Modeling and clinical diagnosis of dead regions in the cochlea

Warnaar, B.

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Chapter 4

SIMULATING PSYCHOPHYSICAL TUNING CURVES IN LISTENERS WITH DEAD REGIONS

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B. Warnaar
M. L. Jepsen
W. A. Dreschler
Objective: This study investigates the relation between diagnosis of dead regions based on off-frequency psychophysical tuning curve (PTC) tip and the frequency and level of the probe tone.  
Design: A previously developed functional model of auditory processing was used to simulate the complete loss of inner hair cells (IHCs), dysfunction of outer hair cells (OHCs), complete loss of IHCs in combination with OHCs dysfunction, and IHC insensitivity. The model predictions were verified through comparison with experimental data.  
Study sample: This study compares PTC data of five normal-hearing listeners and six hearing-impaired listeners with model simulated PTC data.  
Results: It was shown that OHC activity and IHC insensitivity may significantly alter the shift of PTC tips with increasing probe level.  
Conclusions: Model results suggest that OHC activity and IHC insensitivity can change the outcome of dead region diagnosis using PTCs. Supplementary to PTC dead region diagnostic information, model results may provide additional information regarding the edge frequency of a dead region and OHC function.

4.1 Introduction

A cochlear dead region indicates a profound loss of auditory function within a specific frequency region of the cochlea. Dead regions have been associated with a completely insensitive region of the cochlea (Moore & Glasberg, 1997; Moore & Alcántara, 2001), noise-like and distorted perception of pure-tones presented inside a dead region (Huss & Moore, 2005), and decreased benefit of hearing aid amplification for sounds with frequency components inside the frequency range of a dead region (Vickers et al., 2001; Baer et al., 2002).

Dead regions have been defined as regions of the cochlea lacking evoked neural activity due to missing or non-functional inner hair cells (IHC) and/or fibers of the auditory nerve (Moore & Glasberg, 1997; Moore et al., 2000). Unfortunately, currently, it is not possible to directly measure the pathology of IHCs or the auditory nerve fibers without damaging the auditory system. To overcome this limitation within clinical and experimental measurements, it has been suggested that one formulates dead regions in terms of psychophysical properties. Within this paradigm, a dead region is a range of characteristic frequencies (CF) corresponding to IHCs or fibers of the auditory nerve (Moore, 2001), that function poorly, in which case signals presented within the dead region are detected through off-frequency listening (Moore, 2004). Off-frequency listening is the ability of the auditory system to detect frequency components of sounds through basilar membrane (BM) excitations that are produced in neighboring functional regions of the cochlea (Johnson-Davies & Patterson, 1979; O’Loughlin & Moore, 1981).

Moore et al. (2000; 2004) suggested that the relationship between physical
dead regions (loss of IHCs and/or auditory nerve fibers) and off-frequency listening could be used to diagnose dead regions in listeners, and could be used to estimate the edge frequency of the physical dead region, denoted as $F_e$. The rationale of measuring physical dead regions through off-frequency listening is based on several assumptions. First, the BM excitation produced by any signal is not transmitted to neural activity inside a physical dead region (Moore & Glasberg, 1997; Moore, 2001). Limited transmission may still be possible, but it would not lead to the detection of signals. Second, signals presented inside a physical dead region can be detected, if they are sufficiently intense, at an off-frequency region outside the physical dead region (Patterson & Nimmo-Smith, 1980). Third, the preferred frequency of detection, i.e. the strongest detectable response, of a signal presented inside a physical dead region corresponds to $F_e$ (Turner et al., 1983; Moore & Alcántara, 2001). In this study, the above three assumptions are assumed to be valid and will be used to qualify a physical dead region.

Psychophysical tuning curves (PTCs) and the Threshold Equalizing Noise (TEN) test (Moore et al., 2000; 2004) are most frequently used to identify the presence and range of psychophysical dead regions. In the present study, we will focus on the applicability of PTCs. A PTC is obtained by presenting a probe, fixed in frequency and intensity, and measuring the thresholds at which a masker presented at different frequencies masks the probe. The masker’s ability to mask the probe tone, i.e. the effectiveness of the masker is inversely proportional to the masker level at masking threshold; an effective masker produces a relatively low masking threshold. Most commonly, the curve forms a ‘V-like’ shape with a minimum, i.e. the tip of the PTC. The tip is assumed to correspond to the most sensitive place of the BM. In normal-hearing (NH) listeners, the PTC tip is located ”on-frequency” at the frequency of the probe tone (Turner et al., 1983). In listeners with cochlear dead regions, where probes are not audible on-frequency, the PTC tip is believed to shift ”off-frequency” to $F_e$ (Turner et al., 1983; Moore & Alcántara, 2001).

It is commonly assumed that physical dead regions may be measured through off-frequency listening. However, it has not been demonstrated that a psychophysical measurement of off-frequency listening, henceforth referred to as a psychophysical diagnosis of dead regions, implies the presence of a physical dead region. Moore et al. (2000; 2004) recognized that off-frequency listening is more than the detection of residue BM excitation; it is an ability of the (normal-hearing) auditory system to optimize signal detection. They suggested a spectrally shaped noise (TEN) for the measurement of off-frequency listening that only shows the effects of detecting residual excitation, i.e. a physical dead region. Despite many studies using this particular noise and different comparisons between different methods to diagnose dead regions through off-frequency, it has never been proven that the measurement of off-frequency listening actually indicates the presence of a physical dead region. Instead, two studies (Markessis et al., 2009; Warnaar & Dreschler, 2012) found results in which the diagnosis of dead regions changed with level. Level effects are a direct violation of the basic assumptions that relate the psychophysical diagnosis of dead regions to
the physical presence of dead regions, particularly with regard to the estimation of Fe and the non-detection of signals inside dead regions.

