Modeling and clinical diagnosis of dead regions in the cochlea

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Citation for published version (APA):
Chapter 5

SIMULATING THRESHOLD EQUALIZING NOISE TEST RESULTS IN LISTENERS WITH DEAD REGIONS

International Journal of Audiology, submitted

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Objective: This study investigates level effects in diagnosis of dead regions with a threshold equalizing noise (TEN) test.

Design: A previously developed functional model of auditory processing was used to simulate physical hearing impairment, including complete loss of inner hair cells (IHCs), IHC insensitivity, and various degrees of outer hair cell (OHC) dysfunction. Model simulations are analyzed and compared to psychophysical listener data.

Study sample: This study compares modeled results to TEN[HL] test data of five hearing-impaired listeners measured in our lab and two hearing-impaired listeners from literature.

Results: The results show that various types of IHC impairment and OHC functionality can significantly affect TEN[HL] test diagnostics

Conclusions: Interpretation of TEN[HL] test results can be unreliable when measured at a single TEN level, and may not be accurate for estimating the edge of a dead region. Supplementary diagnosis can be provided by measuring at various TEN levels, comparing results with psychophysical tuning curves, and by models simulating physical impairment.

5.1 Introduction

This is a second paper about modeling dead regions in hearing-impaired listeners using a functional model of auditory processing. While the first paper (Warnaar et al., 2013) concentrated on simulating psychophysical tuning curves (PTCs), this paper concentrates on simulating Threshold Equalizing Noise (TEN) test results.

A cochlear dead region indicates a frequency region of the cochlea that is associated with missing or non-functional inner hair cells (IHC) and/or fibers of the auditory nerve (Moore & Glasberg, 1997; Moore et al., 2000). The region itself is completely insensitive to auditory stimuli (Moore & Glasberg, 1997; Moore & Alcántara, 2001), but neighboring frequency regions may still be able to perceive stimuli presented inside the dead region through off-frequency listening (Johnson-Davies & Patterson, 1979; O’Loughlin & Moore, 1981; Moore, 2004). The perception of off-frequency detected probe tones is used in psychophysical diagnosis of dead regions using experimental and clinical tests, such as PTCs and the TEN test.

The TEN test (Moore et al., 2000; 2004) was conceptually designed to diagnose dead regions in a clinical setting. The test is fast and can be administered in a routine setup for clinical audiometry. The TEN test measures the masked threshold of pure-tone probes in a broadband noise. The noise is shaped spectrally in such a way that it produces about equal masking levels in normal-hearing listeners over a wide range of frequencies. TEN in sound pressure level, TEN[SPL], (Moore et al., 2000) and TEN in hearing level, TEN[HL], (Moore et al., 2004) were created in order to produce equal masking levels in dB SPL
5.1 Simulating TEN test in listeners with dead regions

and dB HL, respectively. In comparison to TEN[SPL], the bandwidth of the TEN[HL] was reduced to a range from 354 Hz to 6500 Hz and the noise was produced with a low crest factor to reduce excessive loudness at high presentation levels of TEN (Moore et al., 2004).

The level of TEN is expressed as a level per equivalent rectangular bandwidth (ERB) of the auditory filter in normal-hearing listeners (i.e., dB HL/ERB\textsubscript{N} for TEN[HL]). ERB\textsubscript{N} at 1 kHz equals 132 Hz (Moore & Glasberg, 1996). This convention assumes that the masked threshold is related to a constant ratio between the masker and the probe at the output of the auditory filter, given by (Patterson & Moore, 1986):

\[
\frac{P_s}{N_o} = K \cdot \text{ERB}
\]

where \(P_s\) is the power of the signal, \(N_o\) denotes the noise spectral density, and \(K\) is the masker-to-probe ratio. The ratio \(K\) was experimentally measured to be approximately 1 (0 dB S/N) at 1 kHz (Moore et al. 1997). The spectral shape of the TEN (\(N_o\)) compensates for variations of \(K\) with frequency (Moore et al. 1997; 2000; 2004). Variations in \(K\) with level are not compensated in the spectral shape of the TEN (Moore, 2001).

The rationale of the TEN test for the diagnosis of dead regions is based on measuring the masked threshold of a probe independent of the detection frequency, i.e. the masked threshold at the most sensitive place on the BM. In normal-hearing listeners, probe tones are perceived on-frequency and are masked by TEN presented at a TEN level equal to the probe level (Moore et al., 2000). In case of a listener with a dead region, a high-level probe tone presented inside the dead region is typically perceived at a low-level off-frequency place. A relatively low-level broadband TEN provides sufficient masking to mask the off-frequency perceived probe. The TEN test uses two conditions to indicate a dead region. First, the probe level is elevated above the absolute threshold level in quiet by a predefined criterion. This assures that the TEN is presented at a sufficient level to produce masking of the probe. Second, the probe level is elevated above the TEN level at masked threshold by a predefined criterion. Hereby, it is assumed that the probe is masked at an off-frequency location of the BM. Moore et al. (2000) suggested to use elevation criteria of +10 dB to diagnose a dead region that extends at least the frequency of the probe.

