

# Comparison of clinical feasibility of behavioural and physiological estimates of peripheral compression

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Previous research has shown that the rate of peripheral compression (estimated from the slope of the basilar-membrane input-output function) is not correlated with the pure-tone sensitivity (the audiogram). However, efficient estimation of peripheral compression has proven challenging and the methods are based on several assumptions. The aim of this study was to investigate and compare results from three methods of estimating peripheral compression in terms of their accuracy and clinical feasibility. Two psychoacoustic behavioural measures, based on forward (temporal masking curves, TMC) and simultaneous masking with notched-noise (NN), were investigated together with a physiological, distortion-product otoacoustic-emissions (DPOAE), based measure. Forty-five hearing-impaired (HI) listeners with mild-to-moderate hearing loss were tested. Correlation analysis of the data was performed, including partial-correlations, in order to factor out the potential influence of the pure tone-thresholds on the compression estimates. The results demonstrated limitations of each of the considered methods; however, the experiment involving estimates of auditory filters showed good stability and small training requirements across the listeners.

## INTRODUCTION

Currently, the main method used to categorize hearing loss is the audiogram, reflecting sensitivity to pure tones. While useful, it is not sufficient to predict supra-threshold perception and performance of individual hearing-impaired (HI) listeners. In other words, two individuals with similar audiograms can differ widely on perceptual and hearing-aid outcome measures (Fereczkowski *et al.*, 2017). Therefore, there is a need for additional supra-threshold measures that may improve categorization of HI listeners.

Plack *et al.* (2004) used the temporal masking curve (TMC) method of Nelson *et al.*, (2001) to measure peripheral compression behaviourally and found the compression rate to be uncorrelated with audiometric thresholds for listeners with mild-to-moderate hearing loss. However, a major challenge in estimating peripheral compression with psychoacoustical methods is the relatively low time-efficiency of the measurements. In particular, the TMC method is very time consuming, requires extensive training before listeners reach stable performance, and the estimated thresholds are often characterized by large within-subject variability (Rosengard *et al.*, 2005). Physiological methods, based on otoacoustic

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emissions (OAE), have been developed (e.g., Kummer *et al.*, 1998) but are also limited by variability, such as notches and plateaus in the estimated input/output (I/O) characteristics (e.g., Johannesen and Lopez-Poveda, 2010).

Estimates of auditory filter characteristics, and thus frequency selectivity, can be derived behaviourally by examining how thresholds for a tone in notched noise varies as a function of notch bandwidth (Patterson *et al.*, 1976). Since the outer hair cells (OHC) influence both the nonlinear compression and frequency selectivity in the cochlea, some characteristics of the auditory filter and estimates of cochlear compression should be related.

The aim of the present study was to investigate the relation between different measures believed to estimate cochlear compression (and reflect the OHC status), i.e., TMC- and OAE-based estimates and auditory filter bandwidths in a large group of listeners, to explore whether these measures are consistent and/or could complement each other.

## **METHODS**

### **Participants**

Forty-five HI listeners (twenty-three female), with a mean age of 72.5 years participated in the study. The listeners had sensorineural hearing loss (with an air-bone gap not greater than 10 dB at any audiological frequency) and were recruited and tested at the audiological departments of the Bispebjerg Hospital and the State Hospital (Rigshospitalet), located in Copenhagen, Denmark. In order to participate in the study, the listener's threshold at 1 or 2 kHz could not exceed 45 dB HL in at least one ear. All participants provided informed consent and the experiment was approved by the Science-Ethics Committee for the Capital Region of Denmark (reference H-16036391).

### **Setup and Procedure**

The experiments were performed over three sessions, on three separate days, in a double-walled listening booth. The OAE task was performed using the ER10-X probe system and the behavioural tasks were performed on a PC equipped with Matlab with stimuli presented via calibrated Sennheiser HDA200 headphones connected directly to an RME Fireface UCX soundcard. All tests focused on investigation of the cochlear nonlinearity at two frequencies: 1 and 2 kHz.

