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Factors Affecting Outcomes on the TEN (SPL) Test in Adults with Hearing Loss

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Abstract

Background—Recent work using the Threshold Equalizing Noise (TEN) test as a gold standard suggests that the presence of cochlear dead regions in persons with moderate-to-severe hearing loss may be quite common. In addition, previous data suggest that certain characteristics of hearing loss, such as severe-profound high-frequency hearing loss or steeply sloping configurations may be more commonly associated with positive TEN findings. These findings, however, are based largely on studies including a relatively small number of participants and/or participants that were included based on specific audiometric criteria (e.g., the presence of severe high-frequency hearing loss). Likewise, results from many of these studies are limited to the frequency regions of 500–4000 Hz. There has been less work that has systematically evaluated the relationship between audiometric characteristics and TEN test findings, particularly in the frequency regions above 4000 Hz, on a large number of individuals with a wide range of hearing losses and hearing loss configurations.

Purpose—The purpose of this study was to further examine the effects of audiometric characteristics such as degree and slope of hearing loss on the rate of positive, negative, and inconclusive findings on the TEN test over a wide frequency range (250–8000 Hz). Given that the functional impact of positive findings (i.e., findings suggestive of a dead region) may vary with the extent of potential damage, we were also interested in determining the relative occurrence of “patchy” versus contiguous positive findings on the TEN.

Research Design—Fifty-nine adults (117 ears) with a wide range of SNHL participated. To examine results over a wide frequency range (250–8000 Hz), the TEN (SPL), rather than the TEN (HL), was utilized. Thresholds, in both ears, were measured in quiet and in the TEN (SPL). Results were categorized as positive (suggestive of a dead region), negative (not suggestive of a dead region), or inconclusive.

Results—Consistent with past research, positive TEN (SPL) results were more common when hearing losses exceeded 60 dB HL; however, there was not a systematic increase in positive results with increases in threshold. In contrast to previous work, however, positive test results among individuals with milder hearing losses (<60 dB HL) were not uncommon, suggesting a potential for false positive results. In regard to audiometric slope, also consistent with past research, slope of hearing loss was an inadequate predictor of TEN (SPL) results. Negative results (not suggestive of a dead region) were less common in participants with steeply sloping losses while positive test findings were unaffected by hearing loss slope. Although a large proportion of participants had positive results on the TEN (SPL), for most participants, these positive findings occurred in isolated (i.e., one or two frequencies) rather than in contiguous frequency regions.

Conclusions—The relatively large number of inconclusive results and the potential for false positive results makes interpreting the functional impact of TEN (SPL) results difficult, particularly when positive results are in the high (>4000 Hz) frequencies. In addition, although a large proportion (84%) of study participants had positive findings on the TEN (SPL), the functional impact of these findings is not clear as, in the majority of cases, positive findings occurred at only one or two test frequencies.

Keywords

Cochlear damage; dead regions; hearing aids; hearing loss; threshold

It is well documented that providing appropriate amplification can substantially improve both speech understanding and quality of life for many persons with hearing loss (Mulrow et al, 1990; Larson et al, 2000). However, the benefits of amplification are not well predicted based on improvements in audibility due to hearing aid use. Substantial residual problems and deficits in speech understanding may remain despite the provision of appropriate amplification (Plomp, 1986; Souza et al, 2000; Humes, 2003; Kochkin, 2000, 2005, 2007; Hornsby and Ricketts, 2006). Multiple factors are responsible for the continued difficulty of persons with hearing loss, despite the provision of appropriate amplification, and the relative importance of these factors may vary across individuals. Research in this area suggests that contributing factors include, but are not limited to, the reduced audibility of speech (despite the provision of appropriate amplification), deficits in frequency and/or temporal resolution associated with hearing loss and/or aging, and reduced cognitive function (e.g., Dreschler and Plomp, 1985; Humes, 2002; Gatehouse et al, 2003; Jin and Nelson, 2006).

Another factor suggested in the literature that may affect the utility of amplified speech information, and thus potential benefit from hearing aid use, is the presence and extent of “cochlear dead regions” (Vickers et al, 2001; Moore, 2001, 2004; Baer et al, 2002; Macksersie et al, 2004; Preminger et al, 2005). The term *dead region* has been popularized in recent years, largely due to systematic research by Moore and colleagues (e.g., Moore et al, 2000; Moore, 2001, 2004; Vickers et al, 2001; Baer et al, 2002; Moore et al, 2004; Munro et al, 2005; Aazh and Moore, 2007; Cairns et al, 2007; Vinay and Moore, 2007a, 2007b, 2007c). Consistent with implications associated with general usage, the term “dead” region is used to suggest a “complete loss of inner hair cells (IHCs) over a certain region of the basilar membrane” and/or to suggest that “afferent auditory neurons innervating those places may be non-functioning” (Moore et al, 2000, p. 205).

The absence of functioning (or the presence of severely damaged) IHCs and/or auditory neurons in a given region of the cochlea could limit the accurate transmission of amplified speech information to higher auditory areas for processing or interpretation. Consequently, benefits from amplification, in terms of aided speech understanding, would be expected to be limited compared to conditions where speech information was presented to regions with healthy IHCs and auditory neurons.

