Modeling and clinical diagnosis of dead regions in the cochlea

Warnaar, B.

Citation for published version (APA):
Chapter 6

GENERAL DISCUSSION
6.1 Discussing study results

The studies described in this thesis evaluated the clinical diagnosis of dead regions using PTCs and TEN test results. The tests use masking techniques to estimate the frequency at which probes presented at frequencies corresponding to the region of interest (e.g., the dead region) are detected. The rationale is that a dead region does not allow the listener of detecting a probe on-frequency. An off-frequency detected probe in controlled masking conditions must, therefore, indicate the presence of a dead region. The evaluation of dead region diagnosis aimed at finding evidence supporting or invalidating this last assumption. The fundamental research question of this thesis was: Is the relation between physical impairment of IHCs and psychophysical measurement of off-frequency listening bidirectional?

The results of Chapter 2 supported the findings of Summers et al. (2004) that the diagnosis of dead regions based on PTCs do not necessarily agree with TEN test results. The results also showed that the diagnosis can be affected by the presentation levels and frequencies of probe and masker. This study suggests test criteria to maximize the diagnostic agreement between PTCs and the TEN test results. However, a high percentage of agreement between two test methods using an identical strategy does not necessarily imply that the diagnoses are correct. The rationale and assumptions of the test strategy may still be invalid. This study also discussed the test of preference and the optimal test conditions for diagnosis, but pushed the discussion about the test validity to later studies. For example, the study argued that PTCs provide more information at the cost of clinical test-time. But even so, how does the extra information lead to a better diagnosis of dead regions when PTCs that are measured with different probes show tips at different frequencies?

Chapter 3 evaluated simulations of PTCs and TEN test results by the CASP model using normal-hearing listener data. The strategy to use a filterbank, in particular the DRNL filterbank, to simulate the functionality of the peripheral auditory system has many strengths, such as the potential to predict on-, and off-frequency masking thresholds in PTCs and TEN test results. However, the use of a filterbank must be considered carefully. It was shown that the selection of channels in the filterbank affected the outcome of simulated masking thresholds. The placement of channels should be such that all frequencies that contribute to the detection of the probe are represented in the channels of the filterbank. Also, the placement of a channel in close proximity of the frequency that contributes most to the detection of the probe is necessary to predict masking thresholds accurately. In case of normal-hearing simulations, the requirement to place a channel in proximity of the most optimal frequency for detection is satisfied by a channel centered at the probe frequency. In case of dead regions, the optimal frequency of detection is near the edge frequency of the dead region, $F_e$. An effective approach to guarantee accurate simulation of masking thresholds is to increase the channel density. This approach comes, unfortunately, at the cost of increased simulation time.

Chapters 4 and 5 used an alternative and indirect approach to establish a
6.2 General discussion

Physical impairments were modeled and used to simulate psychophysical results that could be analyzed and compared with listener data. The simulations showed that a bidirectional relation between physical dead regions and psychophysically measured off-frequency listening results is too simplistic. Other types of hearing impairment can affect off-frequency listening. It is easy to confuse a region with severely impaired IHCs with a dead region. Intact OHCs can change diagnostic results and shift the estimated edge frequency of a dead region. Fortunately, the model results also showed that PTCs and TEN[HL] test results could be simulated accurately with a single set of model parameters per listener. The model was able to predict absolute thresholds, PTC tip frequencies and levels, and to some degree the tuning of PTCs regardless of probe frequency and probe levels. The same parameter set could predict, for the same listener, elevations in masking thresholds in TEN[HL] for various levels of TEN. On the basis of simulations and model assumptions, it is possible to uncouple the estimation of the edge frequency of a dead region from the tip frequency in PTCs and the frequencies of probes used in the TEN[HL] test.

We argue that PTCs and the TEN test results can be used for diagnosis of dead regions. However, a diagnosis should be based on fitted model parameters instead of the traditional PTC tip frequency shifts and masking threshold elevation in TEN. The results presented in this thesis show that a functional model approach may improve present-day diagnosis of dead regions, because it takes into account the complex relationships between perceptual effects of on-, and off-frequency listening. Modeling tools can improve the diagnostic specificity and can be used to estimate the edge frequency of dead regions more accurately. The tools may even be used to roughly estimate the functionality of IHCs and OHCs. Unfortunately, a modeling approach in its present form has some serious drawbacks. The modeling tools and procedures were not evaluated on a large data set and are not standardized for clinical use. In addition, the measurement of several PTCs and TEN tests at different levels are required. Finally, the long simulation times are not practical for clinical use.

