Reference thresholds for the TEN(HL) test for people with normal hearing

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Abbreviations

ANOVA	Analysis of variance
CI	Confidence interval
DR	Dead region
HL	Hearing level
SPL	Sound pressure level
STR	Signal-to-TEN ratio
TEN	Threshold equalizing noise
TEN(HL)	Threshold equalizing noise calibrated in dB HL
TEN(SPL)	Threshold equalizing noise calibrated in dB SPL

Abstract

Objective: The objective was to obtain normative values of thresholds for the TEN(HL) test for diagnosing dead regions in the cochlea, as a function of signal frequency and TEN(HL) level. *Design:* The TEN(HL) test was administered twice for each ear of each participant (in two separate sessions) using signal frequencies from 0.5 to 4 kHz and TEN(HL) levels of 30, 50 and 70 dB HL/ERB$_N$. *Study sample*: 29 young participants and eight older participants were tested. All had normal audiograms with no indication or history of any hearing problems. *Results*: The results showed good repeatability across sessions, with no systematic change from session 1 to session 2. There was no significant effect of ear or age group. The average signal-to-TEN ratio (STR) at threshold was close to 0 dB, as expected. For low signal frequencies, the STR at threshold varied only slightly with TEN(HL) level, but for the signal frequencies of 3 and 4 kHz the STR at threshold increased to about +2.7 dB for the TEN(HL) level of 70 dB/ERB$_N$. *Conclusions*: For a high TEN(HL) level, the “normal” STR at threshold at 3 and 4 kHz is closer to +2 dB than to 0 dB. Therefore, the criterion for diagnosing a DR at 3 and 4 kHz should be that the signal level at threshold is at least 10 dB above the absolute threshold and at least 12 dB (rather than 10 dB) above the TEN(HL) level/ERB$_N$.

A dead region (DR) is a region in the cochlea with very few or no functioning inner hair cells, neurons, and/or synapses (Moore et al, 2000; Moore, 2001). No information about basilar-membrane vibration within a DR is transmitted to the brain. However, a sinusoid that produce peak basilar-membrane vibration within a DR may be detected, if it is sufficiently intense, via the spread of basilar-membrane vibration to a region that is still functioning. This is called “off-frequency” or “off-place” listening (Moore, 2001; Moore, 2004).

Diagnosis of the edge frequency or frequencies and extent of a DR may be useful for the counselling of patients with hearing loss, for assessing whether a patient might be a candidate for a cochlear implant, for fitting a combination of a hearing aid and a cochlear implant (Moore et al, 2010; Zhang et al, 2014), and for fitting of hearing aids (Moore & Malicka, 2013). For adults or children with extensive continuous high-frequency DRs, there appears to be little benefit of amplifying frequencies falling above about 1.7 times the edge frequency, *f*e, of the DR (Vickers et al, 2001; Baer et al, 2002; Malicka et al, 2013; Moore & Malicka, 2013). Reducing the gain for frequencies above 1.7*f*e does not affect the benefit provided by amplification but can reduce problems with acoustic feedback, distortion and potential damage to residual hearing caused by the very high sound levels required to achieve audibility. However, for adults or children with more restricted DRs or with patchy DRs, the greatest benefit is obtained by providing amplification over the widest possible frequency range (Cox et al, 2012; Malicka et al, 2013; Moore & Malicka, 2013). For people with low-frequency DRs, reduction of gain for frequencies below 0.57*f*e may lead to improved intelligibility of speech in quiet and in noise (Vinay & Moore, 2007; Vinay et al, 2008).

Methods for diagnosing DRs are based on the detection of off-frequency listening. One method is to measure psychophysical tuning curves (PTCs). The PTC is a measure of the level of a narrowband masker required to mask a fixed low-level signal as a function of the center frequency of the masker (Chistovich, 1957). When the signal frequency falls in a functioning frequency region of the cochlea, the tip of the PTC (the frequency at which the masker level is lowest) falls close to the signal frequency (Moore, 1978). When the signal frequency falls in a DR, the tip of the PTC is shifted away from the signal frequency, downwards in the case of a high-frequency DR (Moore et al, 2000; Moore & Alcántara, 2001; Kluk & Moore, 2005; Kluk & Moore, 2006). PTCs can be time-consuming to measure, and even the "fast" method using a masker that sweeps in frequency takes about four minutes per signal frequency (Sek et al, 2005; Sek & Moore, 2011).