Given the potential negative consequences of dead regions, identification of these areas could be of significant clinical benefit. Intuitively one might expect that a dead region could be readily identified via the audiogram (e.g., no measurable response to tones in that frequency region). Unfortunately, while the *lack* of a measurable response to a pure tone at high levels is highly suggestive of a dead region, the presence of a response does not preclude the existence of a dead region at that frequency. A listener may detect and respond to a pure tone stimulus falling within a dead region, despite the fact that there are no functioning IHCs or auditory neurons in that region of the cochlea, due to physiologic spread of excitation along the basilar membrane (see Robles and Ruggero, 2001, for a review). The term *off-frequency listening* has been used

to describe situations where this spread of excitation leads to detection of a stimulus due to excitation at some place other than the characteristic location on the basilar membrane expected for the frequency of the stimulus (Patterson and Nimmo-Smith, 1980). Off-frequency listening can be particularly important when assessing detection thresholds for pure tones in persons with cochlear dead regions. For these individuals, a tone presented in a “dead” region of the cochlea may be detected due to spread of activity to IHCs and neural fibers in adjacent “live” or “healthier” regions of the cochlea (Moore, 2004; Kluk and Moore, 2005).

The most *direct* method of verifying the presence and extent of a dead region in humans would entail sacrificing the cochlea to complete a histological analysis of surviving inner and outer hair cells. Since this is clearly not a clinical option, researchers have used various *indirect* psychophysical methods that take advantage of the occurrence of off-frequency listening to estimate the presence and extent of dead regions. This led Moore (2004) to suggest an alternative definition of a dead region. Specifically, “a dead region is a region in the cochlea where IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening” (Moore, 2004, p. 100). This definition is consistent with the idea that “dead regions” identified *indirectly* via psychophysical methods, may not actually be “dead.” A positive finding on these behavioral tests, as discussed later, may be consistent with a severely damaged region, or in some cases the findings may not be suggestive of severe cochlear damage at all.

Although a variety of psychophysical methods have been proposed to identify dead regions, the most researched, and currently the only clinically available, psychophysical method is the Threshold Equalizing Noise (TEN) test (Moore et al, 2000; Moore et al, 2004). For a detailed discussion of the rationale for and development of the TEN test see Moore, 2004. Briefly, the TEN is a steady-state noise that has been spectrally shaped so that, for young normal hearing adults, thresholds measured in the noise will be approximately equal (in dB SPL or dB HL depending on the version of the test), across a wide frequency range. For individuals with hearing loss, *in the absence of a dead region*, thresholds measured in the TEN may be slightly elevated (<10 dB) compared to persons with normal hearing thresholds but still relatively equal across a wide frequency range.

In contrast, if a dead region were present and thresholds measured in quiet were actually due to detection of off-frequency basilar membrane activity, then masked thresholds in the TEN may (depending on the noise level) be significantly (≥ 10 dB) higher than those found in persons with normal hearing. Specifically, TEN test results are suggestive of a dead region if, at a given frequency, (1) the pure tone threshold measured in the TEN is 10 dB, or more, higher than the level of the TEN¹ and (2) presenting the TEN produces at least 10 dB of masking (i.e., masked threshold is at least 10 dB higher than quiet threshold). There are two commercially available versions of the TEN test, the TEN (SPL) and the TEN (HL). The TEN (SPL) uses a noise and pure tones, recorded on a CD, that are calibrated in dB SPL. The TEN (SPL) noise bandwidth allows testing over a frequency range of 125-10,000 Hz. The TEN (HL) is a modified version of the TEN (SPL). The TEN (HL) shares the basic test structure of the TEN (SPL) but varies in terms of calibration (in dB HL), frequency range (500-4000 Hz) and amplitude characteristics of the noise (lower crest factor).

¹The level of the TEN masking noise is referenced to the level in a one ERB (equivalent rectangular band) wide band centered at 1000 Hz. The ERB is the bandwidth of a rectangular filter that passes the same power as the auditory filter, at moderate input levels, for young normal hearing adults. The TEN noise is shaped and calibrated such that thresholds for pure tones measured at a given level of TEN should all be approximately equal to the level of the noise. For example, if the TEN noise is presented at a dial level of 80 (which corresponds to 80 dB/ERB), then thresholds (for individuals with normal hearing), across a wide frequency range, measured in this noise should also equal 80 dB SPL.

The development of the TEN was prompted, in part, by previous work suggesting that audiometric thresholds alone were an inadequate predictor of the presence or absence of dead regions (Thornton and Abbas, 1980; Halpin et al, 1994). Despite this, due to the physiologic responses within the cochlea associated with off-frequency listening (e.g., greater spread of excitation toward the basal region of the cochlea and at high stimulus levels), dead regions appear to be more commonly associated with certain audiometric characteristics, such as high frequency thresholds >90 dB HL and low frequency thresholds >75-80 dB HL, reverse slope SNHL (sensorineural hearing loss), particularly with low frequency thresholds >50 dB, and steeply sloping (50 dB/octave or more) high frequency SNHL (Moore, 2001).

