A mechanoelectrical mechanism for detection of sound envelopes in the hearing organ

To understand speech, the slowly varying outline, or envelope, of the acoustic stimulus is used to distinguish words. A small amount of information about the envelope is sufficient for speech recognition, but the mechanism used by the auditory system to extract the envelope is not known. Several different theories have been proposed, including envelope detection by auditory nerve dendrites as well as various mechanisms involving the sensory hair cells. We used recordings from human and animal inner ears to show that the dominant mechanism for envelope detection is distortion introduced by mechanoelectrical transduction channels. This electrical distortion, which is not apparent in the sound-evoked vibrations of the basilar membrane, tracks the envelope, excites the auditory nerve, and transmits information about the shape of the envelope to the brain.
auditory nerve (AN) fiber synapses (i.e., cochlear synaptopathy), assumed to be selective for medium and low-
spontaneous rate (SR) fibers. In the present study, envelope following response (EFR) level-growth functions were
recorded in normal-hearing (NH) threshold and mildly hearing-impaired (HI) listeners at frequencies above 2 kHz. EFRs
were elicited by sinusoidally amplitude modulated (SAM) tones with a carrier frequency of 2 kHz that was modulated at 93
Hz with modulation depths of 85% (strong) or 25% (shallow). Whereas the EFR level-growth functions for strongly
modulated tones were similar for all listeners, EFR level-growth functions for shallowly modulated tones were reduced at
medium stimulation levels in some of the NH threshold listeners and saturated in HI the
listeners for the whole level range. A phenomenological model of the AN was considered to investigate the effects of off-
frequency contributions (i.e., displaced
from the characteristic place of the stimulus) and the differential loss of different AN fiber types on EFR level-growth
functions. The model simulations suggest that: (1) EFRs are dominated by the activity of high-SR fibers at all stimulus
intensities, and (2) EFRs at medium-to-high stimulus levels are dominated by off-frequency contributions. Postulated
synaptopathy led to simulations generally consistent with the recorded data; however, a substantial reduction in the
number of all types of AN fibers was required to account for the results.

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Objective measures for detecting the auditory brainstem response: comparisons of specificity, sensitivity and detection
time
Objective: To evaluate and compare the specificity, sensitivity and detection time of various time-domain and multi-band
frequency domain methods when detecting the auditory brainstem response (ABR). Design: Simulations and subject
recorded data were used to assess and compare the performance of the Hotelling's T-2 test (applied in either time or
frequency domain), two versions of the modified q-sample uniform scores test and both the Fsp and Fmp, which were
evaluated using both conventional F-distributions with assumed degrees of freedom and a bootstrap approach. Study
sample: Data consisted of click-evoked ABRs and recordings of EEG background activity from 12 to 17 normal hearing
adults, respectively. Results: An overall advantage in sensitivity and detection time was demonstrated for the Hotelling's T-
2 test. The false-positive rates (FPRs) of the Fsp and Fmp were also closer to the nominal alpha-level when evaluating
statistical significance using the bootstrap approach, as opposed to using conventional F-distributions. The FPRs of the
remaining methods were slightly higher than expected. Conclusions: In this work, Hotelling's T-2 outperformed the
alternative methods for automatically detecting ABRs. Its promise as a sensitive and efficient detection method should
now be tested in a larger clinical study.

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Toward EEG-Assisted Hearing Aids: Objective Threshold Estimation Based on Ear-EEG in Subjects With Sensorineural Hearing Loss

