Simultaneous measurement of auditory-steady-state responses and otoacoustic emissions to estimate peripheral compression

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Assessment of the compressive nonlinearity in the hearing system provides useful information about the inner ear. Auditory-steady state responses (ASSR) 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, it is desirable to selectively obtain information about the inner ear. In the current study, the signal in the ear canal present during ASSR measurements is utilized to extract sinusoidally-amplitude modulated otoacoustic emissions (SAMOAEs). It is hypothesized 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 otoacoustic emission (OAE) and provide information about cochlear processing. Results indicate that SAMOAEs can be extracted while measuring ASSRs using sinusoidally-amplitude modulated tones. However, comparison of simulations using a transmission model and the data show that the SAMOAE measured above 50 dB SPL are strongly influenced by the system distortion. A robust extraction and evaluation of SAMOAE in connection with ASSR may be possible by a proposed method to minimize the distortion. The ability to evaluate SAMOAE over a large input level range during ASSR measurement will provide information about the state of the peripheral auditory system without the need of additional measurement time.

INTRODUCTION

The healthy auditory system exhibits a nonlinear behavior related to the frequency selectivity and the sensitivity to soft sounds. In psychoacoustical experiments, it is commonly assumed that outer hair cells are the main contributor to the compressive nonlinearity. The growth of neural responses suggests however, that peripheral compression also occurs at retro-cochlear stages (Cooper and Yates, 1994). Since psychoacoustical experiments such as growth of masking (Plack and Oxenham, 1998) and temporal masking curves (Nelson and Schroder, 2004) allow the evaluation of the system as a whole, they should be interpreted as the total compression of the system rather than exclusively of the inner ear. In addition, comparison across measures is

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difficult since different stimuli (pure tones, band-limited noises, etc.) are used in the different techniques.

Physiological non invasive measurements using sinusoidally amplitude modulated (SAM) tones revealed that the basilar membrane grows compressively as a function of input level for these stimuli (Rhode and Recio, 2001). If peripheral compression is, at least partially, due to cochlear compression, the amplitude of auditory steady state responses (ASSR) measured using SAM tones as a function of level, can be assumed to reflect the compressive growth of the cochlear nonlinearity. Recently, Encina Llamas *et al.* (2014) showed compressive input-output functions by measuring ASSR evoked by SAM tones as a function of stimulus level. In the same study, distortion product otoacoustic emissions (DPOAE) level growth functions were measured for the same listeners, showing smaller compression than the ASSR data. However, the nonlinear nature of generation of the DPOAE complicates a direct comparison of the results, especially on an individual basis.

In order to avoid this difficulty, evaluation of OAEs at the stimulus frequencies might help to facilitate the interpretation. Such stimulus frequency otoacoustic emissions (SFOAE) have been measured as a function of the presentation level (Schairer *et al.*, 2003). Their data also show a compressive growth as a function of stimulus level. The ability to extract information about cochlear compression from SAM tones rather than from pure tones will enable the simultaneous measurement of SAMOAE and ASSR, and hence provide two sources of information about auditory processing in the inner ear without the need of additional measurement time.

In order to estimate OAE, the stimulus sound pressure P_0^x at the ear canal needs to be estimated. In SFOAEs, this is commonly done using either a suppression or compression paradigm (Kalluri and Shera, 2007). In the suppression paradigm, the OAE is extracted by comparison of the ear canal sound pressure in the presence and the absence of a suppressor tone, aimed to suppress the basilar membrane vibration at the cochlear partition corresponding to the stimulus frequency. In the compression paradigm, the OAE is extracted by scaling and subtraction of two intervals at different stimulus levels, assuming compressive growth of the OAE and linear scaling of the stimulus pressure in the ear canal. Since SAM tones are similar to pure tones in terms of bandwidth, this technique might also be applicable to SAM tkones. Nevertheless, ASSR recordings require long steady state intervals in order to capture the envelope-following responses.

The current study presents data on SAMOAEs measured following a method that allows simultaneous ASSR and OAE recordings and presents an approach to improve the signal-to-noise ratio of the SAMOAEs by reduction of transducer artefacts.

METHOD

Otoacoustic emissions evoked by SAM tones were measured at four different carrier frequencies. The modulation frequencies were chosen to match the stimuli used in

Encina Llamas *et al.* (2014). To verify the applicability of the compression paradigm for SAM tones, SFOAE at a frequency of 2 kHz were measured. To estimate the influence of system distortion, the measurements were repeated using an ear simulator (coupler B&K type 4157).