Although researchers using the TEN have reported findings consistent with these suggestions, considerable variability has also been observed. Vickers et al (2001) and Baer et al (2002) examined the effects of high-frequency dead regions on speech understanding in quiet and noise. Participants with high-frequency dead regions generally had greater hearing loss in the high frequencies than those participants without dead regions. Thresholds for the dead regions group were, on average, approximately 100 dB HL at frequencies of 3000 Hz and higher. In contrast, average thresholds over the same frequency range were less than 70 dB HL for individuals without dead regions in those studies. However, in some cases individuals with dead regions had thresholds substantially lower than 100 dB HL. Vinay and Moore (2007b) reported similar, but less variable, findings for individuals with low-frequency hearing loss. In their subject pool, individuals that did not have low-frequency dead regions had low-frequency thresholds of 70 dB HL or less, while individuals that had low-frequency dead regions had thresholds of 70 dB HL or more in the low frequencies.

Findings related to slope of hearing loss have also been variable. Several participants with high-frequency dead regions in the Vickers et al (2001) and Baer et al (2002) studies had audiometric slopes of 50 dB/octave or more in some frequency regions. However, some participants with dead regions had shallower slopes and some without dead regions had equally steep slopes (e.g., ≥ 50 dB/octave). Preminger et al (2005) examined participants with a relatively narrow range of high-frequency thresholds (50-80 dB HL) and found that those participants with positive TEN test results in the high frequencies (i.e., suggestive of a dead region in the high frequencies) had, on average, a more steeply sloping loss (~ 19 dB/octave between 500-2000 Hz) than those individuals that did not have positive TEN test results (i.e., not suggestive of a dead region and slopes ~ 11 dB/octave). Slopes for both groups, however, were substantially shallower than 50 dB/octave and, similar to results observed by Vickers et al (2001), there was substantial overlap in slopes between groups. In contrast, Aazh and Moore (2007) found no difference between average slopes of hearing loss (defined as the threshold difference between 2 and 4 kHz) for a group of individuals without (slope of 17.5 dB/octave) and with (17.1 dB/octave slope) dead regions at 4 kHz.

The studies mentioned above suggest that, although substantial variability exists, audiometric configuration may affect the likelihood of positive findings on the TEN. In an attempt to increase the likelihood of identifying individuals with potential dead regions when using the TEN, some studies have recruited participants with specific audiometric criteria, such as moderate-to-severe (or greater) hearing loss, steeply sloping losses, and/or flat or reverse slope losses (e.g., Moore et al, 2003; Preminger et al, 2005; Aazh and Moore, 2007; Vinay and Moore, 2007b). While selective recruitment is often required to achieve specific study goals, it may influence estimates of the prevalence of dead regions (based on a positive TEN finding) among persons with hearing loss.

In contrast to some previous studies targeting individuals with specific audiometric characteristics, Vinay and Moore (2007a) recruited a large number of participants with hearing loss (308 individuals, 556 ears) that varied substantially in terms of degree and configuration

of loss. They used the TEN (HL) test to examine the prevalence of dead regions over the frequency range of 250-4000 Hz. Hearing thresholds among participants varied between 15 and 85 dB HL, and losses were sensorineural in nature. To improve the precision of threshold estimates, thresholds in quiet and the TEN were obtained using a 2 dB step size as recommended by Moore et al (2004). The authors assumed that a positive finding on the TEN (HL) was the gold standard for identification of a dead region. Based on results from the TEN (HL) they reported that dead regions were quite common in their clinical population. In this study over 57% of participants had a dead region in one or both ears. When results were examined based on degree of hearing loss, the likelihood of positive findings on the TEN increased with hearing loss. For any frequency tested (250-4000 Hz), when thresholds were between 75 and 85 dB HL, 59% (at 1000 Hz) to 81% (at 3000 Hz) of ears had positive results on the TEN (HL), suggestive of a dead region. These percentages increased to 83-93% when only thresholds between 80 and 85 dB HL were included. Although positive TEN results were quite common in the presence of severe hearing loss, the authors reported they were unable to find an audiometric criterion that provided both high sensitivity and specificity.

In summary, studies using the TEN as a gold standard suggest that the presence of dead regions in persons with moderate-to-severe hearing loss may be quite common. In addition, results suggest that certain characteristics of hearing loss, such as severe-profound high-frequency loss or steeply sloping configurations may be more commonly associated with positive TEN findings. However, only one study to date (Vinay and Moore, 2007b) has systematically evaluated the relationship between audiometric characteristics and TEN test findings on a large number of individuals with a wide range of hearing losses and hearing loss configurations. The purpose of this study was to further examine the effects of audiometric characteristics on the rate of positive, negative, and inconclusive findings on the TEN test over a wider frequency range (250-8000 Hz) than previously examined.