A method for rapid diagnosis of DRs in clinical practice is based on measurement of the detection threshold for a sinusoid in threshold equalizing noise (TEN). A TEN is designed to produce equal masked thresholds for all signal frequencies within a certain range, for people with normal hearing. The TEN produces approximately equal basilar membrane vibration at all places within the cochlea corresponding to that frequency range. The signal and masker levels can be specified as dB sound pressure level (SPL) (the TEN(SPL) test, Moore et al, 2000) or dB hearing level (HL) (the TEN(HL) test, Moore et al, 2004). The TEN level is usually specified as the level in a 1-ERB_N-wide band centered at 1 kHz, where ERB_N stands for the equivalent rectangular bandwidth of the auditory filter measured at a moderate sound level for young listeners with no known hearing problems (Glasberg & Moore, 1990). The signal threshold can be conveniently specified as the signal-to-TEN ratio, STR, in dB.

The rationale behind the TEN test is as follows. If the cochlea is functioning well at the place tuned to the signal frequency, then the signal is detected through an auditory filter centered close to the signal frequency. In this case, the "expected" STR is close to 0 dB (Moore et al, 2000). If the cochlea is functioning at the place tuned to the signal frequency, but there is some hearing loss at that frequency, the auditory filter may be broader than normal, and this can lead to a higher STR at threshold by 2-4 dB (Pick et al, 1977; Glasberg & Moore, 1986). If there is a DR in the cochlea at the place tuned to the signal frequency, the signal will only be detected if it produces sufficient basilar-membrane vibration at a remote place in the cochlea that is still functioning. i.e. if it is detected via off-frequency listening. In order for the signal to be detected at the remote place, its level has to be markedly higher than normal. The usual criteria for diagnosing a DR are that the signal level at threshold should be at least 10 dB above the absolute detection threshold, and the STR should be 10 dB or more (Moore et al, 2000; Moore et al, 2004; Pepler et al, 2014).

The criteria for diagnosing a DR are based on the assumption that the "normal" STR at threshold is 0 dB, independent of the signal frequency and the TEN level. However, the

TEN(SPL) and TEN(HL) were designed to give an STR at threshold of 0 dB when the TEN level is moderate (30-50 dB/ ERB_N). In clinical practice, TEN levels of 60 dB/ ERB_N or more are often used, in order to ensure that the TEN does sufficient masking and the masked threshold is at least 10 dB above the absolute threshold. It is known that the auditory filter broadens with increasing level, more so at high center frequencies (Moore & Glasberg, 1987; Baker et al, 1998; Glasberg & Moore, 2000; Unoki et al, 2006), and this would be expected to increase the STR at threshold for listeners with normal hearing. If the “normal” STR at threshold is above 0 dB at high TEN levels, then the criteria for diagnosing a DR should be adjusted to reflect this. The purpose of this experiment was to establish normative values for the TEN(HL) test as a function of signal frequency and TEN(HL) level, to assess the extent of changes in the STR at threshold as a function of level and frequency.

Method

Participants

Two groups of participants were tested. Group 1 consisted of 29 participants (19 female and 10 male) all between 20 and 29 years old (mean age = 24 yrs and SD = 2.3 yrs). Group 2 consisted of eight participants (5 women and 3 men) between the ages of 41 and 58 years. All participants met the inclusion criteria described below, and all were tested using both the left ear and the right ear.

Inclusion criteria

All participants were screened to ensure that they had normal pure-tone thresholds and were unaffected by ear pathologies for both ears. Screening included otoscopy, tympanometry and pure tone audiometry along with a questionnaire asking participants whether they suffered from tinnitus or other relevant otological symptoms. Otoscopy was conducted to ensure that the ear canal was not clogged by cerumen and that there were no signs of infection or abnormality of the tympanic membrane. Tympanometry established that all participants had normal middle ear function, with either A, As or Ad type tympanograms. Pure tone audiometry was done following the modified Hughson-Westlake procedure described by

Carhart and Jerger (1959). All participants from group 1 had pure tone thresholds ≤ 20 dB HL for all frequencies from 0.25 to 8 kHz, while all participants from group 2 had thresholds ≤ 25 dB HL for all frequencies from 0.25 to 8 kHz.