Warnaar and Dreschler (2012) showed in a population of twenty-four hearing-impaired (HI) ears that the estimation of Fe may depend on the probe frequency and level in PTC measurements. A level dependent behavior in the cochlea is often associated with outer hair cell (OHC) activity. Dead regions are normally associated with the loss of IHCs, and not with OHCs. When OHCs are considered, it is often assumed that the functionality of OHCs is lost inside a dead region because OHCs are more prone to damage than IHCs (Liberman & Dodds, 1984). However, it is plausible that remaining OHCs may affect the measurement of off-frequency listening. The activity of OHCs shifts the place of the BM that is maximally displaced by a stimulus, i.e. the best place or best frequency (BF) basally with an increase of the cochlear input (Ruggero, 1992; Ruggero et al., 1997; Alcántara & Moore, 2000). A shift of BF affects the place at which the BM is most sensitive to sounds, which in turn may affect the estimation of Fe.

Markessis et al. (2009) showed that the level of Threshold Equalizing Noise (TEN) in the TEN[HL] test can change the psychophysical diagnosis of dead regions. To explain the level dependent results, Markessis et al. (2009) suggested the presence of so-called ‘sick regions’, or regions where IHCs are insensitive to low-level input, but are still sensitive to high-level input. A sick region transmits basilar membrane vibration at high-level input and must, therefore, not be considered as a physical dead region. However, at low-level input to a sick region may produce off-frequency listening effects similar to a physical dead region. This implies that psychophysical dead regions can only be diagnosed reliably up to levels that are acceptable for the listener\(^a\).

The goal of this study is to investigate the relationship between OHC activity and IHC insensitivity on the level effects in dead region diagnosis using PTCs. The relationship is tested by comparing PTCs obtained in listeners diagnosed with dead regions with model simulations of OHC activity and IHC insensitivity in combination with IHC loss. In the section below, headed ‘Functional simulation of psychophysical tuning curves’, a model is described that is capable of simulating NH psychophysical thresholds given an auditory task. In the section headed ‘Simulation of normal-hearing’, this model is verified for the simulation of NH PTCs by a comparison with NH listener data. In the section headed ‘Consequences of simulating hearing impairment’, the model is modified to simulate various types of hearing loss, including the complete loss of IHCs, the complete loss of IHCs in combination with various degrees of OHC activity, and insensitivity of IHCs. The relation between each type of hearing loss and off-frequency listening effects are described in terms of model trends on which conclusions can be drawn. The section ‘Experimental Method’ describes the experimental method used to obtain NH-, and HI listener data. In the Re-

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\(^a\)High level presentations are problematic in some listeners with loudness recruitment. This is even more problematic for the TEN test, because the TEN is a broadband noise that ranges between 354 Hz and 6500 Hz. However, the total loudness perception of the TEN can be reduced by limiting the frequency range of the noise by filtering (Markessis et al., 2006).
4.2 Simulating psychophysical tuning curves 79

In the results section the model trends are compared and verified to be consistent with listener data. For each listener, one set of model parameters was fitted to all PTCs produced by the listener. In the Discussion section the simulation of the edge frequency of a dead region, $F_e$, and the clinical application of the model are discussed.

4.2 Model based hypothesis

In the sub-section below, a functional model of the auditory system is described. The model can, given an auditory input, simulate the psychophysical response of a normal-hearing listener. The model response to PTC stimuli is described in the sub-section ‘Simulation of normal-hearing’. In the sub-section ‘Consequences of simulating hearing impairment’, the model is modified to simulate hearing impairment for different types of cochlear hearing loss. The consequences of the different types of loss on the PTCs are deduced from simulations and are described in terms of trends in the model.

4.2.1 Functional simulation of psychophysical tuning curves

Several models of the auditory system (e.g., Dau et al., 1996a; Plack & Oxenham, 1998; Plack et al., 2002; Jepsen et al., 2008) have been proposed to simulate auditory features, such as the production and detection of beats and combination tones (CT), OHC nonlinearity, off-frequency listening and suppressive masking. The model by Dau and colleagues has been successfully applied to data obtained in NH listeners in a number of studies (Dau et al., 1996b, 1997a; 1997b; Derleth & Dau, 2000). The computational auditory signal processing and perception (CASP) model of Jepsen et al. (2008) was an extension of the Dau et al. model by including nonlinear effects associated with basilar-membrane processing (Ruggiero et al., 1997; Robles & Ruggiero, 2001). The CASP model has been validated for tone-in-broadband noise and tone-in-narrowband (80 Hz) noise detection, intensity discrimination and forward masking (Jepsen et al. 2008), and frequency selectivity and forward masking in listeners with hearing impairment (Jepsen & Dau, 2011).

The CASP model consists of a chain of modules. Each module describes a physiological element or a functionality of the auditory system. The function of the outer- and the middle-ear is modeled by linear frequency dependent transfer functions. The dual resonance non-linear (DRNL) filterbank (Meddis et al., 2001; Lopez-Poveda & Meddis, 2001) simulates the transformation of stapes movement to basilar-membrane movement, and accounts for effects of two-tone suppression, impulse response, and distortion phenomena. The filterbank consists of a number of channels, each with a linear and a non-linear path to simulate passive BM and OHC induced excitation. The paths are tuned to different characteristic frequencies (CF$_{\text{non-linear}}$ is 3% higher than CF$_{\text{linear}}$) to simulate the level dependent behavior at the best frequency. The output of
each channel represents the BM movement at a fixed place on the BM, associated with the channel frequency \( \text{CF}_{\text{channel}} \), and is treated separately in the model, until the channels are combined in the optimal detector.

The DRNL is followed by a hair cell transduction stage, simulating the signal processing operation of the IHCs. The adaptive response to level changes of the hearing system is simulated by a chain of feedback loops in the adaptation stage (Püschel, 1988; Dau et al., 1996a; 1997a). The sensitivity of the hearing system to amplitude modulation is simulated by a lowpass filter with a cutoff at 150 Hz and a modulation filterbank stage (Dau et al., 1997a; Kohlrausch et al., 2000).