The TEN spectral shape and the TEN test elevation criteria are independent of level. Moreover, the TEN test was designed to work at different levels. Therefore, it is required that an increase of probe level is associated with an equal increase of TEN level to achieve masked threshold. However, Markessis et al. (2009) and Warnaar and Dreschler (2012) have shown dependencies between probe elevation at masked threshold and presentation levels of TEN[HL] in some listeners. Markessis et al. (2009) showed TEN[HL] test results of thirteen listeners being diagnosed for dead regions. In four listeners, an increase of TEN level changed the diagnosis from dead region to no dead region for probes presented at frequencies corresponding to a suggested edge frequency of the dead region, \(F_e\). For one listener with a low-frequency dead region, an increase of
TEN level changed the diagnosis from no dead region to a dead region at a single frequency. Markessis et al. (2009) suggested IHC insensitivity to explain their results. A region with IHC insensitivity is irresponsive, similar to a dead region, to low-level stimuli, but responds normal to high-level stimuli. Warnaar and Dreschler (2012) presented similar results in a population of twenty-four hearing-impaired ears. They found the diagnosis of dead regions to be dependent on the presentation levels of the stimuli in PTCs and TEN[HL] test results. In TEN[HL] test results, an increase of TEN level changed the diagnosis from dead region to no dead region (ears HI\textsubscript{03}, HI\textsubscript{09}, HI\textsubscript{13}, HI\textsubscript{14}, HI\textsubscript{15}, HI\textsubscript{17} and HI\textsubscript{20}), and vice versa (ears HI\textsubscript{15}, HI\textsubscript{18}, HI\textsubscript{20}).

The PTC results from Warnaar and Dreschler (2012) were analyzed in more detail in the study of Warnaar et al. (2013) by comparing the listener data to model simulations. In some subjects they found evidence supporting the presence of a region of IHC insensitivity as suggested by Markessis et al. (2009). The authors found evidence that diagnostic changes in PTCs can be explained by OHC functionality near $F_e$. They also found that the simulated frequency of $F_e$ did not necessarily correspond to the estimated $F_e$ as derived from PTC results. The authors suggested to distinguish between the physical location of $F_e$ on the BM and the estimated edge frequency of a dead region as measured by psychophysical tests.

Functional OHCs directly affect the basilar-membrane mechanics (Ruggero et al., 1997; Robles & Ruggero, 2001). Psychophysically, these effects are measured as increased frequency selectivity, lowered absolute thresholds and a nonlinear growth of loudness perception (Pick et al., 1977; Glasberg & Moore, 1986; Tyler, 1986; for a review, see Oxenham & Bacon, 2003). Moore and Glasberg (1997) showed that ERBs of auditory filters are typically different by a factor of 2 to 3 between normal-hearing listeners and hearing-impaired listeners with OHC loss. The sharpening of auditory filters improves the signal-to-noise ratio in listeners with functional OHCs. Experimental measurements using pure-tones in noise show that the masked threshold is typically 2 to 3 dB higher in hearing-impaired listeners with OHC loss than in normal-hearing listeners (Glasberg & Moore, 1986; Moore et al., 2000). These results suggest, consistent with Eq. (5.1), that probe tones in TEN are elevated by several dBs in listeners with OHC loss as compared to listeners with functional OHCs. Furthermore, OHCs are most responsive to on-frequency stimuli presented at low-levels (Cooper & Rhode, 1995; 1997; Ruggero et al., 1997). Probe tones that are presented inside a dead region are not likely to be affected by OHC non-linearity as they are typically presented at high-levels and are detected off-frequency. However, broadband TEN contains frequency components at the place of detection just outside the dead region. These components are on-frequency to the place of perception and are typically presented at levels lower than the level of the probe, possibly within the level range of OHC non-linearity (Robles & Ruggero, 2001). Therefore, probes and TEN may be affected differently by OHC functionality.
The goal of this study is twofold:

1. Explain psychophysically measured TEN[HL] test results from hypothesized physiological impairments. Physiological impairments were simulated using a functional model of auditory processing (Jepsen et al., 2008). Investigated types of hearing impairment were a complete loss of IHCs in combination with various degrees of OHC functionality and insensitivity of IHCs.

2. Compare simulations of TEN[HL] test results to individual listener TEN[HL] test data. Listener data were taken from Warnaar and Dreschler (2012) and Markessis et al. (2009). Data from Warnaar and Dreschler (2012) were compared with TEN[HL] test results simulated with model parameters fitted to PTCs of corresponding listeners (Warnaar et al., 2013). By using a set of model parameters that were not fitted to TEN[HL] test results, the purpose of comparing modeled and measured data was foremost to validate the model simulations with two independent sets of data. In addition, a close fit of simulated results and listener data will indicate that the observed effects in TEN[HL] test data can be fully explained by the simulated hearing-impaired effects. Some comparisons, in particular comparisons to data from Markessis et al. (2009), were made without pre-fitted model parameters. In these cases, model parameters were fitted directly to TEN[HL] test data.

The section headed ‘Model based hypotheses’ describes a functional model of auditory processing, modeling methods, and a detailed analysis of simulated TEN[HL] results. The section headed ‘Experimental method’ describes the experimental method used to obtain TEN[HL] test results in hearing-impaired listeners. The Results section, below, presents comparisons between hearing-impaired TEN[HL] test results and simulated TEN[HL] test results. In the Discussion section the dead region diagnosis using the TEN[HL] test is discussed.

5.2 Model based predictions

This chapter establishes a relationship between physiological impairments associated with dead regions and psychophysically measured TEN[HL] test results by using a functional model of auditory processing. The section headed ‘Functional simulation of the TEN[HL] test’ below describes the functional simulation of normal-hearing physiological properties and the simulation of a psychophysical response to auditory stimuli. The section headed ‘Simulations of normal-hearing’ presents simulated TEN[HL] test results for normal-hearing. The section headed ‘Consequences of simulating hearing impairment’ describes model modifications to simulate physiological hearing impairments and presents simulated physiological results of the various types of impairments.