Equipment

Pure tone audiometry and TEN(HL) testing were done using an Otometrics Madsen Astera audiometer coupled with TDH-39 headphones. The TEN(HL) test is built into this audiometer. Calibration according to ISO 389-8 (2004) was done seven months prior to testing. A Gason-Stadler GSI-33 Middle Ear Analyzer was used for tympanometry, and otoscopy was done using a conventional otoscope or Otometrics Otocam.

Procedure

Before testing commenced the participants were informed about the objective of the study, the schedule for their visit, practicalities, and confidentiality in written form before signing a declaration of participation. For the TEN(HL) test, participants were orally instructed to respond by pressing a button whenever they heard a pure tone presented in the presence of noise. They were told that the test would include seven frequencies and three noise levels for each ear, and that the whole procedure would be repeated after a break. Participants were also informed that the highest level of the noise might be irritating, but not damaging to their hearing.

All testing was done in a sound treated room. The TEN(HL) test was conducted using half-octave spaced test frequencies between 0.5 and 4 kHz, using TEN(HL) levels of 30, 50 and 70 dB HL/ERB$_N$. The lowest TEN(HL) level used, 30 dB HL/ERB$_N$, was high enough to ensure that the threshold of the tone in the TEN(HL) would be above the absolute threshold for all participants. The highest level of the TEN(HL), 70 dB HL/ERB$_N$, was chosen so that the TEN(HL) was loud but not excessively so and so that the TEN(HL) level was not sufficient to produce hearing damage, given the relatively short exposure time of a few minutes. The overall sound level of the TEN(HL) in dB SPL is about 22 dB above the nominal TEN(HL) level, so a level of 70 dB HL/ERB$_N$ corresponds to 92 dB SPL overall

(Moore et al, 2004).

TEN(HL) testing was done using 2-dB steps as recommended by Moore et al (2004). Initially, the signal was presented at a level 10 dB above the TEN(HL) level, which was expected to make the tone easily audible for a person with normal hearing. The level was then lowered in 4-dB steps until the participant did not respond, and was raised in 2-dB steps until the participant responded again. Continuing with this 4 dB descending, 2 dB ascending pattern, the lowest level leading to three consistent responses was registered as the masked threshold.

Two people alternated between being tester and assistant. The tester did the actual testing while the assistant recorded the results. The test and retest for a given participant were conducted by the same tester. For each participant, the ear that was tested first and the order of testing the different TEN(HL) levels and signal frequencies was randomized. This was done to avoid the same level, frequency, and ear being tested at the end of a session, when the participants might experience some degree of fatigue and poor concentration. Each session took about 40 minutes to complete. A break of between 10 minutes and two hours was given between sessions.

Statistical analyses

All data processing and analysis were performed with SPSS version 23. The tone thresholds were expressed as STR in dB. Mixed-model Analyses of Variance (ANOVAs) were used to assess the effects of gender, ear, frequency, TEN(HL) level, and their interaction. The Greenhouse-Geisser correction to the degrees of freedom was applied when Mauchly’s test revealed that the condition of sphericity was not met.

Results

Test-retest differences

Mean test-retest differences were close to 0 dB for all frequencies and levels and for both ears. The grand mean was –0.15 dB (95% confidence interval, CI, –0.32 to +0.02). Thus, the STRs did not change systematically from test to re-retest. An ANOVA was conducted on the test-retest differences with group membership (young or older) and gender as between-subjects factors and ear (left or right), signal frequency, and TEN(HL) level as within-subject factors. There were no significant main effects or two-way interactions. There were significant three-way interactions of level, frequency and gender, $F(8.65, 285.3) = 1.979$, $p = 0.044$) and of ear, level and frequency, $F(8.42, 277.9) = 2.02$, $p = 0.041$, but these accounted for only a small percentage of the variance in the data and will not be considered further.

Absolute values of test-retest differences

To assess the inherent variability in the estimates of the STRs, we calculated the absolute values of the difference between the STR for the first session and the STR for the second session. The grand mean was 1.3 dB, indicating reasonably low inherent variability, given the final step size of 2 dB used to estimate the STRs.