Distortion product otoacoustic emissions (DPOAEs) were measured on the first day, to make sure that a good seal to the better ear could be obtained with the probe tip. If a stable seal could not be obtained, the other ear was used for all further tests. Two DPOAE measurement paradigms were employed – one based on swept tones and the other on pure-tones. The calibration (including estimation of the forward-pressure level), swept-tone DPOAE measurement, and analysis (including source unmixing) procedures were very similar to the scissors-rule-based paradigm used in Anyfantakis *et al.* (2017), but with two major changes. First, the presentation levels of the second primary (L2) were set to 6 values that uniformly span the range from 40 to 80 dB SPL.

Second, in an attempt to reduce the biological noise, and thus improve the signal-to-noise ratio (SNR), participants were seated in the test booth with the lights turned on and could observe a digital timer indicating the time remaining until the next break. In the pure-tone paradigm, the same presentation levels, level rule, and primary frequency ratio (1.22) were used, as in the swept-tone paradigm. The pure-tones presented had a duration of 1.1 s, including 50 ms-long ramps. Nine recordings of each combination of test-frequency and presentation level were performed. While measurements within the swept-tone paradigm took around 90 minutes per participant, the pure-tone paradigm required only 2 minutes per frequency (with 6 levels measured).

The classic notched-noise paradigm (NN; Patterson *et al.*, 1976) was used to investigate the sharpness of the auditory filters and it was performed on day two. In the NN task, the broadband, 300 ms masker had a constant spectral density of 40 dB/Hz and the participants' task was to detect in which of two intervals a 200 ms target tone was present. A 1-up-3-down version of the Grid method (Fereczkowski, 2015) was used to adaptively obtain thresholds. The minimum notch width was set to 0 (which corresponds to the tone-in-noise threshold) and the maximum was set to 0.85 (as a proportion of the test frequency). The step sizes were 3 dB in the target-tone level and 0.05 in the notch width dimensions. Prior to the test, each participant was trained in the 2-alternative-forced-choice (AFC) task and the tone-detection thresholds were measured using the standard 2-AFC, 1-up-3-down paradigm. Next, guided-stepwise training was used to familiarize the listener with the NN task and a warm-up run with the Grid method was administered for the 1 kHz target tone. This training procedure typically took 10-15 minutes. Subsequently 3 test runs were executed at 1 kHz. If the standard error of the estimated thresholds (averaged across the tested notch-widths) exceeded 3 dB, a fourth run was administered and thresholds from the three final runs were averaged. Finally, a warm-up run was performed for the 2 kHz target and 3 or 4 test runs followed. On average, the NN task took a total of 66 minutes, which included all the described training procedures and breaks administered after every two runs.

The TMC experiments were performed in the last session. In this task, a 200 ms pure tone masker was followed by a 16 ms pure tone target (presented at 12 dB sensation level). 8 ms ramps were applied to both the masker and target tones. As in the NN task, a 2-AFC 1-up 3-down version of the Grid method was used. The minimum and maximum masker-target temporal gaps were 10 and 200 ms and the step sizes were set to 3 dB for the tone-level and 5 ms for the temporal gap. Three conditions were tested: 2 kHz off- and on-frequency and 1 kHz on frequency, in that order. In the on-frequency condition, the target and the masker tones were the same frequency. In the off-frequency condition, the masker frequency was set to 55% of the target frequency. Guided-stepwise learning was employed before each test condition and in each condition one warm-up and two test runs were performed. If the average standard error exceeded 3 dB, up to three extra runs could be administered and thresholds from the three final runs were averaged. The TMC experiment took, on average, 94

minutes, which included all the training, test sessions, and breaks administered after every two runs.

### Data analysis

The DPOAE data from the swept-tone paradigm was processed using the same procedure as used by Anyfantakis *et al.* (2017), which included source unmixing. The distortion product (DP) response at a given input level was considered valid, if the estimated SNR exceeded 5 dB. For the case of the pure-tone paradigm, the 8 recordings with the lowest RMS were selected and high-pass filtered at 500 Hz in an attempt to reduce artefacts and excessive noise. The 8 recordings were then averaged and FFT analysis was performed on the 1 s long fragment that did not contain the ramps. The strength of the  $2F_1$ - $F_2$  component was recorded as the final DP response and the SNR criterion was 10 dB.