Measurement setup

Stimuli were generated by a custom software written in MATLAB, using a 24-bit soundcard (RME Fireface 800) with sample rate 48 kHz. After pre-amplification (HB7) the stimuli were transmitted to an Etymotic ER-10B+ probe. The recording signal was obtained by the probe microphone with +20 dB amplification, and band-pass filtered using an analogue bandpass filter between 0.3 and 6 kHz. Calibration was performed using the ear simulator mentioned above for each frequency and stored in the software.

Subjects

Five subjects with normal hearing thresholds (age: 24-31 years) were recruited for the experiment. Subjects were seated in an armchair in a double-wall isolated booth. Subjects were allowed to sleep or read. The time of the whole protocol was limited to three hours including breaks between conditions. All experiments were approved by the Science-Ethics Committee for the Capital Region of Denmark (reference H-3-2013-004).

Stimulus conditions SAMOAE

Stimuli were presented in separated pairs with a level difference of 6 dB. For each set of conditions stimulus levels, the lower level was set from 10 to 70 dB SPL in steps of 10 dB. In the second sequence, the level increment of 6 dB was obtained by playing the same stimulus phase-matched to both channels of the probe (Fig. 1). Recordings were made for four different center frequencies: $f_c = 1002$ Hz modulated by $f_m = 87$ Hz, $f_c = 2005$ Hz modulated by $f_m = 93$ Hz, $f_c = 4011$ Hz modulated by $f_m = 98$ Hz, and $f_c = 498$ Hz modulated by $f_m = 81$ Hz. The modulation depth was $m = 0.85$ for all conditions.

Stimulus conditions SFOAE

A three-interval paradigm using suppression and compression was included in the protocol (see Kalluri and Shera, 2007). The three intervals consisted of a 7-second sequence with a 0.25-s ramp-in and out at the beginning and end of each interval. The first interval contained the stimulus, the second interval the suppressor, with a fixed level of $L_s = 65$ dB and a ratio between the frequencies of the suppressor and the probe $f_s/f_p = 0.88$. The third interval contained the stimulus with a level increment of 6 dB by sending the signals to both channels.

In order to reduce the influence of the small differences between the transducers, a compensation method was included. The transfer function of both channels (H_1

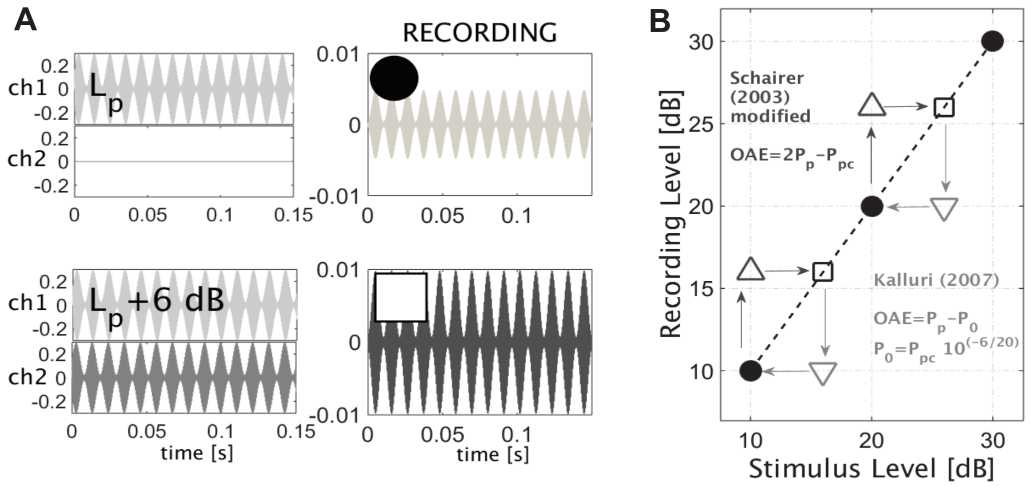

Fig. 1: Compression paradigm to extract SAMOAEs (adapted from Schairer *et al.*, 2003). SAMOAE recording consisted of steady state measurements: P_p(circle) by 1 transducer and P_{pc}(square). A) SAMOAE stimuli and and recording signals. In the first long interval, P_p was played to channel one. The second interval contained the same signal in both channels P_{pc}. In the recoding, the stimulus level L_p had a difference of 6 dB between the two interval due to acoustic constructive interference. B) Measurements were performed at L_p and $L_p + 6$ dB in 10-dB steps. Then by using either up or down scaling, the complex difference between the two measurements provides the SAMOAE. Two recorded intervals are needed for each SAMOAE point.

and H_2) and the transfer function between both channels (H_{12}) were recorded in the coupler by using random white noise at each of the studied conditions. An algorithm for correcting the frequency and phase differences between the two channels was implemented as follows:

$$OAE = P_p + P_p H_{12} - P_{pc}, \quad \text{(Eq. 1)}$$

where P_p is the ear canal sound pressure measured at the probe and P_{pc} is the ear canal sound pressure in the compression interval recording.

