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Research paper

Contralateral electrically-evoked suppression of transient evoked otoacoustic emissions in single-sided deaf patients

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1. Introduction

Within the last decade, cochlear implantation of individuals with single-sided deafness (SSD) has become an established routine clinical treatment option in Germany (Arndt et al., 2011a, 2011b; Jacob et al., 2011). Two of the main therapeutic goals for cochlear implantation in cases of SSD are to optimize directional hearing and the rehabilitation of speech understanding in both quiet and noise. For cochlear-implant (CI)-SSD candidates, the psychological strain of single-sided deafness results primarily from poor speech understanding in spatially distributed competing noise and limitations in directional hearing (Schmiedl, 2011). Some CI-SSD recipients demonstrate good progress in overcoming the above-mentioned restrictions of single-sided deafness (Arndt et al., 2011c). It is reasonable to assume that in those successfully implanted recipients, the binaural processing by the auditory system contributes considerably to the positive outcome in spatial audiometric settings. However, the outcome, characterized by speech audiometry, shows great variability in this recipient group (Arndt et al., 2011c) as well as in the established CI-recipient population (Blamey et al., 2013; Holden et al., 2013).

Amongst other contributing factors, an intact efferent pathway is likely to contribute to successful cochlear implantation in single-sided deaf subjects beyond overcoming head shadow effects (Wesarg et al., 2015). It is known that subjective assessment of the efferent mechanisms in the auditory pathway may provide additional information regarding binaural processing. Experimental studies simulating CI monaural and binaural electrical stimulation (Lopez-Poveda et al., 2016a, 2016b) support the contribution of the contralateral medial olivocochlear reflex in improving binaural hearing in noise but, to date, the effect has not been shown in active CI users. It may already be available in the binaural processing of CI recipients. Indeed, if there is an effect on bilateral CI recipients, then an effect on CI-SSD patients, who regain binaural access to sound, is to be expected. The measurement of otoacoustic emissions (OAE) may provide an objective, easy-to-apply and non-invasive method to measure and characterize one aspect of efferent mechanisms.

The recording of otoacoustic emissions is a well-established tool for the objective assessment of OHC function. Following early investigations of OHC function via OAE recordings (Kemp, 1978), ongoing use of OAE testing led to a broadening of recording techniques and their resultant diagnostic interpretations (Janssen et al., 2006; Robinette and Glattke, 2002). One aspect of the developments is related to efferent inhibition, which can be accessed via the recording of OAE during contralateral acoustical (Collet et al., 1990) and electrical (Popelár et al., 1999) stimulation, the latter showing that the acoustical and electrical effects are similar. The efferent mechanisms may be an important part of the binaural processing in normal-hearing subjects (Hood et al., 1996; Hood, 2002), even though deficits in these mechanisms might be compensated by acquired strategies (May et al., 2004; Scharf et al., 1997). With respect to efferent mechanisms, the innervation of the outer hair cells (OHC) by olivocochlear fibres offer an easy-to-access measure that describes at least one part of this processing (Berlin et al., 1993; Boer et al., 2012; Durante and Carvallo, 2008; Franklin et al., 1991; Hoth et al., 2014; Velenovsky and Glattke, 2002).

The motivation for this study was to identify an objective means to show that the efferent control system of the auditory periphery may contribute to useful binaural hearing skills in CI–SSD recipients. Our premise is that the investigation via OAE on the normal-hearing side of CI-SSD recipients can serve as a valuable diagnostic tool of this effect and be useful in the rehabilitation of

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such patients. At this initial stage, the aim of the study was to investigate the feasibility of TEOAE recordings during contralateral electrical stimulation. The correlation with the speech performance in noise in spatial settings represents a long-term goal of the method introduced here.

2. Material and methods

2.1. Subjects

Seven single-sided deaf subjects were included in this study. All subjects were postlingually single-sided deafened adults with a mean age at cochlear implantation of 48.0 years ranging from 24 to 57 years, five females and two males. The subjects were tested at a mean point in time of 16 months (3–28 months), postoperatively. All subjects were implanted unilaterally with a Cochlear™ Nucleus® cochlear implant model. Three patients received a CI24RE(CA), three a CI422 and one patient received a CI522 implant. All recipients are using their CI-system consistently up to now.

The subjects were recruited from the clinic's patient pool. All subjects were implanted between January 2013 and March 2015. According to the criteria for SSD patients used in a recent study (Arndt et al., 2011a), we recruited subjects with a hearing threshold in the non-implanted ear with a four-frequency pure tone average (4fPTA: 0.5, 1, 2 and 4 kHz) of smaller or equal to 30 dB_{HL}. Additionally the minimum speech recognition percent correct score was set at 80% at 65 dB_{SPL}. Recipients with a conductive hearing loss in the non-implanted ear were excluded since successful OAE measurements presuppose normal middle ear function.

Seven CI-SSD recipients met the above inclusion criteria. The mean air-bone gap, for the seven recipients on the non-implanted ear was <5 dB. All seven subjects were examined prior to the measurements, showing normal otoscopic findings, and formally provided consent to participate in the study. For all subjects a tympanogram was recorded on the normal-hearing side. All subjects showed a tympanogram type A.