The DP I/O curves, resulting from both presentation paradigms, were fitted independently with a broken-stick (1, 2 or 3 sections) function using a similar constrained fitting procedure as Fereczkowski *et al.* (2017). However, no constraints were set on the location of the knee-points. Here, the slope of the most compressive portion of the I/O function, henceforth referred to as compression exponent (CE), was recorded.

To reduce the variance of the OAE-based CE estimates, and facilitate the comparison with the psychophysical methods, the CE values obtained from the pure-tone and swept-tone DPOAE paradigms were averaged to obtain the final OAE CE estimate. This was done since the CE values from both methods were found not to be significantly different, according to a permutation test ( $p > .17$ ).

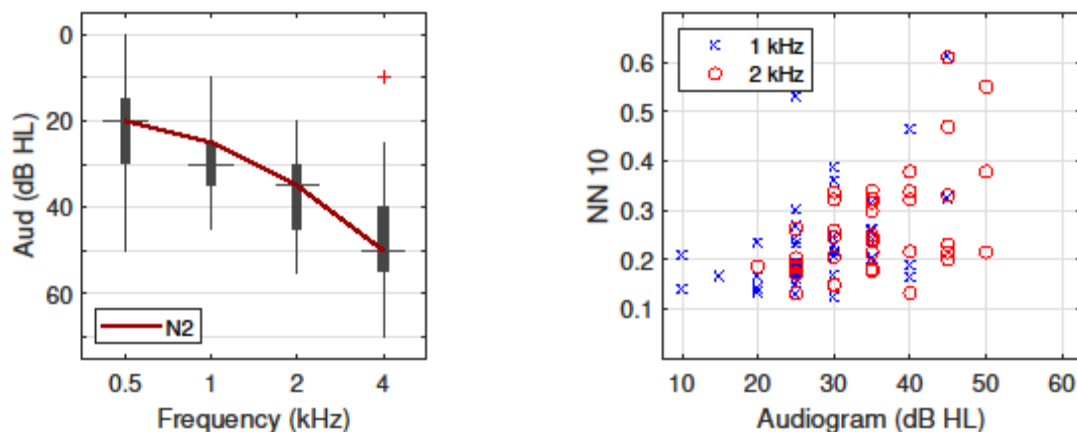
The TMC I/O curves were obtained by combining the on- and off-frequency data, averaged across all test-runs. The CE estimate was obtained in the same manner as for the DP I/O paradigm described above. For the auditory filter estimates, fitting rounded exponential functions occasionally led to unstable (i.e., very high) estimates of the rounding parameter,  $p$ . Thus, the sharpness of tuning in the NN task was estimated in a simpler way. Through interpolation, the notch width that resulted in a threshold 10 dB lower than the tone-in-noise threshold was found and termed the NN10 threshold.

To avoid potential distribution-related issues, Spearman correlation coefficients are reported.

## RESULTS

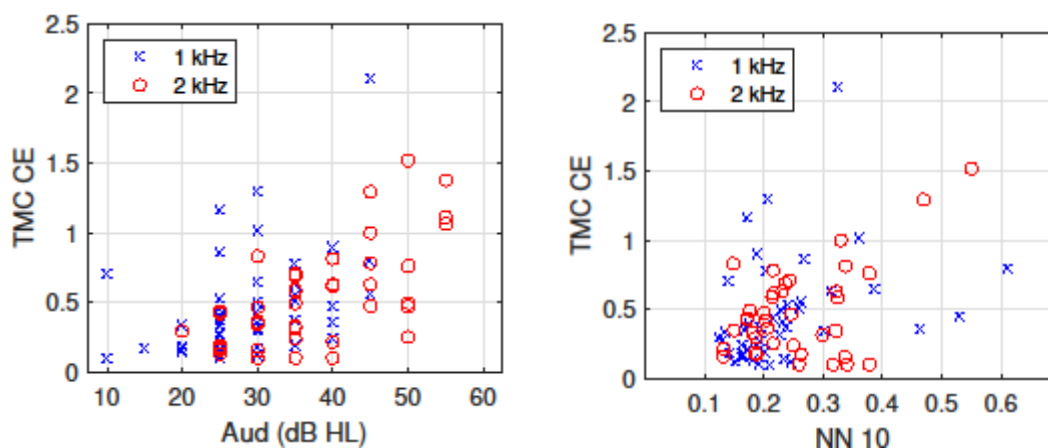
The left panel of Fig. 1 shows the distribution of the test-ear thresholds for frequencies between 500 and 4000 Hz. The right panel of Fig. 1 shows the NN10 data as a function of the audiometric threshold at the tested frequency. Blue crosses represent data collected at 1 kHz and red circles represent the 2-kHz data. A reference NH value of the NN10 threshold was estimated to be 0.148 (Rosen and Baker, 1994), which corresponds well with the results here for hearing thresholds not exceeding 20 dB HL. The estimated correlation, measured across both frequencies, is moderate and