All channels are combined by averaging internal representations in the optimal detector. The optimal detector creates internal representations of the actual stimuli containing the signal and masker, reference samples that contain the masker only, and a reference condition representing a target listening cue containing the signal at suprathreshold level, called the template. The template can be regarded as a mathematical description of "what to listen for" in the model. The output of the optimal detector is the difference between the actual stimuli and the reference samples, all cross-correlated with the template.

The final stage of the model is the decision device that simulates the detection of the model, i.e. the simulation of masking thresholds. An overall Gaussian-distributed internal noise of the model is simulated to the output of the optimal detector to limit the resolution of the model. The intensity resolution of the model followed Weber's law and was set to a just noticeable difference of roughly 1 dB for 1 kHz pure tones and broad band noise (Jepsen et al., 2008).

### 4.2.2 Simulation of normal-hearing

Predictions of PTCs by the CASP model for NH subjects are shown in panel A of Fig. 4.1. Probes at 1 and 4 kHz and levels of 30, 50 and 70 dB SPL are represented by black circles including white symbols. Interpolations of PTCs are represented by the gray curves. The PTC tips were obtained at the probe frequencies and at slightly higher levels than the probe levels. The frequency resolution of the system is expressed by the frequency-to-intensity increase of the PTCs, or PTC tuning. In normal-hearing simulations the PTC tuning depends on the bandwidth of the masker relative to the tuning width of the DRNL channels. Therefore, PTCs are broader around the tip for 1 kHz probes and more sharply tuned for 4 kHz probes. Tuning depends only slightly on probe level; at 4 kHz and 70 dB SPL tuning is broader than at the lower levels. Slopes in dB per Hz at low-frequency skirts are generally less steep than slopes at upper skirts. A direct comparison between the simulated and measured PTCs in the NH listeners is considered further in the Results sub-section, ‘Normal-hearing’.

### 4.2.3 Consequences of simulating hearing impairment

The functionalities of the CASP model were extended to simulate different types of hearing impairment. The frequency range of each type of hearing
4.2 Simulating psychophysical tuning curves

Figure 4.1. Predicted PTC patterns for a variety of cochlear conditions. Simulated trends for normal-hearing (A), IHC loss with $F_e$ at 1200, 1400, 1700, 2000, 2500 and 3500 Hz (B), IHC loss with $F_e$ at 3500 Hz and 1000 Hz probes at 60, 70, 80 and 90 dB SPL (C), OHC dysfunction of 0 dB to a complete loss of OHC activity (-32 dB and -43 dB at 1000 and 4000 Hz, respectively) (D), IHC loss in combination with OHC dysfunction of 0 dB to -38 dB (E), and IHC insensitivity with an attenuation level of 60 dB SPL (F). Probes are presented by black circles including white symbols. Roex fit functions to simulated data are presented by gray lines. The PTC tips are presented by black symbols. Gray areas in panels C, E and F represent regions of IHC loss or IHC insensitivity.

Impairment (IHC loss, OHC dysfunction and IHC insensitivity) could be independently specified.

Simulating complete loss of IHCs
A dead region, defined as a physical loss of IHCs, effectively eliminates the
transduction of BM movement into auditory-nerve compound action potentials. The elimination of transduction is simulated in the CASP model by removing DRNL channels with a CF*channel* falling inside the frequency range of the physical dead region. To determine the cutoff-frequency of DRNL channels, it is important to distinguish between the CF*channel* and the CFs of the linear path and the non-linear path of the DRNL. The paths of the DRNL are tuned to a frequency different from CF*channel*. For example, at a CF*channel* of 2000 Hz the CF*linear* is 1945 Hz (-2.8 %) and CF*non-linear* is 2009 Hz (+0.1 %). Although the non-linear path of the DRNL has some similarities with OHC activity, such as amplification at low-levels and a compressive input-output gain, the non-linear path cannot be interpreted as the exact functioning of the OHCs. A similar comparison between the linear path and the IHCs is likewise incorrect. Both DRNL paths are mathematic descriptors of the total cochlear functionality. Only the sum of the two paths has a physically meaningful output, namely, the displacement of the BM at CF*channel*. Therefore, a cutoff-frequency of DRNL channels at CF*channel* equal to F_e was used to simulate the edge of a physical dead region. Figure 4.1 (panel B) shows the model trend in PTCs, obtained with a fixed probe at 1000 Hz at 70 dB SPL, with various F_e (ranging from 1200 Hz to 3500 Hz) simulating different physical low-frequency dead regions. The model was able to detect the high-level probe with F_e up to 3500 Hz, due to a strong upward spread of excitation in the model. The PTC tip frequencies increase monotonically with increasing F_e. The PTC tip frequency did not necessarily correspond to F_e. In particular, when F_e was shifted more than one octave, the PTC tip frequency was found at an even higher frequency. For example, with a F_e at 3500 Hz the PTC tip was found at 4000 Hz. Panel C in Fig. 4.1 shows the effect of the probe level (sensation level) on PTCs. The probe frequency was fixed at 1000 Hz and F_e was fixed at 4000 Hz, simulating an extensive low-frequency physical dead region. The gray area in the panel represents the range of the physical dead region. Normal-hearing OHC activity was simulated. At very high levels (90 dB SPL) the tip frequency shifted less from the probe frequency. The difference between low-, and high level probes corresponds roughly to 40 % of the tip frequency.