Electrophysiological feedback on activity in the auditory pathway may potentially advance the next generation of hearing aids. Conventional electroencephalographic (EEG) systems are, however, impractical during daily life and incompatible with hearing aids. Ear-EEG is a method in which the EEG is recorded from electrodes embedded in a hearing aid like earpiece. The method therefore provides an unobtrusive way of measuring neural activity suitable for use in everyday life. This study aimed to determine whether ear-EEG could be used to estimate hearing thresholds in subjects with sensorineural hearing loss. Specifically, ear-EEG was used to determine physiological thresholds at 0.5, 1, 2, and 4 kHz using auditory steady-state response measurements. To evaluate ear-EEG in relation to current methods, thresholds were estimated from a concurrently recorded conventional scalp EEG. The threshold detection rate for ear-EEG was 20% lower than the detection rate for scalp EEG. Thresholds estimated using in-ear referenced ear-EEG were found to be elevated at an average of 5.9, 2.3, 5.6, and 1.5 dB relative to scalp thresholds at 0.5, 1, 2, and 4 kHz, respectively. No differences were found in the variance of means between in-ear ear-EEG and scalp EEG. In-ear ear-EEG, auditory steady-state response thresholds were found at 12.1 to 14.4 dB sensation level with an intersubject variation comparable to that of behavioral thresholds. Collectively, it is concluded that although further refinement of the method is needed to optimize the threshold detection rate, ear-EEG is a feasible method for hearing threshold level estimation in subjects with sensorineural hearing impairment.

Can a static nonlinearity account for the dynamics of otoacoustic emission suppression?

This study investigates whether time-dependent compression mechanisms in the cochlea are necessary to explain dynamic properties of otoacoustic emissions (OAEs). Dynamic properties of click-evoked OAEs (CEOAEs) have been observed in temporal suppression; the effect where the CEOAE magnitude is reduced when a click is presented less than 10 ms before the test click. A timedomain model of the cochlea that represented the basilar membrane (BM) as a cascade
of coupled bandpass filters was used to investigate the cochlear origin of temporal suppression in CEOAEs. The model, implemented with a time-invariant nonlinearity, was able to simulate temporal suppression, but was unable to account for the exact time scale and magnitude of the effect. The results suggest that temporal overlap of BM impulse responses can account for suppression in CEOAEs, but that an additional time-dependent cochlear gain mechanism may be needed to account the high suppression maxima at inter-click intervals larger than zero.

Human cochlear tuning estimates from stimulus-frequency otoacoustic emissions

Two objective measures of human cochlear tuning, using stimulus-frequency otoacoustic emissions (SFOAE), have been proposed. One measure used SFOAE phase-gradient delay and the other twotone suppression (2TS) tuning curves. Here, it is hypothesized that the two measures lead to different frequency functions in the same listener. Two experiments were conducted in ten young adult normal-hearing listeners in three frequency bands (1-2 kHz, 3-4 kHz and 5-6 kHz). Experiment 1 recorded SFOAE latency as a function of stimulus frequency, and experiment 2 recorded 2TS isoinput tuning curves. In both cases, the output was converted into a sharpness-of-tuning factor based on the equivalent rectangular bandwidth. In both experiments, sharpness-of-tuning curves were shown to be frequency dependent, yielding sharper relative tuning with increasing frequency. Only a weak frequency dependence of the sharpness-of-tuning curves was observed for experiment 2, consistent with objective and behavioural estimates from the literature. Most importantly, the absolute difference between the two tuning estimates was very large and statistically significant. It is argued that the 2TS estimates of cochlear tuning likely represents the underlying properties of the suppression mechanism, and not necessarily cochlear tuning. Thus the phase-gradient delay estimate is the most likely one to reflect cochlear tuning.
Nonlinear time-domain modeling of balanced-armature receivers

Nonlinear distortion added by the loudspeaker in a hearing aid lowers the signal-to-noise ratio and may degrade the hearing aid user’s ability to understand speech. The balanced-armature type loudspeakers, predominantly used in hearing aids, are inherently nonlinear devices, as any displacement of the loudspeaker diaphragm inevitably changes the magnetic and electrical characteristics of the loudspeaker. A numerical time-domain model capable of describing these nonlinearities is presented. By simulation it is demonstrated how the output distortion could potentially be reduced significantly through careful design of the mechanical properties of the armature.