significant [ $r_s(n = 81) = .51, p < 1e-4$ ], indicating that the sharpness of tuning generally decreases with increasing hearing thresholds. The NN10 value could be estimated in 81 out of a total of 90 cases (2 frequencies for each of 45 listeners). For the remaining cases, the threshold curves decreased by less than 10 dB over the tested notch-widths.



**Fig. 1: Left:** The boxplots show the better-ear hearing thresholds from the 45 listeners. The median thresholds were similar to the N2 audiogram (Bisgaard *et al.*, 2010). **Right:** Estimated tuning-sharpness (NN10) as a function of the audiometric threshold.

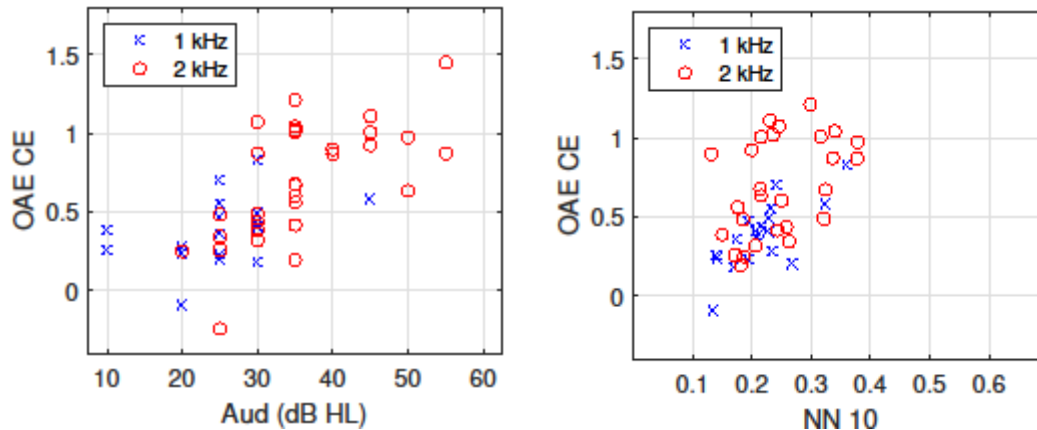
The left panel of Fig. 2 shows the corresponding data for CE estimates from the TMC task (TMC CE). Here, the estimated correlation is similar to the previous case, and significant [ $r_s(89) = .50, p < 1e-4$ ].



**Fig. 2: Left:** CE estimates from the I/O functions fitted to the TMC data as a function of the audiometric threshold. In both panels, blue crosses and red circles represent data from 1 and 2 kHz, respectively. **Right:** Compression exponent of the I/O function estimated from the TMC task as a function of tuning-sharpness (NN10).

The right panel of Fig. 2 presents the dependence between the NN10 and the TMC CE estimates from individual listeners. The correlation is weak, but

significant [ $r_s(80) = .31, p = .0052$ ], which suggests that higher CE indicates broader auditory filters. However, the estimated partial correlation between TMC CE and NN10, controlling for the audiometric threshold, turned out to be weak and insignificant ( $r_{sp}(80) = .12, p > .29$ ).