**Simulating partial-to-complete dysfunction of OHCs**

Normal-hearing OHC activity was simulated unless the OHC activity was reduced by OHC dysfunction. The dysfunction of OHCs was simulated by a reduced gain in the non-linear path of the DRNL. Figure 4.2 explains the effect of reducing the gain on the DRNL input-output function. The input-output level function for NH listeners represents a "broken stick" model with increased gain at low-levels, a compressed mid-level input-output function, and a linear input-output function (gray line) at high-levels. The pathology of OHCs' function results in a decrease of the gain for low-level signals and therefore, in a decrease of hearing sensitivity. Additionally, the absolute threshold is

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bThis was motivated by evidence from studies of Rhode and Recio (2000), and McFadden and Yama (1983) showing that the best frequency (strongest BM excitation) was shifted as function of level.
increased. Panel D of Fig. 4.1 shows the trend of a reduced gain (with normal IHC functionality) on the PTCs as predicted by the CASP model. The PTC tip shifts monotonically to higher intensities with the modeled level of OHC dysfunction, varied between 0 and 34 dB at 1 kHz and between 0 and 43 dB at 4 kHz (Jepsen & Dau, 2011). With increasing amount of OHC dysfunction the absolute threshold for detecting probes increased and the predicted PTCs were less sharply tuned. The level of the tip is also increased with increasing OHC dysfunction by a raised absolute threshold.

Simulating complete loss of IHCs in combination with OHC dysfunction
The effect of increased OHC dysfunction in combination with IHC loss is simulated in panel E of Fig. 4.1. An IHC loss, presented by a gray area, was assumed at low frequencies with a $F_c$ fixed at 2000 Hz. The probe remains fixed in frequency and level. An increase of OHC dysfunction in a dead region introduces several changes in the predicted PTCs. Firstly, the tip frequency shifts towards lower frequencies (or higher frequency in case of a high-frequency dead region) by up to 15% of the tip frequency with normal-hearing OHC activity. Secondly, the tip level and the level of masking noise to just mask the signal are increased.

![Diagram](image.png)

**Figure 4.2.** Model simulation of OHC dysfunction. The normal-hearing input-output function of the DRNL is presented by the dashed broken-stick curve. With increasing OHC dysfunctionality, the input-output function changes towards the linear input-output function presented by the gray line. With a fixed output threshold, it is shown that the minimum input level that is required to produce detectable output levels, i.e. the absolute threshold, is increased. The level of OHC dysfunction is defined by the level change of the absolute threshold.
Simulating IHC insensitivity to low-level sounds

Insensitivity of IHCs was simulated in the CASP model by an attenuation of the IHC input levels, in addition to half-wave rectification and hair cell envelope extraction in the IHC stage. The behavior of IHC insensitivity depends on the projection of the reduced dynamic range on the output of the IHCs. The dynamic range of audible levels can: a) ‘compress’ to the reduced level range, producing a response for all IHC input levels, b) eliminate low-level stimuli and produce normal high level responses, or c) attenuate the IHC input by a fixed level, i.e. the level of attenuation, at all input levels. Attenuation may reflect a reduced generation of receptor potential in IHCs. In this study, an attenuation of the IHC (option c) was used at frequencies below or above a specified cutoff-frequency. The effects of simulating low-frequency IHC attenuation at 60 dB SPL with a cutoff-frequency at 1500 Hz, presented by a gray area, are shown in panel F of Fig. 4.1. The results of IHC insensitivity are comparable to IHC loss for probes presented within the region of simulated IHC impairment and below the attenuation level of IHC insensitivity. Above the attenuation level of IHC insensitivity, the results are comparable to the NH results, with the PTC tip frequency at the probe frequency and similar tuning. The PTC results are the same as simulated NH results when probes are presented at level higher than the attenuation level of the simulated IHC insensitivity region.

4.3 Experimental method

The sub-section below, ‘Procedure and stimuli’ describes the experimental setup used to obtain PTC data in listeners. Results for the normal-hearing and hearing-impaired listeners who participated in this study are presented in the following sub-section, ‘Listeners’. In the sub-section ‘PTC analysis’, an analytical method used to fit the optimal parameter set of the model for each individual listener is presented.

4.3.1 Procedure and stimuli

An adaptive three-alternative forced-choice (3AFC) procedure was used to measure PTCs. Each interval presented a masker with a duration of 400 ms and a pure-tone probe of 200 ms in one randomly chosen interval, centered in time within the interval. Both masker and probe had 50 ms cosine squared ramps. The delay between consecutive intervals was 460 ms. The task of the listener was to specify the interval containing the probe. Maskers were created by multiplying stochastic broadband white noise with a 320 Hz window having cosine squared flanks. A fixed bandwidth of 320 Hz was chosen as an optimum between effects on the broadening of the PTC shape and the masking of beat-detection (Sek et al., 2005). In addition, a stochastic lowpass noise was added to reduce the detection of simple difference tones (SDT). The level and cutoff-frequency of the lowpass noise were determined for each presentation based on the levels
and frequencies of the probe and masker, and excitation pattern calculations (Moore & Glasberg, 2004). The lowpass noise could reduce detection of SDTs of up to 65 dB SPL, which amounted to lowpass spectral levels of < 60 dB SPL.

Normal hearing listeners were tested using 1 and 4 kHz probes presented at 30, 50, and 70 dB SPL. For hearing-impaired listeners, probes were presented inside the suspected dead at 10 dB SL and higher levels. The masker was first presented at 9 logarithmically spaced frequency steps within a frequency range that included the probe frequency and extended to one octave beyond the estimated $F_e$. Then, the PTC was further defined by presenting the masker at 5 linear frequency steps centered at the tip. The starting level of the masker was set equal to the probe level minus 30 dB. The intensity of the PTC masker was adjusted using a 1-down and 2-up adaptive procedure, converging to the 71% level (Levitt, 1971). Step sizes started at 8 dB and were halved after every two reversals until a minimum step size of 1 dB was reached. The average level of 6 reversals at the smallest step size was used to estimate the masking threshold. Listeners received visual feedback after each response. The masker level was limited to a maximum of 100 dB SPL. Stable measurements were obtained after training. The listeners took frequent pauses in between measurements. All presented data points were measured once.