Analysis

Measurements were divided in 1-second epochs. The first and last epoch were discarded. Epochs were also treated by a custom artifact rejection algorithm that removed the epochs with clear artifacts. After time averaging, the OAEs were extracted by using the suppression and compression method. The level of the three spectral components (carrier and sidebands) in dB SPL was obtained from the frequency domain signal with a resolution of 1 bin/Hz.

RESULTS

Average results of the 5 subjects are shown in Fig. 2. The data are clearly separated from the noise level for all conditions. At levels above 50 dB, OAE levels were similar to the coupler residuals.

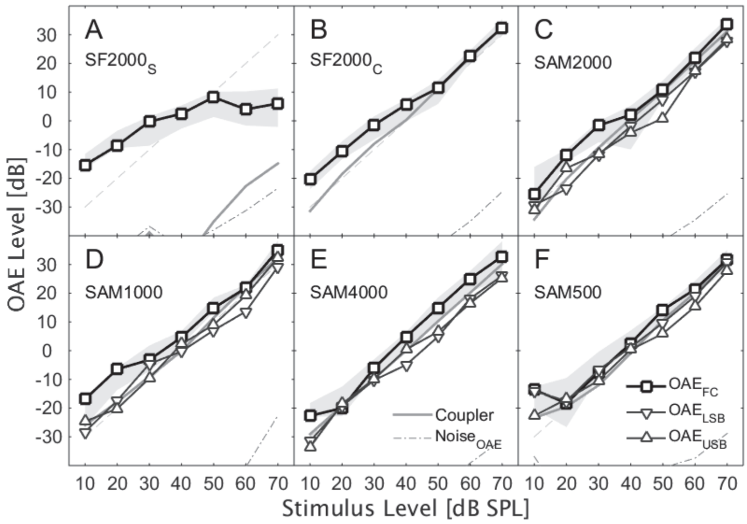

Fig. 2: Median results. SFOAEs measured by suppression (A) and compression (B). Panels C-F show SAMOAEs for centre frequencies of 2005 Hz, 1002 Hz, 4011 Hz, and 498 Hz. The thick grey line indicates coupler residual. The coupler residual was found to grow linearly in all compression conditions. The shadowed area shows the inter-quartile interval.

Figure 3 shows the results of subject APJ after applying the channel difference compensation. Coupler residuals appear closer to the noise than to the measured OAE. However, a considerable influence of the transducer distortion remains above 55 dB SPL.

DISCUSSION

At levels below 50 dB, the measured OAEs could be clearly separated from the transducer once the channel difference is compensated. This indicates, that OAEs evoked by SAM tones can be extracted using paradigms developed for SFOAEs. At levels above 50 dB, the transducer distortion seemed to dominate the OAEs. The distortion was likely due to either the use of acoustic summation in the compression interval and small differences between the transducers or the intermodulation distortion of each loudspeaker, violating the linearity assumption.

In order to investigate the contribution of the distortions to the OAEs at high stimulus levels, simulations were performed with a non-linear transmission model (Epp *et al.*,

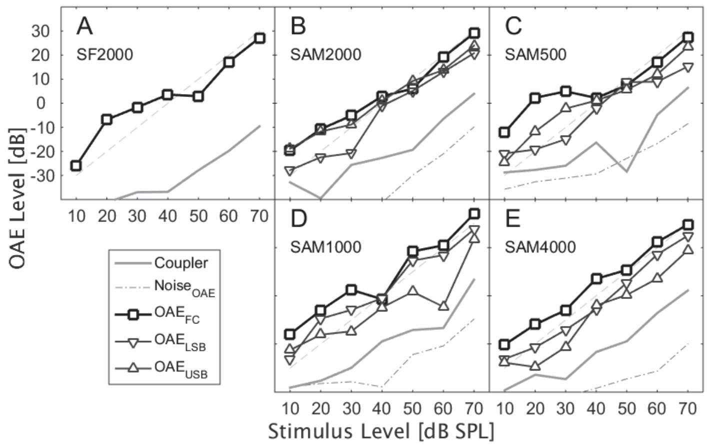

Fig. 3: Results for subject APJ, SFOAEs measured by compression (A). Panels B-E show SAM-OAEs for centre frequencies of 2005 Hz, 498 Hz, 1002 Hz, and 4011 Hz. The method involves a compensation of the difference between transducers (H_{12}).