In addition, an underlying assumption of the TEN test is that positive findings on the TEN are suggestive of greater cochlear damage than suggested by the audiogram. The consequences of this damage, however, may depend on its extent and location. For example, a single positive finding at 8000 Hz is expected to have less functional impact than multiple positive findings concentrated in the speech frequency regions. Therefore an additional goal of this study was to examine the rate of occurrence of “patchy” (isolated positive findings on the TEN) versus “extensive” (cases of multiple positive findings at adjacent frequencies).

PROCEDURES

Participants

Study participants were recruited as part of a larger study examining the effects of degree and configuration of hearing loss on binaural speech understanding. Fifty-nine adults (34 males, 25 females) ages 49 to 88 years (mean 70.7 years) participated in this study. Participants were identified and recruited through a review of audiometric evaluations conducted at the Vanderbilt Bill Wilkerson Center for Otolaryngology and Communication Disorders, in Nashville, Tennessee. All participants had symmetrical SNHL defined as threshold differences between ears: (1) of ≤ 20 dB at any single frequency, (2) of ≤ 15 dB at any two adjacent frequencies, and (3) of ≤ 10 dB in pure tone average at 500, 1000, and 2000 Hz. SNHL was confirmed via audiometric results obtained in the clinic within the six months prior to study participation. Specifically, clinical test results showed air-bone gaps of ≤ 10 dB and the presence of normal type A tympanograms for all participants.

Informed consent was obtained prior to collecting demographic and hearing health information, such as age, gender, years of education, years of hearing loss, years of hearing aid use, and family history of hearing loss from each participant. All participants also passed (scores ≤ 2)

the Short Portable Mental Status Questionnaire (SPMSQ) (Pfeiffer, 1975), thus excluding individuals with significant cognitive deficits. Scores ≥ 5 are suggestive of moderate or greater intellectual impairment. Participants generally scored 0 or 1, and no participant scored higher than 2 on this screener. Air conduction thresholds were measured using a Grason Stadler (GSI-61) audiometer via standard clinical procedures (i.e., down 10 dB up 5 dB) to confirm no significant change in hearing since the previous audiogram. Given the study focus on the effects of audiometric characteristics on TEN findings, study participants were chosen such that degree and slope of high-frequency hearing loss varied over a wide range. Specific audiometric data are provided in the following sections.

TEN (SPL) Measures

Cochlear function was assessed using the TEN (SPL) test (Moore et al, 2000). Because we were particularly interested in assessment of high-frequency cochlear function, we chose to use the TEN SPL, which allows for a wider range of test frequencies than the TEN (HL). Testing was performed in a sound-treated test booth. Pure tones and the TEN (SPL) masker were played from a CD player (Sony CDP-590) and routed through the external inputs of a GSI-61 audiometer to control levels. Stimuli were presented to participants via insert earphones (ER-3A). All testing was completed by certified audiologists.

Thresholds were measured using a 5 dB step size and a standard clinical technique (i.e., down 10 dB up 5 dB). Moore (2004) has suggested using a final step size of 2 dB, rather than 5 dB to more precisely define threshold and, hopefully, more accurately identify potential dead regions. However, while a smaller step size may result in a greater number of positive TEN test findings, it is not clear that this translates into increased accuracy of identification of potential dead regions. That is, using the smaller step size may increase sensitivity of the test, but it may also decrease test specificity by increasing the number of false positives due to incorrectly identifying “borderline” positive results (Aazh and Moore, 2007). Therefore, we chose to use the more clinically efficient step size of 5 dB with the understanding that test specificity (correct categorization of individuals without a true dead region, i.e., fewer false positives) may be improved, potentially at the expense of test sensitivity (i.e., increased misses; failure to identify a true dead region). Thresholds at eight test frequencies (250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz) were first measured in quiet and then in the TEN, using the test tones from the CD. Data were collected on a single ear prior to testing the opposite ear. A single noise level was used for each participant. Noise levels were chosen to be as high as possible without causing the listener loudness discomfort. The median noise level used was 80 dB/ERB (range: 65-105 dB/ERB) with ~90% of participants selecting noise levels between 70 and 90 dB/ERB. Data were collected from both ears of 58 participants and one ear from one additional participant (117 ears total).

TEN (SPL) results were categorized as positive (suggestive of a dead region), negative (not suggestive of a dead region), or inconclusive (criteria for a positive test result were not met, but the presence of a dead region could not be ruled out). Summers et al (2003) suggest that the accuracy with which the TEN test may identify true dead regions may vary based on the criteria used for a positive test result. They found that agreement between TEN and psychophysical tuning curves (PTCs), another behavioral method for identifying potential dead regions, improved when a stricter criterion was used. They compared PTCs and TEN results and found only a 56% agreement rate when 10 dB of excess masking (i.e., masked thresholds 10 dB above the level of the TEN) was used as the criterion for a positive test result. Agreement improved to 89% when this criterion was increased to 14 dB. Therefore, in this study positive results were categorized using both a lax (10 dB of excess masking) and strict (15 dB of excess masking) criteria.