Additional to the CI-SSD criteria (Arndt et al., 2011a), for inclusion, we specified successful TEOAE recording in the non-implanted ear. This enabled a baseline TEOAE measurement in linear mode prior to the study. All seven subjects showed a regular TEOAE response (Hoth and Neumann, 2006) for the normal-hearing ear.

2.2. OAE measurement during contralateral electrical stimulation

The subjects' current map was used with all signal preprocessing disabled. All recipients used a CP910 sound processor in accessory-only mode. All recipients used an ACE map (Skinner et al., 2002) with default parameters. The contralateral stimulation was applied via the electrical input path of the sound processor. The signal was a digitally filtered CCITT noise (Comité Consultatif International Télégraphique et Téléphonique). The digital filter was applied in order to achieve a broadband electrical stimulation via the CI system. The electrical output of the CI system was checked for equal distribution of the stimuli across all electrodes by a Decoder and Implant Emulator Tool (Ali et al., 2013) from Cochlear Corporation.

The recipients performed a bilateral loudness-balancing task for individual scaling of the contralateral electrical stimulation. The task was to adjust the contralateral stimulation level on the CI side in order to match consecutively the loudness of a broadband noise on the normal-hearing side from the audiometer, presented at 30, 40, 50 and 60 dB_{HL}. The maximum level, equivalent to loudness of 60 dB_{HL}, can be considered to occur below the stapedius reflex threshold reported in CI recipients (Gordon et al., 2004; Stephan et al., 1990; van den Borne et al., 1994). These four loudness-matched signals on the CI side were then used for the contralateral suppression of the TEOAE.

The transient evoked otoacoustic emissions of the normal-hearing ear were recorded with the ILO 288 system from Otodynamics Ltd. TEOAE were elicited at a stimulation level of 65 dB_{SPL} in linear mode. As a measure for the reliability of the TEOAE, a minimum reproducibility of the emission of 60% is the established criterion in clinical routine (Hoth and Neumann, 2006); however, in our study, we used 90% reproducibility as stop criterion. Further, a noise floor below 0 dB_{SPL} (Hoth et al., 2014) was confirmed as an additional criterion to preserve signal quality.

First TEOAE for each subject's normal-hearing ear were measured without contralateral electrical stimulation, the "off" condition. Then TEOAE recordings were repeated with four different scaled contralateral electrical stimuli. All conditions were measured twice resulting in a total of ten TEOAE measurements for the five test conditions for each recipient.

All calculations and figures were done with the software R-version 3.2.1 (Ihaka and Gentleman, 1996). For statistical analyses the Wilcoxon signed rank test was used. For multiple testing, the Bonferroni-Holm-correction was applied.

3. Results

Fig. 1 shows the absolute TEOAE level as a function of the contralateral electrical stimulation level. Each data point represents the mean of the two repeated measurements. The TEOAE measurements recorded without contralateral electrical stimulation are marked in Fig. 1 with "*off*". By default of the inclusion criteria, a reliable TEOAE response was evident for each subject in the off condition, ranging between 3.4 and 12.4 dB_{SPL}. In response to consecutive contralateral stimulation, a reliable TEAOE response was observed with a signal-to-noise ratio >6 $dB_{S/N}$. (Hoth et al., 2014). Hence, contralateral stimulation did not lead to a decrease of TEOAE amplitude below detection limit for any test condition.

The TEOAE levels show a large intersubject individual variability regarding the influence of the contralateral electrical stimulation for the subject group (N = 7). On an individual basis, the TEOAE

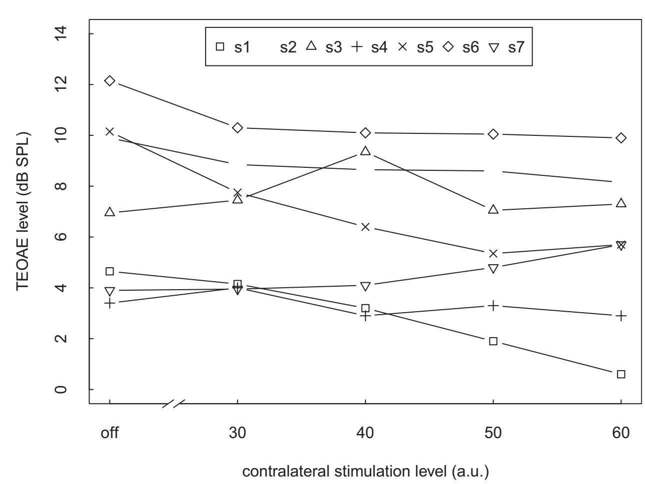

Fig. 1. Absolute TEOAE level as a function of contralateral electrical stimulation level for seven cochlear implant recipients with single-sided deafness. The TEOAE were recorded on the normal-hearing ear with a click stimulation level in linear mode of 65 dB_{SPL} and a contralateral electrical stimulation presented at the cochlear implanted ear. The level of the contralateral stimulation is given in arbitrary units (see methods section: loudness balancing with contralateral stimulation).

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