**Fig. 3: Left:** CE estimates from the DP I/O functions averaged across the OAE paradigms as a function of the hearing threshold. **Right:** Same CE estimates shown as a function of tuning-sharpness estimate. In both panels the OAE CE estimates tend to increase with the increasing abscissa value.

The left panel of Fig. 3 presents the dependence between the audiometric threshold and the OAE CE estimate from individual listeners. Also in this case the correlation is strong and significant [ $r_s(48) = .72, p < 1e-4$ ]. Note, however, that data was obtained in only 48 out of 90 possible cases (a valid OAE CE estimate required DPOAE responses measured at minimum least two input levels). The right panel of Fig. 3 shows a scatterplot of the same OAE CE estimates against the NN10 estimates. The correlation between the two estimates is moderate and significant [ $r_s(45) = .55, p = 2e-4$ ], and the partial correlation (controlling for the audiogram) is, again, moderate and significant [ $r_{sp}(45) = .44, p = 0.0028$ ]. Moreover, a comparison of linear models of OAE CE reveals that a model using both hearing threshold and NN10 values as predictors explains significantly more variance (adjusted  $R^2 = 0.48$ ) than the model employing hearing thresholds alone (adjusted  $R^2 = 0.39$ ) with  $F(2, 42) = 21.48$  and  $p < 1e-4$ . However, no significant correlation was found between the TMC CE and the OAE CE estimates ( $r_{sp}(48) = 0.23, p = 0.12$ )

## DISCUSSION

The data analysis revealed that while there are significant correlations between hearing thresholds and auditory filter sharpness estimates, compression exponents from the TMC task, and compression exponents from the DP I/O

function, as well as a significant correlation between auditory filter sharpness and the OAE CE, the correlation between the TMC CEs and the auditory filter sharpness is mediated by the audiogram and there is no correlation between TMC and OAE CEs.

The findings concerning the TMC CE estimates are somewhat inconsistent with the previous literature. Plack *et al.* (2004) reported no correlation between the hearing thresholds and the TMC CE and Anyfantakis *et al.* (2017) reported a correlation between TMC and OAE CEs. However, those two studies had a smaller number of participants than the current study. A power analysis reveals that a correlation coefficient of 0.5 (the value reported above for TMC CE and the hearing thresholds) requires at least 29 data points, while Plack *et al.* (2004) had 26 points in total and only 12 from HI listeners. Here, the corresponding sample size was 89. This suggests that the Plack *et al.* (2004) study may have not had enough statistical power to detect the existing relations. Similarly, the correlation analyses in Anyfantakis *et al.* (2017) were based on just 8 data points and the lack of correlation between TMC and OAE CEs reported here is consistent with Johannesen and Lopez-Poveda (2010), who found no relation at frequencies below 4 kHz. However, the main limitation of the TMC CE estimates in the current study is their high variability, with values ranging between 0.1 (where a constraint was set) and 2.2. While this variability is consistent with Rosengard *et al.* (2005), it limits the strength of the current conclusion.

On the other hand, the current analysis suggests that NN10 estimates complement the audiogram, as NN10 provides information on OAE CEs that is not present in the hearing threshold data. While, the DPOAE method may return a CE estimate within a few minutes, many HI listeners did not produce strong enough DP responses to estimate an I/O function. However, all listeners could perform the NN task. Therefore, the NN task may be useful to assess the BM nonlinearity when DP responses cannot be measured. Moreover, while the NN task may be too time-consuming to be performed in the clinic, its low training requirement and good stability make it an interesting candidate for at-home, mobile-platform-based testing (e.g., Hyvärinen *et al.*, 2019).

## SUMMARY

Three methods, two behavioural (TMC and NN) and one physiological (DPOAE), of estimating peripheral compression were tested. The results were, in all cases, significantly correlated with audiometric thresholds. When the audiometric thresholds were controlled for, only the correlation between NN and DPOAE estimates remained significant. While the DPOAE task is more time-efficient than the NN task, it did not return an estimate in several individual cases. These results suggest that the NN task could serve as a complementary test of estimating peripheral compression for listeners where DPOAEs are difficult to measure in the individual listener.

## ACKNOWLEDGMENTS

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