Temporal suppression of the click-evoked otoacoustic emission level-curve

The click-evoked otoacoustic emission (CEOAE) level-curve grows linearly for clicks below 40–60 dB and saturates for higher inputs. This study investigates dynamic (i.e., time-dependent) features of the CEOAE level-curve by presenting a suppressor-click less than 8 ms before the test-click. An alteration of the CEOAE level-curve, designated here as temporal suppression, was observed within this time period, and was shown to depend on the levels and the temporal separation of the two clicks. Temporal suppression occurred for all four subjects tested, and resulted in a vertical offset from the unsuppressed level-curve for test-click levels greater than 50 dB peak-equivalent level (peSPL). Temporal suppression was greatest for suppressors presented 1–4 ms before the test click, and the magnitude and time scale of the effect were subject dependent. Temporal suppression was furthermore observed for the short- (i.e., 6–18 ms) and long-latency (i.e., 24–36 ms) regions of the CEOAE, indicating that temporal suppression similarly affects synchronized spontaneous otoacoustic emissions (SSOAEs) and purely evoked CEOAE components. Overall, this study demonstrates that temporal suppression of the CEOAE level-curve reflects a dynamic process in human cochlear processing that works on a time scale of 0–10 ms.
Modeling human auditory evoked brainstem responses based on nonlinear cochlear processing

The aim of this study was to accurately simulate auditory evoked potentials (AEPs) from various classical stimuli such as clicks and tones, often used in research and clinical diagnostics. In an approach similar to Dau (2003), a model was developed for the generation of auditory brainstem responses (ABR) to transient sounds and frequency following responses (FFR) to tones. The model includes important cochlear processing stages (Zilany and Bruce, 2006) such as basilar-membrane (BM) tuning and compression, inner hair-cell (IHC) transduction, and IHC auditory-nerve (AN) synapse adaptation. To generate AEPs recorded at remote locations, a convolution was made on an empirically obtained elementary unit waveform with the instantaneous discharge rate function for the corresponding AN unit. AEPs to click-trains, as well as to tone pulses at various frequencies, were both modelled and recorded at different stimulation levels and repetition rates. The observed nonlinearities in the recorded potential patterns, with respect to ABR wave V latencies and amplitudes, could be largely accounted for by level-dependent BM processing as well as effects of short-term neural adaptation. The present study provides further evidence for the importance of cochlear tuning and AN adaptation on AEP patterns, and provides a useful basis for the study of more complex stimuli including speech.
Comparison of cochlear delay estimates using otoacoustic emissions and auditory brainstem responses

Different attempts have been made to directly measure frequency specific basilar membrane (BM) delays in animals, e.g., laser velocimetry of BM vibrations and auditory nerve fiber recordings. The present study uses otoacoustic emissions (OAEs) and auditory brainstem responses (ABRs) to estimate BM delay non-invasively in normal-hearing humans. Tone bursts at nine frequencies from 0.5 to 8 kHz served as stimuli, with care taken to quantify possible bias due to the use of tone bursts with different rise times. BM delays are estimated from the ABR latency estimates by subtracting the neural and synaptic delays. This allows a comparison between individual OAE and BM delays over a large frequency range in the same subjects, and offers support to the theory that OAEs are reflected from a tonotopic place and carried back to the cochlear base via a reverse traveling wave.

Temporal Adaptation in Click-Evoked Otoacoustic Emissions

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Temporal Adaptation in Click-Evoked Otoacoustic Emissions
Auditory brainstem responses elicited by embedded narrowband chirps

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Temporal suppression and augmentation of click-evoked otoacoustic emissions

This study investigates temporal suppression of click-evoked otoacoustic emissions (CEOAEs), occurring when a suppressor-click is presented close in time to a test-click (e.g. 0-8ms). Various temporal suppression methods for examining temporal changes in cochlear compression were evaluated and measured here for seven subjects, both for short- and long-latency CEOAEs. Long-latency CEOAEs (duration >20ms) typically indicate the presence of synchronised spontaneous otoacoustic emissions (SSOAEs). Temporal suppression can only be linked to changes in CEOAE-compression if the suppressor-click affects the CEOAE magnitude. Phase changes induced by the suppressor-click were shown to bias suppression in two ways: (i) when a specific asymmetric measurement method was used and (ii) when synchronisation between the CEOAE and the click-stimuli was incomplete. When such biases were eliminated, temporal suppression and augmentation (the opposite effect) were observed and shown to be subject-dependent. This indicates that the nonlinearity underlying temporal suppression can work in a more (i.e., suppressed) or less (i.e., augmented) compressive state, depending on the inter-click interval and the subject under test. Temporal suppression was shown to be comparable for CEOAEs and SSOAEs, indicating similar underlying cochlear nonlinear mechanisms. This study contributes to a better understanding of the temporal properties of cochlear dynamics.
Temporal suppression and augmentation of click-evoked otoacoustic emissions