Specifically, a result was considered positive using the lax criterion when (1) masked threshold was ≥ 10 dB above the level of the TEN (SPL), and (2) masked threshold was ≥ 10 dB above quiet threshold (i.e., at least 10 dB of masking occurred). For the strict criterion to be met, masked thresholds were required to be ≥ 15 dB above the noise level and ≥ 10 dB above quiet threshold. Results were considered inconclusive (i.e., a dead region may be present but could not be confirmed) if the results fulfilled one of the following three conditions: (1) Masked threshold was < 10 dB above quiet threshold (i.e., the noise level was too low to create the required 10 dB of masking) and noise levels could not be increased to further elevate threshold due to loudness tolerance issues; (2) Quiet threshold was 5 dB or less than the maximum output at a given frequency, and no response was obtained in noise. In this case it was unclear whether 10 dB of masking would have occurred if the audiometer output could be increased; (3) No response was obtained in quiet to tones from the TEN test CD presented at the limits of the audiometer output. Given the threshold elevation required to meet the second and third conditions, the presence of a dead region would be likely in these cases.

Figure 1 shows the distribution of thresholds in quiet, in dB HL, based on thresholds measured using pure tones from the TEN (SPL) CD. Thresholds were converted to dB HL by subtracting the frequency-specific RETSPL for insert earphones in a 2 cc coupler (ANSI S3.6; American National Standards Institute, 1996) from the 2 cc coupler levels (in dB SPL) of the tones presented from the CD. Because thresholds in quiet were based on pure tones presented from the TEN CD and then converted to dB HL, threshold values did not result in multiples of 5 dB and varied slightly (2-4 dB depending on frequency) between ears due to differences in earphone calibration. For clarity, thresholds in Figure 1 were categorized into 5 dB HL ranges (e.g., thresholds in the 60 dB HL range fell between 55.1 and 60 dB HL).

Mean and median thresholds for our participants were between 60 and 65 dB HL. When calculating mean and median values, cases where no response was obtained in quiet were excluded. Thresholds ranged from approximately 5 dB HL at 500 Hz to no response at the limits of our system at 6000 and 8000 Hz. Thresholds were ≤ 90 dB HL for frequencies ≤ 1000 Hz. The maximum measured threshold was 130 dB HL at 3000 Hz. The vast majority of thresholds ($\sim 95\%$), however, were ≤ 105 dB HL.

RESULTS

When classifying results from the TEN test, outcomes could be negative, positive, or inconclusive. In the current study there were no cases where a single test outcome was observed at all frequencies. This was true even in the case of negative outcomes (i.e., no dead region is suspected). One participant with milder hearing loss had negative results at all but one frequency (1000 Hz), where a positive result using the lax criterion was observed. In all other cases test results for a given ear varied across frequency and included some combination of positive, negative, and inconclusive results. All but three ears (about 97%) had at least one negative test result (not suggestive of a dead region), and almost 84% of ears (98 of 117 ears) had a positive test result, using the lax criterion, at least at one test frequency. Finally, almost 80% of ears had at least one inconclusive result. When examined across ear and frequency, negative results were most common. Of the 936 threshold measures (117 ears $\times$ eight test frequencies) approximately 48% (446 of 936 tests) had negative test results. In these cases TEN (SPL) test results were conclusive, but the criteria for a positive test result were not met.

Degree of Hearing Loss and TEN (SPL) Results

Table 1 shows the frequency of occurrence of a given test outcome as a function of degree of hearing loss. As expected, negative test results were much more common with less hearing loss. The mean threshold at frequencies with negative test results (no dead region) was 48.6 dB HL. Almost 70% (307 of 446 cases) of negative results occurred for thresholds less than

60 dB HL. However, the distribution of results was quite broad, and negative results were observed, in isolated cases, for thresholds up to 95 dB HL (see Table 1).

Also as expected, a somewhat reverse trend was observed for positive TEN findings with positive results being more common in the presence of greater hearing loss. Using the lax criterion, approximately 24% (227 of 936) of test results were positive (suggestive of a dead region) with positive results being more common with hearing losses >60 dB HL. Approximately 61% (138 of 227 cases) of cases with positive results, using the lax criterion, occurred for thresholds greater than 60 dB HL. The mean threshold for cases showing a positive test result, using the lax criterion, was 65.7 dB. The difference between mean thresholds for participants with negative results and those with a positive result using the lax criterion was statistically significant ($t = -11.3$, $df = 671$, $p < .001$). Again, however, significant overlap was observed with 39% of positive results occurring when thresholds were less than 60 dB HL. Positive results were observed, in isolated cases, for thresholds as low as 20-30 dB HL. Although the number of positive test results was reduced (to ~11% or 103 of 936 cases), a similar trend was observed when the strict criterion was used. Mean thresholds for participants having positive findings using the more strict criterion was 68.1 dB HL, which was not significantly different than the mean threshold for the lax group ($t = -1.8$, $df = 328$, $p = .237$). As when the lax criterion was used, positive results were observed for thresholds as low as 20-30 dB HL, which is generally inconsistent with the presence of a dead region.