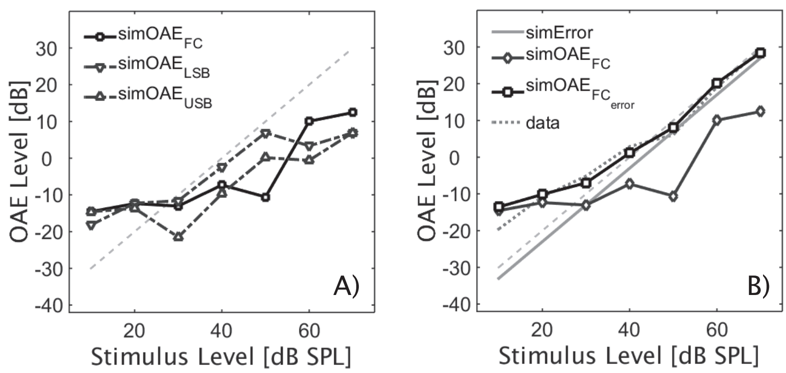

Fig. 4: A) Simulation results for SAMOAE at 2 kHz. B) Simulation results including the coupler residual as an error source.

2010) capable of generating SFOAEs. OAEs were simulated using the same procedure as in the experiment for the condition SAM at 2 kHz. To compare experimental and simulated data, a linearly growing transducer distortion was assumed and added to the simulated OAEs. Simulation results (Fig. 4) suggest that the distortion of the transducer not only affects the results above 55 dB SPL but also leads to an obscure result at lower levels.

One way to reduce the influence of coupler distortion is to make only use of one transducer. In a pilot experiment the compression stimuli was delivered into the ear by the same channel as the probe but a level ($L_{com} = L_p + 10$ dB). As a result, the OAEs were clearly separated from the coupler residuals below 30 dB SPL. At higher levels the nonlinearlity of the transducer still dominated the response (Fig.5A).

Another method to reduce the influence of coupler distortion might be the application of a 3-interval 2-evoked (2E OAE) OAE paradigm used in Schairer *et al.* (2003) where the influence of the transducer's distortion for SFOAEs was only found significant above 60 dB. The 2E OAE method involves two measurements of the P_p, one with each of the transducers, and the P_{pc} by using both transducers at the same time. If the same probe is to be used, the generation the stimuli in the ASSR measurement may be modified in order to involve a sequence of these three measurements (Fig.5B).

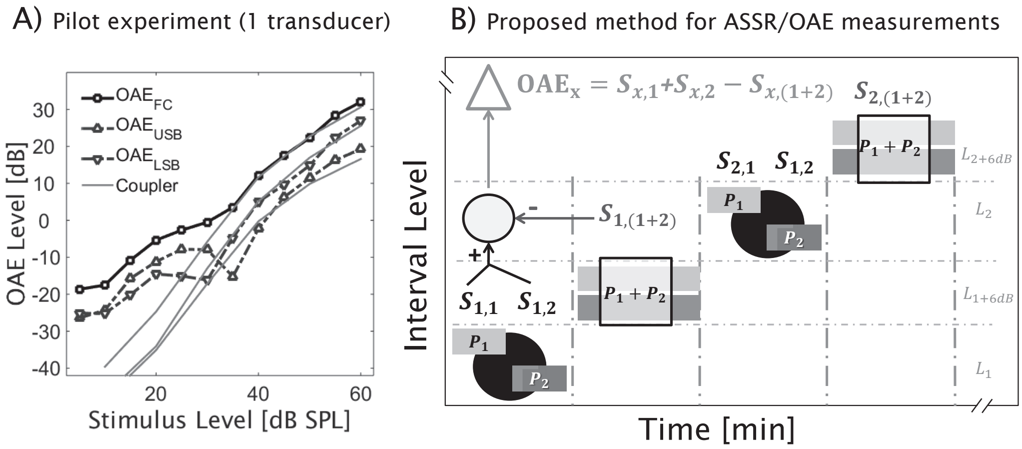

Fig. 5: A) SAMOAE for the 2-kHz condition measured by using only one transducer and $L_{com} = L_p + 10$ dB. B) Proposed solution: the three intervals needed for the OAE measurement by using the 2E OAE (Schairer *et al.*, 2003) are included in the ASSR procedure. P_x denotes the probe and $S_{y,x}$ the recording where *x* is the channel and *y* the measurement point.

CONCLUSION

Extraction of OAE using SAM tones is possible in consecutive steady state intervals. However, due to the transducers' distortion, results were obscured at levels above 50 dB SPL. A proposed alternative method may minimize this problem. If the influence of the transducer distortion on the measured OAEs can be reduced, the simultaneous measurement of ASSR and SAMOAE might provide a more detailed insight into the mechanisms contributing to peripherial compression.

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