5.2.1 Functional simulation of the TEN[HL] test

Jepsen et al. (2008) proposed a computational auditory signal processing and perception (CASP) model for simulating a wide variety of auditory features,
including nonlinear effects associated with basilar-membrane processing such as the production and detection of beats and combination tones, OHC nonlinearity, off-frequency listening, and suppressive masking. The model has been successfully applied in a number of studies to simulate psychophysical behavior in normal-hearing (Jepsen et al., 2008; Moore et al, 2009; Warnaar et al., 2013) and hearing-impaired listeners (Jepsen & Dau, 2011; Warnaar et al., 2013).

The model does not intend to simulate the actual physiology, instead it attempts to simulate the functional response of the auditory system by a chain of modules. Some modules, however, can be related to actual physiological parts, such as the dual resonance non-linear (DRNL) filterbank (Meddis et al., 2001; Lopez-Poveda & Meddis, 2001), which describes the transformation of stapes movement to basilar-membrane movement. The DRNL filterbank consists of a number of channels. Each channel has a linear and a non-linear path to simulate passive and non-linear active BM excitation. The paths are tuned to different characteristic frequencies ($\text{CF}_{\text{non-linear}}$ is 3% higher than $\text{CF}_{\text{linear}}$) 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 optimal detector combines all channels by averaging their internal representations. A combined internal representation is created for a target listening cue, reference samples, and the actual test stimuli. In case of simulating TEN[HL] test results, the target cue is a probe signal at suprathreshold level. The combined internal representation of the target cue provides a template, which can be regarded as a mathematical description of "what to listen for". Reference samples are created with TEN[HL] only, and test stimuli are created with a probe tone in TEN[HL]. The output of the optimal detector is the difference between the test stimuli and the reference samples, all cross-correlated with the template.

The final module of the model is a decision device. The decision device simulates the psychophysical response of the model, i.e. the masked threshold in simulations of TEN[HL] test results. An overall Gaussian-distributed internal model noise is added to the output of the optimal detector to simulate the limited resolution of the auditory system. The correlation coefficient between template and the test stimulus was used calculate the probability of detection. When the probability exceeded the detection threshold for the applied test procedure (see section ‘Procedure and stimuli’), the probe was assumed to be detected. The intensity resolution of the model followed Weber’s law. This meant that the just noticeable level difference in dB that the model could detect was independent of level. The just noticeable difference was set to 1 dB for 1 kHz pure tones and broadband noise (Jepsen et al., 2008).

5.2.2 Simulation of normal-hearing

The diagnostic outcome of the TEN[HL] test is based on the masked threshold elevation above the absolute threshold and TEN level. The original CASP
model has a lower detection limit of 0 dB SPL at all frequencies, which satisfies simulation requirements for most applications. However, for simulations of TEN[HL] test results a simulation of a more meaningful threshold level is necessary. In addition to the model functionalities as described by Jepsen et al. (2008), an absolute threshold (ISO 389-8) was simulated at the output of the DNRL filterbank\(^a\), which for normal-hearing listeners was defined at 0 dB HL. Absolute threshold levels were simulated by setting minimal signal levels. Internal model representation with a minimal signal level provided no detection cues in the model. In Fig. 5.1, the absolute thresholds are represented by solid black lines.

Model simulation of TEN[HL] test results for normal hearing listeners are shown in panel A of Fig. 5.1. Masked thresholds for probes with frequencies between 500 and 4000 Hz were predicted at TEN levels of 30, 50, 65, and 75 dB HL/ERB\(_N\). The TEN levels are represented by a dashed horizontal line with a gray filled symbol at the lower cutoff-frequency (354 Hz) of the TEN. Masked thresholds are shown with corresponding open symbols. Open symbols were substituted by corresponding solid symbols when dead region criteria of +10 dB were satisfied. Simulations were repeated 10 times with independently created internal representations. The variation in masked threshold is represented in the figure by error bars representing two standard deviation errors. Masked thresholds were predicted at TEN level within 95 % confidence intervals. No result met dead region criteria.

5.2.3 Consequences of simulating hearing impairment

The functionalities of the CASP model were extended to simulate dead regions by a complete loss of IHCs, OHC dysfunction, and IHC insensitivity. The frequency range of each type of hearing impairment could be independently specified.

Simulating complete loss of IHCs

The loss of IHCs effectively eliminates transduction of BM movement into auditory-nerve action potentials. The physical loss of transduction was simulated in the CASP model by removing DRNL channels with a CF\(_{channel}\) corresponding to the frequency range of the physical dead region. The cutoff-frequency at CF\(_{channel}\) was used as indicator of the physical edge of the dead region, i.e. \(F_e\). Panel B in Fig. 5.1 shows simulations of TEN[HL] test results with modeled IHC loss. Low-frequency and high-frequency cutoff-frequencies for \(F_e\) were set at 1400 Hz and 3000 Hz, respectively. At very low-level TEN (30 dB HL/ERB\(_N\)), probes that were presented inside the frequency range of eliminated IHCs were elevated above the test criteria, indicating dead regions. At other frequencies, masked threshold were simulated at TEN level, except for an average elevation of 5 to 8 dB of probes presented just below the simulated high-frequency dead regions. In case TEN[HL] was presented at intermediate levels

\(^a\)More specifically, absolute thresholds were modeled between the modules “expansion” and “adaptation”. See Jepsen et al. (2008) for details.
(50 and 65 dB HL/ERB\(_N\)), masked thresholds between 875 Hz and the low-frequency cutoff of 1400 Hz were slightly elevated but did not meet dead region criteria. At high-level TEN (65 and 75 dB HL/ERB\(_N\)), the masked thresholds just below the simulated high-frequency met dead region criteria. In conclusion, the elevation of masked thresholds depends on the level of TEN with a trend of elevated masked thresholds at frequencies below \(F\_e\) for high-level TEN maskers.