However, first and foremost, it is necessary to find statistical evidence on a large population of listeners for the application of a fitting algorithm to PTC and TEN test data, that accurately simulates the various types of hearing impairment.

6.2 Relevance of dead region diagnosis

It is common practice in clinical audiology to characterize the auditory system with pure-tone audiograms and speech audiograms. Dead regions cannot be diagnosed based on pure-tone audiograms and speech audiograms alone. Instead, dead regions are most likely measured as a range of frequencies with severe sensorineural hearing loss. For a patient with a dead region, the lack of a reliable diagnosis may have consequences. A typical clinical course may proceed according to a scenario similar to the following example: The dead region will be
diagnosed as a sensorineural hearing loss. Hearing aids are fitted according to standardized amplification strategies to compensate for the loss. This compensation fails to meet the expected results, because there are no benefits gained by amplification in the dead region. After several unsuccessful attempts, the rehabilitation strategy may be reconsidered. At best, these reconsiderations may lead to specific testing on dead regions by using PTCs and the TEN test, but may also lead to more extensive clinical tests, such as a brain evoked response of the auditory system (BERA) to investigate retrocochlear causes. This way of working is not cost efficient and far from optimal for the patient. A disappointed patient may have stopped the rehabilitation process before the impairment was even recognized as a dead region.

The example above raised the question whether it is at all possible to improve the situation for patients with dead regions using present-day knowledge and testing tools. General awareness of dead regions is low, and there is a lack of scientific evidence relating the effects of dead regions to the auditory system and to conventional rehabilitation strategies. Only a few studies (Vickers et al., 2001; Baer et al., 2002) have correlated the benefits of dead region diagnosis to the rehabilitation of HI listeners with moderately convincing evidence (Summers, 2004). In addition, several studies (Summers et al., 2003; Hornsby & Dundas, 2009; Warnaar & Dreschler, 2012) give reasons to reconsider the validity of PTCs and the TEN test as dead region diagnostic tools. We have noticed a polarization of prescribers and researchers into two groups with a different opinion about clinical diagnosis of dead regions. One group identifies the TEN test as a ‘bronze standard’ for dead region diagnosis and this group uses the test, regardless of test reliability, to classify listeners with dead regions and listeners without dead regions. Members of the other group do not trust the accuracy of the TEN test, and generally do not test on dead regions at all. We believe that the best approach is found somewhere in between these poles. The use of diagnosis of dead regions and a critical review of the data may lead to improvements in rehabilitation programs for patients with dead regions and this will give opportunities to expand our basic scientific knowledge about the auditory system.

6.2.1 An example of a clinical benefit

A correct diagnosis of dead regions provides efficient and cost-effective (near) future applications in clinical audiology. For example, the diagnosis of high-frequency dead regions can be used as a crucial indicator for the implantation of short cochlear implants (CI). A CI is placed in the cochlea through the oval window by pushing the device inwards from the basal side of the cochlea. It is surgically difficult to implant a CI over the full length of the cochlea because of the coiled structure of the cochlea. A short CI, which is inserted less deep into the cochlea may benefit from leaving the BM intact at the low frequencies. An easy to administer and reliable clinical test that is able to diagnose a high-frequency dead region and precisely estimate the frequency of the dead region’s edge ($F_e$) would not only benefit patients with high-frequency dead regions, it
would also save medical costs of extensive diagnostic procedures.

6.2.2 AN EXAMPLE OF A SCIENTIFIC BENEFIT

From a scientific perspective, dead regions open a number of interesting opportunities for research. As an example, the efferent control by hair cells can be further explored. Is two-tone suppression controlled by IHCs or OHCs? Is the OHC function self-regulated or is it controlled externally by efferent nerve fibers? And, which role do OHCs play in contralateral masking? The relationship between these questions and dead regions becomes evident when the neural pathways of the auditory system are examined. Guinan Jr. (1996; 2006; 2010) has written several excellent reports on the pathways and information flow between hair cells and different neural complexes. Afferent and efferent nerve fibers populate the IHCs and the OHCs. Efferent fibers from the lateral olivocochlear innervate the auditory nerve fibers near IHCs to inhibit the action potential evoked by IHCs. The OHCs are innervated by medial olivocochlear (MOC) efferents that originate from the ipsilateral-, and contralateral cochleae. A number of studies (Fex, 1967; Guinan Jr., 2006; Cooper & Guinan Jr., 2006; Rabbit et al., 2009) have shown that efferent control can inhibit BM responses by reducing the OHC amplification. Most of these studies base their results on animal data, e.g. by cutting the olivocochlear bundle. In humans, efferent control can be measured by contralateral masking effects. Kawase et al. (2000) showed in normal hearing listeners that masked thresholds in the skirts of PTCs were decreased by 5 dB due to inhibiting effects of contralateral noise.