Table 1 also shows that the number of positive test results, using either a lax or strict criteria, did not systematically increase as threshold levels increased. Instead, when examined in terms of percentage of positive results in a given threshold range, the occurrence of positive results peaked, at about 40%, when thresholds were in the 65-70 dB HL range. This lack of a systematic increase in the occurrence of positive test results is due, in part, to the increase in inconclusive test results that occur as threshold increases. The mean threshold for inconclusive test findings (excluding cases of “no response” in quiet) was 82.6 dB HL. This was significantly higher than the mean threshold for participants with suspected dead regions based on a lax criteria ($t = -11.8$, $df = 458$, $p < .001$). Figure 2 shows the percent of cases that were positive (using the lax criterion), negative, or inconclusive (for any reason). This figure highlights the large number of inconclusive results that occurred when thresholds were >75-80 dB HL.

The inconclusive results shown in Figure 2 reflect, largely, the inability to present the TEN at a high enough level, due to loudness tolerance issues, to produce sufficient masking to obtain conclusive results (see Table 1, “Inc. 1” column). This occurred in about 24% of cases (221 of 936 threshold measures). Inconclusive results also occurred in some cases because 10 dB of excess masking could not be confirmed. In these cases thresholds in quiet were just below the maximum output of our system, and no response was observed in noise (12 cases), or there was no response to tones in quiet (30 cases).

Threshold Frequency and TEN (SPL) Results

The relative occurrence of a specific test result also varied with frequency. Figure 3 shows the number of occurrences of a given test result as a function of frequency. In our study, sample positive findings (suggestive of a dead region) on the TEN (SPL), using the lax criterion, were relatively uncommon in the low frequencies (<10% at 250 and 500 Hz) regardless of degree of hearing loss. In the mid- to high-frequency regions (1000-8000 Hz) positive findings, using the lax criterion and collapsed across all degrees of hearing loss, were observed in 16-39% of threshold measures. Using the strict criterion, positive findings were relatively uncommon and limited primarily to the higher frequency regions (6-8 kHz). At frequencies between 250 and 3000 Hz, positive findings using the strict criterion were observed in only about 5%, or less, of cases. The number of positive findings increased to about 9% at 4000 Hz and to approximately 30% at 6000 and 8000 Hz.

Figure 3 also shows that the proportion of inconclusive findings varied systematically with frequency. Inconclusive results were relatively uncommon in the low-frequency regions (≤ 1000 Hz) and increased systematically as frequency increased up to 8000 Hz. At 6000 and 8000 Hz, test results were inconclusive in 60-70% of cases. It was common at these frequencies for thresholds to be so poor that the TEN noise could not be presented at a high enough level to ensure effective masking. Inconclusive findings also resulted when thresholds were at the limits of the equipment or thresholds in quiet were not measurable. The large number of inconclusive results, coupled with the increase in positive TEN findings, resulted in very few cases of negative test findings in these frequency regions. In fact only five negative findings (out of 234 threshold measures) were observed at 6000 (three cases) and 8000 (two cases) Hz. This finding is a consequence, in part, of the high incidence of high-frequency hearing loss. Even though our sample was recruited to provide a range of degree and configuration of hearing losses, 93% of thresholds ≥ 90 dB HL occurred in the 3-8 kHz region. In contrast, only six thresholds ($< 2\%$) were ≥ 90 dB HL in the frequency region between 250 and 1000 Hz, and almost 90% of thresholds in this frequency region were ≤ 70 dB HL.

Hearing Loss Slope and TEN (SPL) Results

To examine the role of hearing loss slope on TEN (SPL) results, participants were categorized into one of three groups based on the slope of their hearing loss. Thresholds obtained in quiet using tones from the TEN (SPL) CD, converted to dB HL, were used to categorize individuals. Nine (9) ears from (6) six participants with milder high-frequency hearing loss (average at 3, 4, and 6 kHz < 56 dB HL) were excluded in an attempt to better match high-frequency hearing loss between groups. In cases where there was no response to pure tones in quiet, for the purposes of averaging, thresholds were assumed to be 5 dB greater than the maximum presentation level (approximately 105 dB HL at 6000 Hz).

Slope of hearing loss was categorized as flat, moderate, or steep. Slopes were defined as the mean threshold (in dB HL) at 3, 4, and 6 kHz, minus the mean threshold at 0.25, 0.5, and 1 kHz. Thus positive numbers indicate a sloping high-frequency hearing loss, and the larger the number the steeper the slope of the loss. Slope was categorized as flat if the difference was ± 15 dB; moderate if the difference was between 16 and 45 dB and steep if the difference was > 45 dB. In addition, to capture any cases where thresholds were near normal out to 2000 Hz, slopes that fell more than 45 dB between 2 and 4 kHz were also classified as steep. This occurred in only one ear in the current study. Table 2 provides a breakdown of the audiometric characteristics of the study sample. Figure 4 shows the average audiograms for each group.