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

The loss of OHCs linearizes the basilar membrane response. Linearization was simulated by a reduced gain in the non-linear path of the DRNL\(^b\). A reduced gain increases the absolute threshold of the model, and linearizes the mid-level input-output level of the DRNL. Effectively, the total gain provided of OHCs was reduced, and lower level limit at which compression of the input-output function was simulated was increased (see Fig. 4.2). The level difference between the normal-hearing absolute threshold and the absolute threshold with OHC loss was defined as the level of OHC dysfunction. The level of OHC dysfunction could be varied from zero to a maximum level of OHC dysfunction depending on the characteristic frequency of the channels. A complete loss of OHCs corresponded to a level of OHC dysfunction of 34 and 43 dB at 1 and 4 kHz, respectively (Jepsen & Dau, 2011).

Panel C of Fig. 5.1 shows the simulated TEN[HL] test results with modeled OHC dysfunction (with normal IHC functionality). A TEN that was presented below the level of OHC dysfunction (30 dB HL/ERB\(_N\)) resulted in elevations up to the raised absolute threshold. At higher TEN levels, masked thresholds were on average elevated by 2 dB relative to normal-hearing simulations.

**Simulating complete loss of IHCs in combination with OHC dysfunction**

Panel D in Fig. 5.1 shows simulated TEN[HL] test results for a modeled combination of IHC loss and a complete loss of OHC functionality. Model parameters were similar to the parameters used to simulate IHC loss (panel B) and OHC loss (panel C). The simulated results were, unlike simulations of IHC loss with OHC functionality (panel B), not dependent on TEN level. Masked thresholds were elevated at frequencies below \(F\_e\) for all TEN levels. Dead region criteria were met below 875 Hz (38 % below \(F\_e\) at 1400 Hz) and above 2875 Hz (4 % below \(F\_e\) at 3000 Hz). However, masked threshold were also significantly elevated at frequencies 17 % below the simulated edge of the high-frequency dead region. At 875 Hz, dead region criteria were met with a small margin at very high (75 dB HL/ERB\(_N\)) TEN levels only.

**Simulating IHC insensitivity to low-level sounds**

Insensitivity of IHCs reduces the generation of receptor potential in IHCs for low-level stimuli. A region of IHC insensitivity was simulated by reducing the output levels of corresponding DRNL channels by a fixed level of attenuation.

Panel E in Fig. 5.1 shows simulated TEN[HL] test results of modeled IHC insensitivity to low-level sounds.

\(^b\)In the model paper (Meddis & Lopez-Poveda, 2001) indicated with the parameter ‘a’.
5.2 Simulating TEN test in listeners with dead regions

Figure 5.1. Simulated TEN[HL] test results for normal-hearing (A), dead regions with OHC function (B), OHC dysfunction (C), dead regions without OHC function (D), and high-frequency region with IHC insensitivity (E). Region with impaired IHCs are represented by a light gray area. TEN[HL] levels are presented by dashed straight lines and an gray ending symbol at the low-frequency cutoff of TEN[HL]. Masked thresholds are presented by symbols corresponding to the applied level of the TEN[HL]. Open and solid symbols are used to indicate the diagnostic result no dead region or dead region, respectively. The error bars show 95% confidence intervals for 10 independently simulated results.
insensitivity with an attenuation level of 60 dB. Probes with frequencies near \( F_e \) were masked by TEN well below the level of attenuation (30 dB HL/ERB\(_N\)). Elevations were comparable to elevations simulated with dead regions due to IHC loss (panel B). At TEN levels just below the attenuation level (50 dB HL/ERB\(_N\)) and higher, the masked thresholds were not elevated near \( F_e \). The elevation increased gradually with frequency deeper inside the region of IHC insensitivity for all TEN levels below the attenuation level. The simulated results in TEN presented above the attenuation level were not elevated and were comparable to results in normal-hearing simulations (panel A).

5.3 Experimental method

The sub-section below, ‘Procedure and stimuli’ describes the experimental setup used to obtain TEN[HL] test data in listeners. The sub-section headed ‘Listeners’ describes the hearing-impaired listener population participating in this study. The sub-section headed ‘Analysis’ provides analytical procedures for fitting and comparing simulated to measured TEN[HL] test results.

5.3.1 Procedure and stimuli

The TEN[HL] test results were measured with an adaptive three-alternative forced-choice (3AFC) procedure. Each interval presented a TEN[HL] masker with a duration of 400 ms and a pure-tone probe of 200 ms in one randomly chosen interval. The probe was centered in time within its interval. Cosine squared ramps of 50 ms were applied to the masker and probe. Consecutive intervals were separated by a pause of 460 ms. The task of the listener was to specify the interval containing the probe.

Maskers were presented at fixed TEN levels. Probes were initially presented at suprathreshold levels of TEN level plus 30 dB and adjusted according to a 1-up and 2-down procedure until masked threshold was found. The procedure converged to a 71 % level on the psychometric curve (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 masked threshold. Listeners received visual feedback after each response. Probe levels were limited to a maximum of 90 dB HL. Probes were presented at frequencies at every 500 Hz between 1000 and 4000 Hz.