All tests were administered in a sound-proof booth. Acoustic stimuli were programmed in Matlab©, digitally generated by a RME© Fireface 800 sound-card at a sampling rate of 48 kHz, and presented by Sennheiser© HDA200 headphones. Left and right transducers of the headphones were equalized to a flat frequency response ($\sigma < 0.7$ dB) between 100 Hz and 16 kHz using a technique of adding an inverse minimum phase response filter based on the impulse response of each headphone. The test stimuli were presented at the tested ear (left or right), and a contralateral masking with an independently created noise was provided at the contralateral ear when the audiogram indicated that cross-listening between ears was possible.

4.3.2 Listeners

Five normal-hearing (NH) listeners participated in this study in order to form a NH reference group for the CASP model. All NH listeners were female, aged between 19 and 20 years, with pure-tone audiometric threshold < 10 dB HL at octave frequencies between 0.5 and 8 kHz. Six HI listeners were selected out of a group of listeners representing twenty-four measured ears©, to illustrate representative effects that were found in the results of the whole group. These include listeners who were psychophysically diagnosed as having low-frequency (L17, L18, and L20), and high-frequency (L12, L14 and L15) psychophysical dead regions, several degrees of level dependency on the PTC tip frequency (no: L12, L17; weak: L14, L20; strong: L18), and a special condition found in a few listeners where probe tones produced almost no tuning (L15). The six HI listeners were aged between 19 and 62 years (median: 41). Table 4.1

©The numbering of listeners (e.g. Lxx) refers to the original numbering of ears (e.g. HIxx) (Warnaar & Dreschler, 2012).
lists auditory details of the listeners and the model simulated OHC-, and IHC functions. The pure-tone audiograms of each HI listener are presented in Fig. 4.3 by customary audiometric symbols and solid lines. Listeners were selected based on pure-tone audiometric data that were measured typically 1 to 2 years prior to collecting the PTC data presented in this study. The presented pure-tone audiograms were measured to verify that the audiograms had not significantly changed since, and to roughly estimate the range of frequencies and levels that could be used to measure PTCs in the listeners. Listeners received compensation for their efforts, and a reimbursement of their travel expenses. The study was approved by the Medical Ethical Committee of the Academic Medical Center in Amsterdam, AMC (MEC 05/183).

Figure 4.3. Pure-tone audiograms of hearing-impaired listeners are presented by marks and solid lines. Simulated absolute threshold using parameters listed in Table 4.1 are presented by dashed lines. The levels were corrected for dB SPL to dB HL conversion using ISO 226:2003, and threshold level differences for using an up-down procedure instead of an audiometric measurement (Levitt, 1971).
### Table 4.1

<table>
<thead>
<tr>
<th>Listener</th>
<th>Age</th>
<th>Gender</th>
<th>Ear</th>
<th>Etiology</th>
<th>OHC Function</th>
<th>Dysfunction Region</th>
<th>IHC Innsensitivity</th>
<th>Attenuation Region</th>
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<tr>
<td>L12</td>
<td>20</td>
<td>f</td>
<td>l</td>
<td>unknown</td>
<td>-43</td>
<td>~3500</td>
<td>3700</td>
<td>≥1700</td>
</tr>
<tr>
<td>L14</td>
<td>27</td>
<td>f</td>
<td>l</td>
<td>mumps</td>
<td>-8</td>
<td>~150</td>
<td>650</td>
<td>≥1700</td>
</tr>
<tr>
<td>L15</td>
<td>62</td>
<td>m</td>
<td>l</td>
<td>noise</td>
<td>-34*</td>
<td>~150</td>
<td>≥150</td>
<td>≤1500</td>
</tr>
<tr>
<td>L17</td>
<td>55</td>
<td>m</td>
<td>l</td>
<td>unknown</td>
<td>-20</td>
<td>~2000</td>
<td>1800</td>
<td>45</td>
</tr>
<tr>
<td>L18</td>
<td>56</td>
<td>m</td>
<td>r</td>
<td>unknown</td>
<td>-3</td>
<td>~2500</td>
<td>1500</td>
<td>≤3500</td>
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<td>19</td>
<td>f</td>
<td>r</td>
<td>meningitis</td>
<td>-3</td>
<td>~4500</td>
<td>≤4500</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Detailed information of hearing-impaired listeners, and individual model parameters simulating their hearing loss. Presented for each listener are the age, gender, tested ear, etiology of hearing loss. The model parameters are ordered by type of hair cells, i.e. dysfunctionality of OHCs (asterisks indicate 100 % losses) and loss of IHCs.
### 4.3.3 PTC analysis

Psychophysical tuning curves obtained for NH subjects were used to evaluate the model. The parameters of the evaluated model were fitted to individual data of HI listeners by comparing PTCs. A PTC can be characterized by its tip and its tuning. Tips were defined, in listeners as well as in model simulations, by selecting the geometric mean frequency and the level of the masker\(^d\) that produced the lowest (minimum) masking threshold. The tuning was calculated in two steps. Firstly, the PTC shape was fitted with third-order rounded exponential (roex) functions (Patterson et al., 1982) on the lower-, and upper skirts using the PTC tip (frequency and intensity) as a boundary condition for the fit. Secondly, quality factors were calculated at different levels relative to the tip level, given by:

\[
Q_{lvl} \ = \ \frac{F_{tip}}{w_{lvl}} \tag{4.1}
\]

where \(Q_{lvl}\) representing the quality factor at the level, \(lvl\), in dBs relative to the PTC tip level, \(F_{tip}\) the tip frequency, and \(w_{lvl}\) the frequency difference between the tip frequency and frequency of the roex fit at a level \((lvl)\) above the tip level:\(^e\):

\[
w_{lvl} \ = \ |F_{tip} - \text{roex}^{-1}(lvl)| \tag{4.2}
\]

A procedure was defined to find the "best" fit between a measured PTC and a simulated PTC. For this procedure to resemble diagnostic measurement, it was recognized that the PTC tip frequency is the most critical parameter for dead region diagnosis, followed by the tip level and finally the tuning of the PTC. The following order was maintained in the comparison of PTCs:

1. The loss of IHCs was modeled such that the simulated and the measured PTC tip frequencies were the same.

2. Dysfunction of OHCs was introduced in all DRNL channels. The level of OHC dysfunction was adjusted to minimize the level difference in the simulated and measured PTC tip intensity.