In most experiments that investigate efferent control it is difficult to estimate the relative contribution of IHCs and OHCs. A known dead region may be used to provide OHC-only control. Figure 6.1 presents a schematic overview of the auditory information flow of afferent and efferent nerve fibers in the cochlea and auditory centers in the brainstem (Guinan Jr., 2006). Within the cochlea, the relative IHCs and OHCs contribution to two-tone suppression can be investigated by presenting a suppressor tone inside a dead region with functional OHCs. The contribution of OHCs can be measured using PTCs by presenting the suppressed tone in a normal-hearing region of the cochlea. The red arrows indicate the pathway of suppressor information from OHCs to type 1 afferent nerve fibers originating from IHCs in a normal-hearing region of the cochlea. An experiment similar to the contralateral masking measurements presented by Kawase et al. (2000) in combination with a contralateral dead region can be used to examine the relative contribution of IHCs and OHCs in controlling OHCs. The blue arrows indicate the pathway of contralateral masking information. The relative contribution of IHCs and OHCs can be estimated by comparing contralateral masking originating from a normal-hearing region or a dead region in the contralateral cochlea.
Figure 6.1. Information flow of electric potentials evoked in the cochlea and olivocochlear reflexes in the hearing system as suggested by Guinan Jr. (2006). Fibers that have a dashed arrow have not been conclusively identified. The hypothetical control of IHCs by ipsilateral OHCs inside a dead region is represented by red arrows. Type II auditory nerve (AN) fibers originate in OHCs and terminate in the cochlear nucleus (CN). The interneurons of the CN excite efferents in the lateral olivocochlear (LOC), which in turn inhibit the type I afferents that originated from IHCs, as indicated by the red circle. Contralateral masking excites medial olivocochlear (MOC) efferents. The contralateral masking information, indicated by blue arrows, is passed through the olivocochlear bundle (OCB) to active OHCs and type II nerve fibers, as indicated by blue circles. The type II nerve fibers have both afferent and efferent connections with OHCs.

6.3 Classification of dead regions

The studies in this thesis have described various types of hearing impairment due to the presence of dead regions. In an effort to structure the different variations we suggest a classification of dead region types. The classification is given in terms of measured variables in dead region diagnosis with PTCs and TEN test results. The new classification, presented in Fig. 6.2, uses the standard diagnostic criteria for dead regions to discriminate between normal-hearing and types of impaired regions, but takes into account potential level effects. A PTC tip shift or elevation of masking thresholds in TEN above criteria set in chapter 2 leads to classification of a type of dead region. A barren region corresponds to the classic interpretation of a dead region as a complete loss of IHCs. However,
barren regions assume explicitly that there are also no functional OHCs. The measured results show no level effects (changes in PTC tip shift or changes in the relative elevation in TEN as function of level) and the results are, therefore, in agreement with the linear rationale of diagnosis of dead regions (Moore, 2001). Desert regions and tundra regions refer to regions where the diagnostic outcome is dependent on the level of presentation of the test stimuli. A desert region has no functional IHCs, but has functional OHCs. The OHCs change the masking behavior from linear to non-linear at low levels (suggested criterion < 50 dB HL). It is important to use the masker level as criterion, because the masking behavior depends on the level at the detected place on the BM. A tundra region refers to a region with relatively insensitive IHCs that respond to high-level stimuli only. The OHCs can be functional or non-functional in a tundra region.

The suggested comparison to landscapes corresponds to how the author of this thesis imagines the physical “landscape” of hair cells.

Figure 6.2. Suggested classification of dead regions based on measured variables in dead region diagnosis with PTCs and TEN test results.

---

\(^{a}\)The author suggests that the name “dead region” is equally unsuitable for clinical use.