The TEN[HL] spectra were calibrated by applying the reference equivalent threshold sound pressure levels for circumaural earphones (RETSPL) (ISO 389-8, Tab. 1) on the coupler to eardrum difference (C/E) of the artificial ear type 4153, i.e. RETSPL + C/E. In addition, the TEN level was corrected for a fixed psychometric level difference of +3.6 dB to account for the difference between using a 3AFC method with an 1-up, 2-down procedure instead of an audiometric method normally used in the TEN[HL] test.

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 (σ < 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 to the test 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.

![Figure 5.2](image)

**Figure 5.2.** This figure is a reworked version of Fig. 4.3. Pure-tone audiograms of hearing-impaired listeners are presented by marks and solid lines. Simulated absolute threshold using parameters listed in Table 5.1 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).
Simulating TEN test in listeners with dead regions

<table>
<thead>
<tr>
<th>Listener</th>
<th>Age</th>
<th>Gender</th>
<th>Ear</th>
<th>Etiology</th>
<th>OHC Function</th>
<th>Dead Region (dB)</th>
<th>IHC Insensitivity</th>
<th>Attenuation Region</th>
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<tr>
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<td>f</td>
<td>l</td>
<td>mumps</td>
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<tr>
<td>L17</td>
<td>55</td>
<td>m</td>
<td>l</td>
<td>unknown</td>
<td></td>
<td>-34*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M17-DR</td>
<td>19</td>
<td>f</td>
<td>r</td>
<td>meningitis</td>
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<td>-43*</td>
<td>105</td>
</tr>
<tr>
<td>M17-SR</td>
<td>56</td>
<td>m</td>
<td>r</td>
<td>unknown</td>
<td></td>
<td>-34*</td>
<td></td>
<td>1415</td>
</tr>
<tr>
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<td>105</td>
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<tr>
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<td>r</td>
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<td></td>
<td></td>
<td>-43*</td>
<td>1415</td>
</tr>
</tbody>
</table>

Table 5.1. This table is a reworked version of 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.
5.3 Simulating TEN test in listeners with dead regions

5.3.2 Listeners

Five hearing-impaired listeners, aged between 19 and 56 years (median: 29), were selected out of the group of listeners representing twenty-four measured ears, to illustrate representative effects that were found in the results of the whole group. Selected listeners were psychophysically diagnosed with high-frequency (L12 and L14), and low-frequency (L17, L18 and L20) psychophysical dead regions with various degrees of dependency on TEN level (no: L12; weak: L18, L20; strong: L14, L17). Table 5.1 lists auditory details of the listeners and the model parameters of the IHC-, and OHC functions. Model parameters were taken from PTC fitted data of corresponding listeners from the study of Warnaar et al. (2013). The pure-tone audiograms of listeners are presented in Fig. 5.2 by customary audiometric symbols and solid lines. Modeled absolute thresholds are presented by dashed lines. All listeners received compensation for their efforts, and a reimbursement of their travel expenses. The study was approved by the Medical Ethical Committee of the Academical Medical Center in Amsterdam, AMC (MEC 05/183).

5.3.3 Analysis

Relationships between physical modeled hearing-impaired functions and psychophysically measured TEN[HL] test data were evaluated by comparing data simulated with a single set of parameters to the results on individual listeners. Model parameters were obtained from Warnaar et al. (2013) or by fitting model parameters directly to TEN[HL] test results. A comparison between TEN[HL] test results was made by evaluating the probe elevations as a function of probe frequency and TEN level.

When model parameters fitted to PTCs were not available, the model parameters had to be fitted directly to TEN[HL] test results. A procedure was defined to find an optimal fit between simulations and measured TEN[HL] test data. The procedure was based on assuming that the highest level of TEN was most likely to produce off-frequency masking of probes (Moore et al., 2000). Various levels of TEN were used to optimize the interpretation of TEN[HL] test results as was recommended by Markessis et al. (2009). The fitting procedure consisted of a step by step procedure:

1. The results of the highest level TEN presented to the listener were used to simulate $F_e$ by modeling IHC loss such that the simulated diagnostic result (dead region or no dead region) and the measured TEN[HL] test data were the same.

2. Dysfunction of OHCs was introduced in all DRNL channels and varied to find the best fit to masked thresholds for all TEN levels and probe frequencies to the listener data using least squares optimization.

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$^c$The numbering of listeners (e.g. Lxx) refers to the original numbering of ears (e.g. HI_{xx}) (Warnaar & Dreschler, 2012).
3. The frequency range of OHC dysfunction was adjusted to minimize masked threshold differences at frequencies outside the dead region.

The procedure was repeated when dead regions were diagnosed at low-level TEN and not at high-level TEN. Step 1 was replaced by simulation of IHC insensitivity:

1a. The results of the highest level TEN presented to the listener were used to simulate $F_e$ by modeling IHC insensitivity with a level of attenuation set equal to the highest level of TEN that produced a dead region result.

1b. The cutoff frequency of IHC insensitivity was adjusted such that simulated and measured TEN[HL] test data had the same diagnostic results.

The fitting procedure was then followed by steps 2 and 3 for fitting OHC dysfunction parameters for TEN[HL] data.

Comparisons between simulated and measured TEN[HL] test results were evaluated based on the level of elevation as a function of probe frequency and TEN level. Results were assumed to match when:

1. The relative elevation of masked thresholds as a function of TEN level were equal within measurement and simulation errors at all frequencies.