3. The frequency range of OHC dysfunction was adjusted to minimize the difference in tuning. The difference in tuning, \(\Delta\)tuning, was defined by integrating the quality factors different between the simulated data, \(Q_{lvl,\text{simulated}}\), and the listener, \(Q_{lvl,\text{listener}}\), near the PTC tip:

\[
\Delta\text{tuning} \ = \ \int_0^{10} |Q_{lvl,\text{simulated}} - Q_{lvl,\text{listener}}| d(lvl) \tag{4.3}
\]

\(^d\)The geometric mean frequency of the masker refers to a frequency that is equal to the root-mean-square of the lower-, and upper cutoff frequencies.

\(^e\)\(Q_3\) and \(Q_{10}\) with \(lvls\) of 3 and 10 dB, respectively, are customary quantities.
In several cases (L12, L17 and L18), it was necessary to iterate steps 1 and 2, since simulations of OHC dysfunction modified the simulation of the PTC tip frequency.

In the case of IHC insensitivity (L18) the attenuation level of two sets of PTCs were compared by first comparing PTCs with a very high level of attenuation and then lowering the attenuation level:

4. The cutoff-frequency of IHC insensitivity at 100 dB attenuation level was simulated such that PTCs with the highest-, or lowest tip frequency, for respectively low-, and high-frequency IHC insensitivity regions, were the same.

5. The level of IHC insensitivity attenuation was lowered such that the tip frequencies of the remaining PTCs matched the measured tip levels.

4.4 Results

The listener data are compared to model simulation in this section. The optimal model parameters used for fitting PTCs are shown in Table 4.1. Absolute thresholds simulated with these parameters are presented in Fig. 4.3 by dashed lines. Comparison between listener data and simulations were made by fitting rounded exponentials (roex) functions to the PTC, using the PTC tip as boundary condition for the lower-, and upper skirts of the roex. However, in the figures, the listener data are shown by individual measured data points, while modeled PTCs are presented by roex fits. This was done to make the figures more clear without losing details.

4.4.1 Normal-hearing

Figure 4.4 shows the PTC data obtained in NH listeners (gray lines). Probes are represented by black circles including white symbols. Fits of roex functions to the CASP model simulation of a NH listener are represented as black curves. The PTCs are shown for probes with frequencies of 1 kHz and 4 kHz, and levels of 30, 50 and 70 dB SPL\(^f\). The dynamic range for the masker is limited for probes presented at 70 dB SPL, which made it difficult to measure the PTC skirts in NH listeners at these levels. At the lower PTC skirts, the variance increased due to the fact that the administered sound levels were close to the uncomfortable loudness level (UCL) of the listeners. At the upper PTC skirts, the masking level exceeded the UCL very close to the frequency of the probe. Therefore, the PTC tuning, in particular in the upper skirts, could not be estimated for 4 kHz probes presented at 70 dB SPL or be compared with the simulated model data. Listener data for 1 kHz probes and simulations with 1 kHz and 4 kHz probes show tips at a higher level (<3 dB and 6 dB for 70 dB SPL probes) than the probe level. The difference at 1 kHz can be explained

\(^f\)This frequency-intensity domain was selected based on the range of probes presented to HI listeners.
by the relative large masker bandwidth (320 Hz) compared to the NH auditory filter bandwidth (133 Hz). The effective masking level of the masker was 3.8 dB\textsuperscript{8} lower than the level at which the masker was presented. The tip levels for 1 kHz probes with intensities of 30 and 50 dB were simulated at slightly lower levels than those measured in the NH listeners. At 4 kHz, listeners and simulations produced tip levels at the probe level. All tip level differences between listeners and the model were within the measurement uncertainty of 2 dB. Simulated PTCs had Q-values for tuning within one standard deviation of those found

\textsuperscript{8}The masking level of a broadband noise that exceeds one DRNL channel (or auditory filter of a listener) can be calculated from: effective masking level = 10-log(ERB/bandwidth noise).
in the NH listeners, except for probes presented at 4 kHz at 70 dB SPL. The Q-values for the 4 kHz probes presented at 70 dB SPL could not be determined because the upper PTC skirt data of the NH listeners could not be obtained. The simulated masking thresholds by the model are represented by solid black squares, in addition to the roex fit, for the 4 kHz probe presented at 30 dB SPL. All individually simulated thresholds were within one standard deviation of the NH data, except for the simulated thresholds at the lower skirt of the PTC. The model estimates relatively high masking thresholds between 0.6 and 0.9 times the probe frequency compared to the NH listener data. Similar irregularities in PTCs were observed in NH listeners when no background noise was applied to mask CT-detection.

4.4.2 Hearing-impaired

Figure 4.5 and 4.6 show measured data of HI listeners and model simulations, fitted with the parameters described in Table 4.1, that were based on the PTC analysis described in the section ‘Listeners’, above. The upper panels show the measured data (denoted with "L" and the corresponding listener number), and the lower panels show the model simulations (denoted with "M" and the corresponding listener number). The simulations are presented by roex fits to the simulated data points. Interpretation of the figures, i.e. PTC tip and tuning, are not affected by using roex fits instead of simulated data points. Probes are indicated as open black circles including a white symbol. Corresponding symbols were used to present data points (gray) and PTC tips (black). Same symbols were used in listener data and the corresponding simulations.

Figure 4.5 shows the results of the three individuals who were psychophysically diagnosed as having a low-frequency dead region:

- Listener L17 was selected because PTC tip frequencies showed no dependency on probe frequency and level. For probes presented at 750 and 1000 Hz, listener L17 produced a PTC tip shift to between 1720 and 1750 Hz. The model was able to simulate the same tip frequencies. The simulated tuning based on Q-values had slightly steeper low-frequency skirts, and less steep high-frequency skirts.