A primary question of interest here was, given a similar degree of high-frequency hearing loss, do steeper slopes affect the rate of occurrence of TEN findings in the high-frequency regions? To examine the role of high-frequency slope on TEN (SPL) findings, test results across the high-frequency regions (3000-8000 Hz) were grouped for analysis. Figure 5 shows the percent of test results, for the frequency regions between 3000 and 8000 Hz, that were negative, positive (lax criteria), or inconclusive (for any reason) as a function of slope of hearing loss. For example, the steeply sloping group consisted of 148 data points (37 ears $\times$ 4 frequencies). For each ear in this group, TEN results at four frequencies (3000-8000 Hz) were categorized as either negative (14; $\sim 10\%$), positive (lax criterion; 45, $\sim 30\%$), or inconclusive (89, $\sim 60\%$).

When examined in this fashion, slope appears to play a significant role in negative test findings (chi-square = 12.41, $p = .002$). Specifically, participants with steeply sloping high-frequency losses were less likely to have negative test outcomes (no dead region, i.e., result *not* suggestive of a dead region). The likelihood of negative test findings systematically increased as hearing loss slope decreased from steep to moderate to flat. In contrast, no significant difference between slope groups was observed when comparing the probability of a positive test finding (dead region lax; chi-square = 1.56, $p > .05$). The effect of slope on inconclusive results

approached significance (chi-square = 5.9, $p = .052$); in this case participants with steep or moderate slopes were more likely to have inconclusive test results than participants with flat losses.

It is also worth noting the large proportion of inconclusive results observed across all groups, particularly for the steep (~60% of cases) and moderate (~55% of cases) slope groups. Inconclusive results were significantly more common than positive findings (dead region lax) for the steep (chi-square = 10.0, $p = 0.002$) and moderate slope groups (chi-square = 14.8, $p < 0.001$). In contrast, both test results were equally common for participants with flat losses (chi-square = 0.74, $p > 0.05$). These results suggest that slope of hearing loss plays a role in TEN test outcomes; however, consistent with past research (e.g., Aazh and Moore, 2007), they also highlight the fact that slope alone is an inadequate predictor of TEN outcomes. Ignoring inconclusive results, there were an approximately equal number of positive and negative results for the flat (29 positive vs. 32 negative) and moderate (42 positive vs. 40 negative) groups, respectively. In contrast, participants with steeply sloping losses were three times more likely to have a positive result (45 positive results using the lax criterion) than a negative test outcome (14 negative results). These values could still, however, underestimate the number of actual dead regions in our sample. That is, given the severity of hearing loss commonly observed with inconclusive results (see Fig. 2), it is possible that the number of positive test outcomes would be greater if higher noise levels could be used to obtain a conclusive test outcome.

“Patchy” Dead Regions

Positive findings in our participant group were relatively common when using a lax criterion (up to 40% of cases for some threshold ranges). However, the functional consequences (e.g., effects on benefit from amplification) of these findings remain unknown. One factor that may influence the functional consequences of positive test findings is the range of frequencies affected. For example, if positive findings were limited to a single frequency or to isolated cases at a few widely scattered frequencies, the negative consequences may be less than if large adjacent frequency ranges were effected. Figure 6 shows the percentage of ears that had positive findings as a function of number of frequencies with positive findings. There were eight frequencies tested (250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz); thus, a participant could have between zero and eight positive test findings. The distribution of positive test findings was clearly skewed with positive findings occurring most often at only one or two test frequencies. Only 29% of participants had positive findings at three or more frequencies, and no participants had more than six positive findings.

Figure 6 shows that the majority of study participants had two or fewer positive test results. However, also of interest is the frequency with which positive results occur at adjacent rather than separate frequencies as the consequences of disparate versus adjacent positive results may vary. Table 3 shows the number of ears where positive findings were observed at adjacent frequencies (two, three, four, five, six, and seven adjacent) as a function of starting frequency. For example, Table 3 shows that positive findings at adjacent frequencies occurred more often in the very high frequencies. Twenty-two of 117 ears had positive findings, using the lax criterion, at the adjacent frequencies of 6000 and 8000 Hz. Extensive adjacent positive findings, suggesting a wide extent of cochlear damage, were fairly uncommon in the high frequencies. Only four of 117 cases showed positive findings extending from 2000 to 8000 Hz. However, this is likely an underestimate due to the large number of inconclusive findings observed in the very high-frequency regions. For example, almost 50% of ears (56 of 117 ears) had positive and/or inconclusive findings at four or more adjacent frequencies (data not shown).

Table 3 shows that extensive low-frequency positive findings were even more uncommon in our group. Only one ear (0.9% or 1 of 117 ears) had adjacent positive findings at four frequencies (250, 500, 1000, and 2000 Hz). Two additional ears (three total or 2.6%) had

positive findings at three adjacent frequencies (1000, 500, and 250 Hz). In this case, inconclusive results likely did not play a significant role due to their limited number in the low-frequency regions (see Figure 4). However, it is important to note that participant thresholds were generally better in these low-frequency regions with almost 90% of thresholds being ≤ 70 dB HL.