An ANOVA was conducted on the absolute values of the test-retest differences with group membership (young or older) and gender as between-subjects factors and ear (left or right), signal frequency, and TEN(HL) level as within-subject factors. There were no significant main effects or two-way interactions. There was a significant three-way interaction of ear, level and age group, $F(1.91, 63.0) = 4.38$, $p = 0.018$, but this accounted for only a small percentage of the variance in the data and will not be considered further.

STR values

The grand mean STR was –0.06 dB (95% CI –0.47 and +0.35), close to the “expected” value of 0 dB. An ANOVA of the STR values revealed no significant main effect of age, gender, or ear. The mean STRs for the young and older groups were very similar, at –0.3 and +0.2 dB, respectively. The mean STRs for the female and male groups were also very similar, at –0.4 and +0.3 dB, respectively. Finally, the mean STRs for the left and right ears were very similar, at 0.0 and –0.1 dB, respectively. There was a significant effect of frequency, $F(3.85, 127.1) = 12.1$, $p < 0.001$. The average STR values across TEN levels were slightly negative for the two lowest frequencies and slightly positive for the two highest frequencies. There was a significant effect of level, $F(1.51, 49.9) = 103.0$, $p < 0.001$. The mean STRs were –1.1

dB at 30 dB/ERB$_N$, –0.2 dB at 50 dB/ERB$_N$, and +1.1 dB at 70 dB/ERB$_N$. All pairwise comparisons of level were significant at $p < 0.001$. There was a significant interaction of level and frequency, $F(7.55, 2.61) = 17.8$, $p < 0.001$. For the lowest level, the STR at threshold varied only slightly with frequency (range –1.7 to –0.4 dB). However, for the highest level the STR at threshold varied from –0.7 dB at 0.5 kHz to 2.8 and 2.7 dB at 3 and 4 kHz, respectively. This is illustrated in Figure 1. There were some other significant interactions, but they accounted for only a small proportion of the variance in the data, and will not be discussed further.

Discussion and conclusions

The STRs at threshold increased significantly with increasing level, the effect being greatest at medium and high frequencies. This is what would be expected from prior work showing that the increase in auditory filter bandwidth with increasing level tends to increase with increasing center frequency (Moore & Glasberg, 1987; Baker et al, 1998; Glasberg & Moore, 2000; Unoki et al, 2006). A similar pattern of results was found by Moore et al (2000) for the TEN(SPL) test, although in their data there was not a clear increase in threshold at 3 and 4 kHz at the TEN(SPL) level of 70 dB SPL/ERB$_N$. The discrepancy may have occurred because a TEN(SPL) level of 70 dB SPL/ERB$_N$ corresponds to a TEN(HL) level of about 63 dB HL/ERB$_N$, so the highest level used by Moore et al was lower than the highest level used here.

For the highest TEN(HL) level used here, 70 dB HL/ERB$_N$, the STR at threshold was slightly over +2 dB for the signal frequencies of 3 and 4 kHz, but was only about +1 dB at 1, 1.5 and 2 kHz. Given the step size of 2 dB that is recommended when conducting the TEN(HL) test, it would seem sensible to use a “reference” STR of +2 dB at 3 and 4 kHz when using TEN(HL) levels of 70 dB HL/ERB$_N$ and above. In other words, at 3 and 4 kHz, the criteria for diagnosing a DR should be that the signal level at threshold is at least 10 dB above the absolute threshold and at least 12 dB above the TEN(HL) level/ ERB$_N$.

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Figure caption

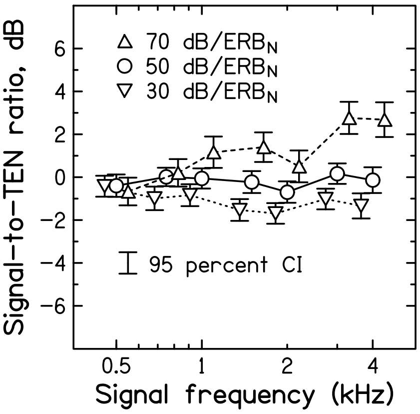

Figure 1. Signal-to-TEN ratios (STRs) at threshold as a function of signal frequency for three TEN(HL) levels, as indicated in the key. Error bars indicate 95% confidence intervals.