- Listener L20 was selected because PTC tip frequencies were strongly affected by the probe level and frequency. For the 1 kHz probe presented at 70 dB SPL, the PTC tip shifted to 4 kHz. This large shift suggests strong upward spread of excitation similar to the simulated data presented in panel B of Fig. 4.1. For probes presented at higher frequencies (2 kHz), or at higher levels (90 dB SPL), the PTC tip shifted to 3.5 kHz and 2.3 kHz, respectively. The model (M20) was able to simulate corresponding PTCs with IHC loss at low-frequencies and some OHC dysfunction at high frequencies.

- Listener L18 was selected because the PTC tip frequency was 2250 Hz for probes presented at 1.5 kHz at 40 dB SPL, 1500 Hz for probe presented at 1 kHz at 50 dB SPL and at the probe frequency (no tip shift) for probes
presented at 1 kHz at 70 dB SPL. Simulations of IHC loss were able to predict the measured data for probes presented at 1 kHz at either 50 dB SPL or 70 dB SPL. However, the shift to 2250 Hz was larger than predicted by the model (1600 Hz). By applying steps 4 and 5 from the fitting procedure described in the section ‘PTC analysis’ above, additional IHC insensitivity were able to predict PTC data for probes presented at 1 kHz at 70 dB SPL and probes presented at 1.5 kHz at 40 dB SPL. The combination of $F_e$ at 1500 Hz and IHC insensitivity at frequencies below 1700 Hz for levels up to 45 dB SPL, shown as M18, was able to predict PTCs for all measured probes. The modeled situation indicates a transition of IHCs, with IHC loss below 1500 Hz, insensitive IHCs between 1500 Hz and 1700 Hz, and normal-functioning IHCs at frequencies above 1700 Hz.

Figure 4.6 shows results for three individuals who were psychophysically diagnosed as having a high-frequency dead region:

- Listener L12 was selected because PTC tip frequencies showed no dependency on probe frequency and level. For 4000 Hz probe tones presented at 70 and 85 dB SPL and for a 4350 Hz probe tone presented at 90 dB SPL, listener L12 produced a PTC tip at 3 kHz. Corresponding model predictions M12 were obtained by estimating high-frequency IHC loss and a complete loss of OHC functionality (43 dB OHC dysfunction) at higher frequencies.

- Listener L14 was selected because PTC tip frequencies were strongly affected by the probe level and frequency. The PTCs were moderately tuned, producing shallow plateaus with limited variation between masking thresholds (<5 dB). A plateau produced by probes presented at 750 Hz at 50 dB SPL extended between 400 and 600 Hz. For probes presented at 1000 Hz at 90 dB SPL, a plateau was found between 500 and 1000 Hz. Probe tones of 750 Hz presented at 80 dB resulted in a broadly tuned PTC tip at 625 Hz. The best fitting model predictions M14 were found for a high-frequency loss of IHCs with $F_e$ at a relatively low frequency and some OHC dysfunction. The PTC plateaus were not reproduced by the model, but were simulated as relatively broadly tuned PTCs. The masking levels for probes at 750 Hz at 50 dB SPL were lower than the level of the probe in the listener and the model.

- Listener L15 was selected because the PTC data present a special case (found in two listeners out of the original populations of twenty-four), where some probes produced almost no tuning. Probes presented at 4 kHz at 80 dB SPL produced a nearly flat (masker threshold range <5 dB) PTC between 2 kHz and 5 kHz. The listener perceived pure tones presented at high frequencies as noise-like, and had to make large efforts to discriminate the probe from the masker noise. The model was unable to predict similar results by simulations of IHC loss, OHC dysfunction and IHC insensitivity. A simulation with additional noise with a narrow bandwidth presented at nearly the level of the probe could replicate PTCs with almost no tuning. However, the simulation
of noise-like probes, and thereby simulated model results of listener L15, was outside the scope of this study.

Figure 4.5. Comparisons between listener data and model simulations. Listeners (denoted by the letter ‘L’) with a psychophysically diagnosed low-frequency dead regions are presented in the upper panels. Simulations of these listeners (denoted by the letter ‘M’) are presented in the bottom panels. Probes are presented by black circles including white symbols. The listener data are presented by gray symbols connected by gray lines. The PTC tips are presented by black symbols and roex functions that were fitted to the simulated data are presented by gray lines. See the text for a description of the results.
4.5 Discussion

4.5.1 PTC tip frequency and $F_e$

The presented model was able to simulate PTC data with a loss of IHCs (see panels B and C in Fig. 4.1), various degrees of OHC pathology (see panel D in Fig. 4.1), and IHC insensitivity (see panel F in Fig. 4.1). The simulations suggest that remaining OHC activity in addition to the loss of IHCs (M14 and M20) and the loss of IHC sensitivity (M18) introduced the PTC tip frequency to be dependent on probe frequency and level. Depending on the diagnostic criteria for dead regions, these level effects may change the psychophysical diagnosis of dead regions. Listeners L12 and L17 showed fixed tip frequencies that were
4.5 Simulating psychophysical tuning curves

independent of the presented probes. The corresponding simulations (M12 and M17) showed that these results were best described by a complete loss of OHCs, in addition to the loss of IHCs.