2. The absolute levels of elevation were equal within measurement and simulation errors at all frequencies.

3. Diagnostic results indicating a dead region or no dead region were equal within measurement and simulation errors at all frequencies and TEN levels.

4. Results obtained at a specific TEN level showed a similar trend of elevation as function of frequency.

5.4 Results

In this section, listener data are compared to model simulated results. Table 5.1 presents model parameters that were taken from Warnaar et al. (2013) or were fitted to TEN[HL] test results.

5.4.1 Comparison with data from Warnaar et al. (2012)

Figures 5.3 and 5.4 show measured data of hearing-impaired listeners and the simulated model results for high-, and low-frequency dead regions, respectively. The upper panels show the measured listener 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). Measured pure-tone audiograms and simulated absolute thresholds are represented by thick black lines. TEN levels are represented by dashed horizontal lines with
5.4 Simulating TEN test in listeners with dead regions

gray filled symbols at the lower TEN cutoff frequency of 354 Hz. Masked thresholds are represented by symbols corresponding to the masking TEN levels. Open and solid symbols were used to indicate no dead region and a dead region diagnostic results based on +10 dB criteria, respectively.

Figure 5.3 shows the results of two listeners who were psychophysically diagnosed for high-frequency dead regions:

- Listener L12 was selected because TEN[HL] test results indicated a dead region at 4000 Hz and no dependency on TEN level. The model (M12) simulated a high-frequency dead region with $F_e$ at 4000 Hz and slightly elevated levels at 3000 and 3500 Hz for TEN presented at 50 and 65 dB HL/ERB$_N$. The measured and simulated results showed no significant dependency on TEN level.

- Listener L14 was selected because of level dependent TEN results. Probes presented at 500 Hz and 1000 Hz were elevated by, respectively, 15 to 5 dB and 25 to 20 dB when the TEN level was raised from 50 to 65 dB HL/ERB$_N$. The model (M14) simulated a similar dependency on TEN[HL] level at 500 and 1000 Hz. Consistent with listener data, elevations were relatively low in TEN presented at 65 dB HL/ERB$_N$ compared to elevations in TEN presented at 50 dB HL/ERB$_N$.

Figure 5.4 shows the results of three listeners who were psychophysically diagnosed for low-frequency dead regions:

- Listener L17 was selected because of TEN level dependent results. While there were no indications of dead regions, the masked thresholds at 1000 Hz were elevated by 17 (3 relative to absolute threshold), 8 and 2 dB with TEN presented at 37, 57 and 67 dB HL/ERB$_N$, respectively. Model simulations were made with parameters taken from Warnaar et al. (2013) (M17-DR) and with parameters directly fitted to TEN[HL] test data (M17-SR). Simulations with M17-DR showed a linear increase of masking elevations inside the dead region. This is inconsistent with the listener data. Simulated TEN[HL] test results with M17-SR model parameters showed results consistent with the listener data.

- Listener L18 was selected because of a weak dependency of TEN[HL] test results on TEN level near 1500 Hz, and increased masked thresholds at frequencies above 3000 Hz. Model simulations (M18) indicated a dead region near 1000 Hz and elevated masked thresholds at 1500 Hz. The simulations showed a more linear increase of masked thresholds at 1500 Hz than the listener. The masked thresholds at frequencies above 3000 Hz were, similar to the listener, simulated at elevated levels. Unlike the listener, the elevations did not meet dead region criteria.

- Listener L20 was selected because of a weak dependency of TEN[HL] test results on TEN level. Masked threshold elevations at 2000, 3000 and 3500 Hz were all measured within a small level margin of 4 dB at levels just above
and just below dead region criteria. Model simulations (M20) indicated dead regions at low-level TEN (50 dB HL/ERB_N) and no dead region at high-level TEN (65 dB HL/ERB_N) between 2000 and 3000 Hz. Masked thresholds measured in 65 dB HL/ERB_N TEN were significantly higher at 1500, 3000 and 3500 Hz (86, 77 and 78 dB, respectively) than the simulated thresholds (78, 71 and 67 dB, respectively).

**Figure 5.3.** Comparisons between listener data and model simulations. Listeners (denoted by the letter ‘L’) with psychophysically diagnosed high-frequency dead regions are presented in the upper panels. Simulations of these listeners (denoted by the letter ‘M’) are presented in the bottom panels. The absolute threshold levels measured in pure-tone audiometry are represented by black solid lines. See caption of Fig. 5.1 for a description of the other symbols. See the main text for a description of the results.
5.4 Simulating TEN test in listeners with dead regions

Figure 5.4. Comparisons between listener data and model simulations. Listeners with psychophysically diagnosed low-frequency dead regions (upper panels) and model simulations of the same listeners (bottom panels). See captions of Fig. 5.1 and Fig. 5.3 for an explanation of the figure and the main text for a description of the results.
Figure 5.5. Comparisons between measured results derived from a description of participant P16 in the study of Markessis et al. (2009) and model simulations. Simulated dead region results (MP16 - DR) are shown in the middle panel, and the results that were simulated with a region of IHC insensitivity (MP16 - IIHC) are shown in the bottom panel. See captions of Fig. 5.1 and Fig. 5.3 for a description of the symbols.
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5.4.2 Comparison with data from Markessis et al. (2009)

Markessis et al. (2009) measured probe tones in TEN presented at 60, 70, 80 and 90 dB HL/ERB\(_N\). They described two types of TEN[HL] test results that were investigated in more detail in this study:

1. A low-frequency region that was diagnosed as no dead region with intermediate-level TEN and as dead region in high-level TEN: Listener P4 in the study of Markessis et al. (2009). The listener had a low-frequency hearing loss with absolute thresholds of 50 dB HL below 750 Hz and 38 dB HL at 1000 Hz, which may indicate a low-frequency dead region with \(F_e\) between 1000 Hz and 1500 Hz. Absolute thresholds indicated normal-hearing at frequencies above 1500 Hz. The listener was diagnosed with intermediate-level TEN as having no dead region, and with high-level TEN as having a dead region with \(F_e\) at 1000 Hz. The simulated trends for complete IHC loss (see Fig. 5.1, panels B and D), showed similar results as those described by Markessis et al. At 875 Hz, simulations of a complete loss of low-frequency IHCs with \(F_e\) at 1400 Hz, showed no dead region at intermediate TEN levels (65 dB HL/ERB\(_N\)) and a dead region at high TEN levels (75 dB HL/ERB\(_N\)).

2. Second, a high-frequency region that was diagnosed as a dead region with intermediate-level TEN and as no dead regions in high-level TEN: Listener P16 in the study of Markessis et al. (2009). The results of this listener are plotted in the upper panel of Fig. 5.5. The participant had a very steep sloping hearing loss between 1000 and 2000 Hz. The masked threshold elevations at 1500 Hz indicated a dead region with TEN presented at 60 to 80 dB HL/ERB\(_N\), but for the TEN presented at 90 dB HL/ERB\(_N\) no indications for a dead region were found. This transition in diagnostic result is consistent with trends of IHC loss with normal OHC functionality (Fig. 5.1, panel B) and with the results of listener L14 (Fig. 5.3). Markessis et al., on the other hand, suggested a region of IHC insensitivity to explain the results. The TEN[HL] test results of P16 were fitted with a complete loss of IHCs (MP16-DR) and with IHC insensitivity (MP16-IIHC) to find an optimal set of model parameters. The simulated results are shown in the bottom two panels of Fig. 5.5. Simulations with MP16-DR showed a high-frequency dead region with \(F_e\) at 1415 Hz, and showed a complete loss of OHCs above 1000 Hz. Simulations with MP16 - IIHC showed a high-frequency region of IHC insensitivity with \(F_e\) at 1415 Hz, an attenuation level of 105 dB HL, and a complete loss of OHCs above 1000 Hz. A transition of dead region to no dead region with increasing TEN level were predicted by MP16-DR and MP16-IIHC. However, the transition was estimated in MP16-DR between 60 and 70 dB HL/ERB\(_N\), which was inconsistent with P16. The transition was consistent with listener data estimated by MP16-IIHC between 80 to 90 dB HL/ERB\(_N\). Furthermore, MP16-DR results showed a monotonic increase towards higher frequencies, which became inconsistent with the lis-
tener data above 2000 Hz. The results of MP16-IIHC were more consistent with the listener at these frequencies. The results were fairly similar up to a frequency of 4000 Hz and suggest that IHC insensitivity, as suggested by Markessis et al. (2009), is likely.

5.5 Discussion

5.5.1 Effects of different types of hearing impairment on masked thresholds

Probe tones that were presented inside a dead region, simulated by a complete loss of IHCs, produced elevated masked thresholds in TEN. This is consistent with the TEN[HL] test rationale (Moore et al. 2000). However, the model results of this study do not support an accurate estimate of $F_e$ by using the diagnostic results of the TEN[HL] test. The simulated results showed that dead region criteria were met below $F_e$. Probes presented inside a low-frequency dead region met test criteria only at frequencies deep inside the region, and masked thresholds measured just outside a high-frequency dead region were elevated above test criteria. The difference might be explained by a strong upward spread of excitation on the BM. Places on the BM that are associated with frequencies just above a low-frequency dead region are sensitive to probes presented inside the dead region. Probes presented inside the dead region may be detected at masked thresholds (just) below the diagnostic criteria of the TEN[HL] test. The difference between simulated and estimated $F_e$ was less pronounced for high-frequency dead regions. Probe tones presented just below a high-frequency dead region may be partially masked by high-level TEN without benefit of high frequency probe information.

Simulations showed that even a complete loss of OHCs elevated masked thresholds by a few dBs only and does not significantly change dead region diagnosis of the TEN[HL] test. In combination with IHC loss, a complete loss of OHCs resulted in a linear increase of masked thresholds with increasing TEN level. However, simulations of OHC functionality in combination with IHC damage showed a significant dependency of TEN[HL] test diagnosis on presentation levels. Masked thresholds were most affected in low-level TEN. Possibly, amplification of probes and TEN maskers is differently affected by OHC non-linearity. The OHCs near the edge of the dead region provide no amplification to the off-frequency probe tone, while providing non-linear on-frequency amplification of frequency components of TEN just outside the dead region. In the model, the effects of OHC amplification are limited to levels below 70 dB SPL (Jepsen and Dau, 2011). The model trends that are presented in Fig. 5.1, panel B, are consistent with this limit by showing a non-linear increase of elevation only at TEN levels up to 65 dB HL/ERB$_N$. Participant P16 (Markessis et al., 2009) produced level dependent results at levels up to 90 dB HL, which are much higher than the expected upper limit of OHC functionality and consistent with the simulated results showing that low-level insensitivity of the IHCs
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is a more likely candidate as type of hearing impairment for this listener. Plack et al. (2004) showed that the compression and the gain of the basilar membrane input-output function can shift to a higher level. It may, therefore, be argued that listeners may be susceptible to non-linear TEN[HL] test behavior even at higher levels than indicated by the normal-hearing level range of OHC functionality.