This study investigates and models temporal suppression of click-evoked otoacoustic emissions (CEOAEs). This suppression-effect is created when a suppressor-click is presented close in time to a test-click. The analysis was carried out for short time-frames of short- and long-latency CEOAEs. The latter is defined as a CEOAE with duration greater than 20 ms, typically observed for test subjects with spontaneous otoacoustic emissions (SOAEs). Previous studies have tended to exclude these test subjects but they are incorporated here. The results from six exemplary subjects demonstrate that temporal suppression is present in all CEOAEs for inter-click intervals (ICIs) less than 8 ms. The long-latency CEOAEs showed augmentation (i.e., negative suppression) for ICIs of 6-7 ms which was not reported for the short-latency CEOAE at these ICIs. A phenomenological approach is adopted here to explain both temporal suppression and augmentation of CEOAEs. Recently, a feedback automatic gain control (AGC) system has been used to model CEOAE suppression. However, this system cannot account for augmentation and therefore another, dynamic nonlinear model was developed. Suppression and augmentation were modeled phenomenologically using compression or expansion of the system output. This was obtained by shifting the operating-point on the input-output-characteristic in relation to the ICI.
Temporal suppression of long-latency click-evoked otoacoustic emissions

A comprehensive set of results from double click suppression experiments on otoacoustic emissions (OAEs) have been presented by Hine and Thornton (2002) and Kapadia and Lutman (2000). They found that suppression of a click-evoked otoacoustic emission (CEOAE) varied with the timing and level of a suppressor-click presented close in time to the test-click. Maximal suppression was found when the suppressor-click led the test-click by 2-4 ms. The double click suppression experiment set out by Hine and Thornton (2002) was repeated here and the analysis extended to the long-latency CEOAE (duration > 20 ms) whereas previous studies only focused on the short-latency CEOAE (duration <20 ms). The hypothesis was that suppression would continue over the long-latency CEOAE since this region is probably dominated by spontaneous OAEs (SOAEs) synchronising with the click stimulus. The results for two exemplary subjects showed that the nonlinear suppression effect remained on the long-latency CEOAE, indicating that both SOAEs and CEOAEs originate from the same cochlear nonlinearities, as earlier suggested by Kemp and Chum (1980). The apparent similar origin of both types of emissions implies that the same temporal effects influence their responses.
Individual cochlear delays measured with tone-burst evoked otoacoustic emissions

Methods to estimate cochlear delay in humans have been traditionally based on either phase-derived group delays from otoacoustic emissions (OAEs), or auditory brainstem responses (ABR). These methods demonstrate large variability in cochlear delay estimates, and are derived from across subject averages. This work aims to assess the individual variability in cochlear delay. Tone-burst evoked otoacoustic emissions (TBOAEs) are used in this study to estimate cochlear delay. The OAE is analysed by separating the non-linear components of cochlear origin, and the linear reflection in the time domain. The observed latencies as a function of frequency are qualitatively similar across subjects. For the individual subjects, the delay for each tone-burst frequency is reproducible. Defining OAE latency as the time between the onset of the stimulus and the peak of the first OAE burst yields results in agreement with previous studies. However, care must be taken when comparing the results of previous studies. This is due to an ambiguity in the time domain regarding the true onset point of the OAE, and hence the derived cochlear travelling wave latency. The inter-subject variability explains the discrepancy observed in other studies e.g. using different stimulus paradigms. The relatively small within-subject variability suggests that the present method is a good approach for estimating cochlear delay. Comparing these results with estimates based on ABR, the assumption that OAE delay is twice the basilar membrane delay (as implied by the theory of coherent reflection) does not hold for frequencies below 2kHz.