Active OHCs in combination with IHC loss (see panel E in Fig. 4.1) can shift the PTC tip frequency as a function of level. This relationship might be explained by a different amplification of probe and masker by the OHCs. A probe tone presented inside a physical dead region is probably not affected by OHC activity. On-frequency OHC activity is not transmitted by IHCs, and off-frequency OHCs are not sensitive to the residual probe excitation. However, a masker presented outside the physical dead region can be amplified by on-frequency OHC activity, and can be more effective than maskers presented inside the physical dead region. An increase in level reduces the benefits of improved detection of the masker by OHC activity, reducing the masker effectiveness by an amount equal to decrease in OHC gain at frequencies outside the physical dead region. The relation between masker effectiveness and probe detection changes, which in turn may cause a shift of the PTC tip frequency. Another explanation for the effects of OHC activity on the PTC tip frequency is a shift of the best frequency towards a lower CF on the BM with reduced OHC activity. In the model, the shift of the BF is simulated by a slightly different CF of the linear and nonlinear paths in the DRNL. Reducing the gain of the nonlinear path shifts the combined CF in favor of the CF of the linear path, which is at a lower frequency. The maximum tip shift that can be induced in the model is 3 %, equal to the difference between \( \text{CF}_{\text{linear}} \) and \( \text{CF}_{\text{non-linear}} \). Furthermore, this effect is only in one direction (towards lower frequencies) and, therefore, cannot account for the simulated shifts of PTC tips.

It seems likely that OHC activity has a more prominent role than IHC insensitivity in level dependent shifts of PTC tips. However, the modeling results in this study suggest that IHC insensitivity may produce tip shifts over a large frequency range (M18). A characteristic property of IHC insensitivity is that the tip moves from a shifted tip frequency to a tip frequency corresponding to the probe frequency with increasing probe level. When PTCs can be obtained at sufficiently high probe levels, this property can be used to demonstrate IHC insensitivity. In addition, it was observed that PTC tips could shift nearly one octave towards the probe frequency at very high probe levels. In the model, the excitation patterns of the BM were extended at these high levels over several octaves, with the most sensitive place of the BM (Turner et al., 1983) found about halfway between the probe frequency and \( F_e \). Listener L20 showed a similar result of shifted PTC tip for probes presented at 90 dB SPL deep inside the psychophysically diagnosed dead region.

In psychophysical diagnosis of dead regions based on PTCs, the tip frequency is used to estimate \( F_e \). Probe frequency and level dependent shifts of the PTC tip complicate such estimations. The results of this study suggest that the relation between \( F_e \) and the PTC tip frequency depends on OHC activity and the level difference between the probe and the tip masking threshold. Tip frequencies are shifted more distant from the probe frequency than \( F_e \) in case of OHC activity and increased level difference between the PTC tip and probe
level. For example, in panel B in Fig. 4.1 and in the simulations of M14 and M20, the difference between F_e and the probe frequency was smaller than the difference between the PTC tip and the probe frequency. The frequencies of the PTC tip and F_e corresponded best when the probe was presented at a low sensation level (below 20 dB SL) and the tip frequency was close to the probe frequency (less than one octave).

4.5.2 Clinical value of the model

The relationship between psychophysical diagnosis of dead regions using PTCs and the underlying pathology is not always transparent, in particular when level effects are observed. This study showed that model simulations may help in understanding this relationship. However, before the presented model can be considered for clinical diagnosis of dead regions, masking of CT-detection in the model should be considered. Model simulations of on-frequency masking were in agreement with results found by Kluk and Moore (2005) that did not apply measures to avoid CT-detection. Additional testing of the model, motivated by the CT-detection found in NH predictions (see Fig. 4.4), revealed that the model did not simulate suppression of CTs across DRNL channels. Unsuppressed stimuli produce higher level CTs, resulting in less effective masking by CT-detection masking noise in the model. A comparison of L14 with M14 showed that the HI listeners may be affected by CT-detection in a similar manner as the model. The listener L14 showed sub-threshold masking levels for 750 Hz probe tones presented at 50 dB SPL. This may indicate that the listeners detected distortion components originating from the dead region (Moore, 2004).

An interesting clinical aspect is that, providing a set of PTCs measured at different levels and frequencies, the presented model can roughly suggest the type of hearing loss that can be responsible for the results. Dead regions and IHC insensitivity regions were simulated as a homogeneous loss of IHCs with sharp cutoff frequencies, and OHC dysfunction was assumed constant over the full frequency range of OHC dysfunction. These assumptions were made to minimize the number of free parameters for simulations, at the cost of in-detail estimations of the hearing loss. While the model was able to simulate most data of listeners reasonably well, it was not able to simulate PTC plateaus (L14) and PTCs with a broad frequency range without tuning (L15).

4.5.3 Future prospects

The noise-like perception of tones was not investigated in this study. Future studies may concentrate on how noise-like perception can be simulated in the model, and how this affects dead region diagnosis. Preliminary modeling results for noise-like perception show that dead region diagnosis may change due to a change in the nonlinear behavior of the model, for example by creating additional CT-bands.

Future work is planned to use the same model approach to simulate the effects of dead regions for TEN test results. Examination of model simulations
in TEN may provide an explanation for the differences between PTC and TEN test diagnostic results found in several studies (Summers et al., 2003; Warnaar & Dreschler, 2012).

4.6 Conclusions

This study investigated the diagnosis of dead regions using PTCs by measurement of off-frequency listening. In particular, it was hypothesized that OHC activity (in combination with a complete loss of IHCs) and IHC insensitivity may cause level-dependent effects in off-frequency listening. The hypothesis was tested by modeling various types of hearing loss, and by comparing simulated PTC results with listener data. The model results can be summarized as follows:

1. PTC tip frequency was shifted by IHC loss (dead regions), consistent with earlier findings;
2. dependent in case of active OHC functionality and IHC insensitivity;
3. The effect of OHC activity on PTC tip frequencies was limited to a shift of roughly 15%, (except at very high sensation levels where shifts were observed up to 40%);
4. IHC insensitivity can also produce shifts in PTC tip frequencies that cannot be distinguished from shifts caused by a complete loss of IHCs, for probes presented at levels below the amount of attenuation caused by IHC insensitivity;
5. The presented model was able to satisfactorily simulate most data of listeners. The model was not able to simulate some effects like PTC plateaus, and PTCs with no tuning over an extended frequency region;
6. The presented model can improve diagnosis to systematically estimate $F_e$, OHC activity, and IHC insensitivity from a set of measured PTCs by using the dependency of the PTC tip frequency on the probe level and frequency.

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