Modeling and clinical diagnosis of dead regions in the cochlea
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SUMMARY

The mammalian auditory system is a highly evolved sensory organ. Humans use auditory information for awareness and for speech communication. The extensive physical properties of the auditory system are possible due to, among others, the non-linear mechanoelectrical operations of the hair cells in the cochlea. Hair cells are the sensory cells of the auditory system.

DEAD REGIONS

Unfortunately, the ingenious structure of the auditory system is at the same time one of its main weaknesses. The highly specialized structures are fragile and susceptible to damage. There are many causes of auditory impairment, including undeveloped growth, intoxication, loud sound causing noise-induced hearing loss, and presbycusis due to old age. The consequences of auditory impairment for the hearing-impaired listener affect communicative skills as well as social participation.

A dead region is a type of severe hearing impairment, which can be defined as a functional loss of inner hair cells (IHC) over a wide range of frequencies. IHCs are responsible for the mechanoelectrical transduction of pressure waves to action potentials in the auditory nerve.

CLINICAL MEASUREMENT OF DEAD REGIONS

The clinical diagnosis of dead regions affects the rehabilitation strategy of hearing-impaired patients. Inside a dead region, for example, the use of hearing aid amplification should better be omitted. And, while still in early experimental stages, the identification of a dead region may become crucial for surgical interventions in the cochlea. Modern clinical testing of dead regions relies on the psychophysical measurement of off-frequency listening. Off-frequency listening is the ability of the auditory system to use any frequency information, whether it is tuned to the frequency of the sound source or tuned to any other frequency, i.e. off-frequency, to improve the perception of the sound source.

The psychophysical tuning curve (PTC) method uses a narrowband masker to measure the masked threshold of pure-tone probes as a function of the masker frequency in order to estimate off-frequency listening. The frequency of the most efficient masker corresponds to the tip frequency of the PTC. In listeners with dead regions it is believed that the tip is shifted towards the edge of the dead region. The threshold equalizing noise (TEN) test is a method that has been optimized for the clinical diagnosis of dead regions. The test measures the masked threshold of pure-tone probes in a spectrally shaped broadband
noise, called TEN. The results are evaluated by comparing the probe masked thresholds relative to the TEN masker level. It is assumed that a probe that is masked by a relatively low-level TEN indicates that the probe is presented inside a dead region.

**Dead region simulations**

The results of Summers (2004) and the results presented in Chapter 2 showed that PTC and TEN test diagnostic dead region results are inconsistent between 25% and 40% of the tested listeners. In addition, Moore and Alcántara (2001) found some indications that the PTC tip frequency could shift as a function of level. In Chapter 2 it was shown that these tip shifts in PTCs can change diagnostic dead region results. Markessis et al. (2009) found similar level effects in the TEN test. They showed that the diagnostic outcome of the TEN test can be affected by the level of the TEN.

The inconsistency between PTCs and the TEN test results, and the unexplained level effects suggest that the conceptual design of PTCs and the TEN test to diagnose dead regions may not be entirely accurate. A direct measurement in the hearing system is problematic. Therefore, a model of the hearing system was used to simulate the psychophysical response of listeners. Chapter 3 analyzed and validated the model for simulating PTCs and TEN test results by a comparison of simulated results to normal-hearing listener data. In Chapters 4 and 5 the model was modified for dead regions and used to investigate whether the physical impairment of dead regions is equal to the psychophysical measurement of off-frequency listening, and also how off-frequency listening in PTCs and the TEN test is affected by linear-, and non-linear operations in the cochlea. Several observations were made based on simulated results:

- The loss of IHCs produces off-frequency listening effects in PTCs and the TEN test. This observation is consistent with earlier findings,

- Simulations of IHC insensitivity to low-level sounds showed that partial IHC loss can produce effects that are similar to dead region results in the TEN test,

- The off-frequency listening results were affected by non-linear outer hair cell (OHC) functionality. The contribution of OHCs was not considered in earlier studies,

- The non-linear level effects could be simulated by OHC functionality near the edge of a dead region.

These observations show, firstly, that the loss of IHCs implies off-frequency listening, but that off-frequency listening does not necessarily implies the loss of IHCs. Secondly, it was observed that non-linear cochlear operations near the edge of a dead region can significantly affect the off-frequency detection of a probe presented inside the dead region.
GENERAL CONCLUSIONS

The diagnosis of dead regions by means of psychophysical measurement of off-frequency listening is based on inaccurate assumptions. The off-frequency detection of a probe indicates that the content of an off-frequency region contains more functional information about the probe than the region near the frequency of the probe. Such a situation can occur in a dead region ("residual" off-frequency information) or when the perceptual probe-to-masker ratio is higher at the off-frequency region ("optimal" off-frequency information). A carefully chosen masker, i.e. the narrowband noise in PTCs and the TEN, provides predictable results by controlling the probe-to-masker ratio in an (approximately) linear auditory system. However, in a non-linear auditory system, the probe may be affected differently by off-frequency listening than the masker. A difference in probe-to-masker ratio can introduce level effects, which invalidate the rationale of clinical dead region diagnosis based on a linear relation between off-frequency listening and level.

Fortunately, this thesis also showed that current tests for the diagnosis of dead regions can be improved. The modeling tools that are described in Chapters 3 through 5 can be used to analyze the loss of IHCs and the functionality of OHCs based on clinically measured results. The modeling results provide substantiated or contradictory diagnostic evidence and improve estimations of the edge frequency of dead regions. The clinical diagnosis improves in PTCs by presenting probes at different frequencies and levels, and in the TEN test by measuring at different TEN levels.