A comparison of two methods for obtaining derived, noise-evoked otoacoustic emissions

Methods to estimate cochlear delay in humans have been traditionally based on either phase-derived group delays from otoacoustic emissions (OAEs), or auditory brainstem responses (ABR). These methods demonstrate large variability in cochlear delay estimates, and are derived from across subject averages. This work aims to assess the individual variability in cochlear delay. Tone-burst evoked otoacoustic emissions (TBOAEs) are used in this study to estimate cochlear delay. The OAE is analysed by separating the non-linear components of cochlear origin, and the linear reflection in the time domain. The observed latencies as a function of frequency are qualitatively similar across subjects. For the individual subjects, the delay for each tone-burst frequency is reproducible. Defining OAE latency as the time between the onset of the stimulus and the peak of the first OAE burst yields results in agreement with previous studies. However, care must be taken when comparing the results of previous studies. This is due to an ambiguity in the time domain regarding the true onset point of the OAE, and hence the derived cochlear travelling wave latency. The inter-subject variability explains the discrepancy observed in other studies e.g. using different stimulus paradigms. The relatively small within-subject variability suggests that the present method is a good approach for estimating cochlear delay. Comparing these results with estimates based on ABR, the assumption that OAE delay is twice the basilar membrane delay (as implied by the theory of coherent reflection) does not hold for frequencies below 2kHz.
A comparison of various nonlinear models of cochlear compression

The vibration response of the basilar membrane in the cochlea to sinusoidal excitation displays a compressive nonlinearity, conventionally described using an input-output level curve. This displays a slope of 1 dB/dB at low levels and a slope in <1 dB/dB at higher levels. Two classes of nonlinear systems have been considered as models of this response, one class with static power-law nonlinearity and one class with level-dependent properties (using either an automatic gain control or a Van der Pol oscillator). By carefully choosing their parameters, it is shown that all models can produce level curves that are similar to those measured on the basilar membrane. The models differ, however, in their distortion properties, transient responses, and instantaneous input-output characteristics. The static nonlinearities have a single-valued instantaneous characteristic that is the same at all input levels. The level-dependent systems are multi-valued with an almost linear characteristic, for a given amplitude of excitation, whose slope varies with the excitation level. This observation suggests that historical attempts to use functional modeling (i.e., Wiener of Volterra series) may be ill-founded, as these methods are unable to represent level-dependent nonlinear systems with multi-valued characteristics of this kind.

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Dynamic nonlinear cochlear model predictions of click-evoked otoacoustic emission suppression

Dynamic nonlinear cochlear model predictions of click-evoked otoacoustic emission suppression

Dynamic nonlinear cochlear model predictions of click-evoked otoacoustic emission suppression

Dynamic nonlinear cochlear model predictions of click-evoked otoacoustic emission suppression
Using the short-term correlation coefficient to compare transient- and derived, noise-evoked otoacoustic emission temporal waveforms

Prediction of OAE suppression with a dynamic nonlinear model

The compression curves for different models of cochlear nonlinearities
The compression curves of different models of cochlear nonlinearities

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Projects:

**Deep learning methods for otoscopy and wideband tympanometry for the diagnosis of otitis media with effusion and acute otitis media**
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01/05/2019 → 30/04/2022
Project: PhD

**Effect of room acoustics and head movements on aided and unaided sound-field auditory steady state response (ASSR) measurements**
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**Characterizing cochlear hearing impairment using electrophysical methods**
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**Nonlinear balanced armature receivers**
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**Signal Processing in the human auditory system: Auditory-evoked Brain Responses as a Correlate of Hearing Function**
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Characterising temporal nonlinear processes in the human cochlea using otoacoustic emissions
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Modelling human auditory-evoked brain responses to complex sounds
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