Simulations of low-level insensitivity of the IHCs showed that the attenuation of IHCs increased the masked thresholds of low-level stimuli in the TEN[HL] test, while not affecting high-level stimuli. Simulated results of listeners L17 and P16 supported the assumption that regions with IHC insensitivity to low levels may affect TEN[HL] test diagnosis. However, the functional changes in the model simulating IHC insensitivity may also be caused by a region that produces a reduced IHC output, e.g. a region with severely damaged IHCs and/or IHC stereocilia (Liberman et al., 1986, for a review). Additional studies on this subject are required to establish IHC insensitivity as a relatively common type of hearing impairment causing a level dependency in the TEN test results.

5.5.2 Dead region diagnosis with the TEN[HL] test

A dead region diagnostic result obtained with the psychophysical TEN[HL] test may not indicate a physical dead region in terms of a complete loss of IHCs. Alone, simulations of TEN[HL] test results show that the TEN[HL] test is not sufficient to confidently differentiate a loss of IHCs from other types of hearing impairments causing masked threshold elevations. However, the TEN[HL] test can provide additional information about the auditory system in combination with PTCs and modeling techniques. As an example, the TEN[HL] test results of listener L17 indicated a low-frequency region of IHC insensitivity at 1000 Hz based on low-, intermediate-, and high-level TEN. The PTC fitted parameters indicated a low-frequency dead region. However, the set of PTCs used to fit model parameters estimated a dead region and lacked information to identify a region with IHC insensitivity. Figure 5.6 shows PTC data of listener L17 from Warnaar et al. (2013). The gray lines\(^d\) represent PTCs used to fit the parameters. The model parameters fitted to TEN[HL] test results (M17 presented in Table 5.1) indicated that PTCs at 1000 Hz were measured with probes presented at too low levels. An additional PTC measurement with a probe presented at 1000 Hz and 70 dB SPL, represented by a solid black line, revealed information that would have identified the region of IHC insensitivity. A TEN[HL] test is, however, much faster than measuring PTCs and requires less training.

The results of this study suggest that the diagnosis of dead regions with the TEN[HL] test can be improved by measurement of TEN at various levels and by modeling the results with a functional model of the hearing system. The presented model and the model analysis of TEN[HL] test results are, however, currently too complex for clinical use, and could be further standardized and

\(^d\)Note that the levels are given in dB SPL and should not be compared directly to presented TEN[HL] test data.
improved in order to support clinical investigation of dead regions. Assessment of the status of IHCs and OHCs based on model parameters is complicated and problematic. A dead region is defined in the model as a complete loss of IHCs with an infinitely sharp frequency edge. In the human hearing-impaired ear, a hearing impairment is more likely to be a combination of several types of hearing impairments with transition regions having less strictly defined edges. Also, the identification of $F_e$ is not reliable. For example, the results of listener L20 could be, at best, approximated based on simplified model assumptions. The present model provided some evidence of a transition from no dead region to dead region with increasing TEN level (see Fig. 5.1, panel B and D), but did not predict such transition at 3000 and 3500 Hz with the given parameters. On the other hand, the TEN[HL] does provide clear indications when IHCs are severely impaired. TEN[HL] test results at various TEN[HL] levels, in combination with modeling tools, can be used to roughly identify regions of IHCs impairment and can roughly identify the type of IHC impairment and estimate remaining OHC functionality near those regions. However, it is the authors’ opinion that PTCs provide much more information for such a purpose (Warnaar et al., 2013).

Figure 5.6. Psychophysical tuning curves of listener L17. Note that levels are given in dB SPL. Probes are presented by black circles including white symbols. The symbol corresponds to the PTC tip presenting as a black symbol. The listener data is presented by gray and black lines connecting the actual measured masker thresholds. Simulated data points are not shown. The gray lines were used to fit model parameters in Warnaar et al. (2013). The black line was simulated with model parameters fitted to TEN[HL] test results of listener L17.
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5.6 Conclusions

This study investigated the diagnosis of dead regions with the TEN[HL] test. Various types of IHC impairment and various degrees of OHC functionality were functionally simulated by a model of auditory processing. Model parameters were fitted indirectly to PTCs and directly to TEN[HL] test data. The results based on model simulations and comparison between simulated results and listener data are summarized below:

1. Masked thresholds increase linearly with increasing TEN level in case of IHC loss (dead region) and a complete loss of OHC functionality, which is consistent with the original rationale of the TEN[HL] test;

2. Masked thresholds are affected by OHC functionality causing a non-linear level response;

3. Functional OHCs near the edge of a dead region can result in a transition in TEN[HL] test diagnosis as a function of TEN level from the presence to the absence of dead regions, or vice versa;

4. Simulations indicate that the physical edge frequency of a dead region is systematically underestimated by interpretations of a change in diagnostic result in the TEN[HL] test;

5. Regions with IHC insensitivity can also result in a transition in TEN[HL] test diagnosis from the presence to the absence of dead regions with increasing TEN level. This finding supports the hypothesis that so-called ‘sick regions’ can lead to TEN level dependent results (Markessis et al. 2009);

5.7 Acknowledgments

Part of this study was financially supported by the Heinsius-Houbolt Fund. We would like to thank Ray Meddis for his help in understanding the DRNL filter-bank, particularly we value his advice on approaches in the model to simulate OHC dysfunction. Furthermore, we would like to thank Torsten Dau for his role in the preparation of this manuscript.