interference effects of the stimulus and the reflected OAE,
leading to destructive interference and hence a reduced amplitude.

The linear and consistent growth at levels above 50 dB SPL indicates a systematic influence of the
setup on the results. The solid grey lines in figure 1 shows OAEs derived in the absence of a cochlear,
measured in an ear canal coupler. The coincidence of the data above 50 dB SPL indicates, that at these
levels the measurement is dominated by the coupler response rather than by an otoacoustic emission.
At levels below 50 dB however, the measured response is clearly of cochlear origin and shows the
possibility to extract SAMOAEs

3.2 Multi-component stimulation

In clinical practice, ASSRs are often measured simultaneously for multiple centre frequencies. To
investigate the applicability of the current approach to such a multi-frequency stimulation, OAEs were
measured for all components simultaneously. The results are shown in fig. 3. The similarity of the
results for low-level stimuli between single- and multicomponent stimulation indicates, SAMOAEs
can be extracted simultaneously at multiple frequencies. Deviations were mainly found at levels
above 50 dB SPL where the nonlinearity of the coupler dominates the response.
Figure 1: Results for a representative listener. Panel A shows the measured SFOAE at 2 kHz, panels B-D show the measured SAMOAEs for centre frequencies of 2005 Hz, 498 Hz, 1002 Hz and 4011 Hz, respectively. The thick line indicates the frequency component of the carrier, and the two thin lines the upper and lower side band. The dashed lines indicate the estimated noise floor.

Figure 2: Same as Fig. 1 but for another listener. For this listener, some dips were found in the OAEs around 1 kHz and 4 kHz.

4. Conclusions

The data of the current study shows, that OAEs can be extracted from the ear canal signal recorded during the measurement of ASSR evoked by SAM tones. The nonlinearities in the transducer con-
founded the results at levels above 50 dB SPL such that no final conclusion can be drawn about the applicability of the method to estimate cochlear compression. The results at levels up to 50 dB SPL are however encouraging to further investigate this method by reducing the transducer distortion in order to obtain information about SAMOAEs at higher levels. For audiological applications, this method might be a promising source of additional information about the state of the hearing system without requiring extra time during audiological screening.

REFERENCES