Discussion

The primary goal of this study was to examine the effects of degree and configuration of hearing loss on TEN (SPL) results. To this end, individuals with a wide range of hearing losses and configurations were recruited to participate. The general findings of this study are in agreement with past work using both the TEN (SPL) and the TEN (HL). Positive findings were more common for greater degrees of hearing loss, and negative findings were more common for those with less hearing loss (see Figure 3). In addition, there was significant overlap in audiometric thresholds between those with and without positive TEN (SPL) results, suggesting that threshold alone is not a good predictor of TEN test outcomes in persons with hearing loss. Likewise, and also consistent with previous work, slope of hearing loss was found to be related to, but not an adequate predictor of, TEN findings. In the current study, participants with steeply sloping losses were *less* likely to have a negative (i.e., not suggestive of a dead region) result than participants with either moderately sloping or flat losses. However, this appears to be due to a high number of inconclusive test findings in this group rather than a large number of positive TEN findings. There was no difference between the steep, moderate, or flat loss groups in terms of the likelihood of positive test findings (i.e., suggestive of a dead region).

Although general trends were similar to past findings, notable differences were also present. A major difference in the distribution of positive test results as a function of threshold was observed. For example, Vinay and Moore (2007a) reported positive TEN (HL) findings in less than 1% of cases (13 of 2448 thresholds) when thresholds were 65 dB HL or less (collapsed across frequencies) and no positive results were observed for thresholds of 55 dB HL or less. In the current study, however, positive results, using the lax criterion, were observed for thresholds as low as 20-30 dB HL with approximately 39% of positive cases (89 of 227) occurring when thresholds were less than 60 dB HL (see Table 1 and Fig. 2). When data were examined only over the frequency range of 500-4000 Hz, comparable to Vinay and Moore (2007a), similar findings were still observed with about 37% (51 of 139) of cases showing positive results.

Interestingly, utilizing a stricter criterion (masked threshold at least 15 dB above the level of the TEN) reduced the total number of positive findings but did not affect the range of thresholds over which positive results were observed. Even with the strict criterion, positive findings were still observed for thresholds as low as 20-30 dB HL (see Table 1). The high percentage of positive results in the presence of mild to moderate hearing loss are inconsistent with the presence of significant cochlear damage and are likely reflective of false positive results rather than the presence of true cochlear dead regions. If this is the case then caution must be used when interpreting results from the TEN (SPL), at least when using the methods employed in the current study.

Another major difference between the current study and previous work was the large number of inconclusive results observed in the current study. Using the TEN (HL), Vinay and Moore (2007a) noted inconclusive results in only a tiny percentage of cases when thresholds were 85 dB HL or less (only 7 of 556 ears had at least one inconclusive result at one or more frequencies). In contrast, inconclusive results in the current study were quite common and most often associated with an inability to present the TEN (SPL) at a high enough level to create the required 10 dB of masking above quiet threshold ("Inc. 1" in our Table 1). In the current study

94 of 117 ears (~80%) had an inconclusive result at least at one test frequency while over 30% (38 of 117) had inconclusive results at three or more frequencies.

This large difference may be due, in part, to the range of hearing losses (>85 dB HL) and frequencies (up to 8000 Hz) included in the current study compared to that assessed by Vinay and Moore (2007a). These authors noted that inconclusive results were also common among their participants when thresholds were greater than 85 dB HL and thus data from thresholds of this magnitude were excluded from their analysis. In the current study, even when only thresholds of 85 dB HL or less were considered, inconclusive results remained much more common than previously reported with ~64% of ears showing at least one inconclusive result (75 of 117 ears). The continued high prevalence of inconclusive results in our data set may also be due, in part, to the range of frequencies tested.

One motivation for the use of the TEN (SPL) rather than the TEN (HL) in the current study was our interest in examining TEN results at high frequencies (>4000 Hz). Unfortunately, inconclusive results were particularly common for frequencies above 4000 Hz (see Fig. 3), even when only thresholds of 85 dB HL or better were considered. For example, when excluding thresholds greater than 85 dB HL, more than 50% of ears still had inconclusive results in the 6000 (54%) and 8000 Hz (59%) regions. The large number of inconclusive results observed in the 6000-8000 Hz region may also be a consequence of the earphones used in the current study. To obtain valid results with the TEN (SPL), a relatively flat frequency response is required. Moore (2004) suggested that TEN (SPL) results may be unreliable in frequency regions where the test earphone has a sharp roll-off. The ER-3A insert earphones used in this study have a substantial roll-off above 4000 Hz (~25 dB between 4000 and 8000 Hz). This steep roll-off may have impacted the masking effectiveness of the TEN in these frequency regions potentially leading to the large number of inconclusive results. It should be noted, however, that the TEN (SPL) was validated using TDH-50 earphones, which have a frequency response similar to the ER-3A earphones used in the current study (Moore et al, 2000). Therefore, the contribution of earphone frequency response to the rate of inconclusive results seen in the current study remains unclear.

In the current study we were interested in assessing higher frequency regions than are capable of being assessed by the TEN (HL). For this reason, the TEN (SPL) was used. However, it should also be noted that the TEN (HL) has several advantages that likely helped limit inconclusive results in the study by Vinay and Moore (2007a). One of the goals in the development of the TEN (HL) was to allow for higher noise presentation levels in order to reduce the number of inconclusive test results among individuals with more severe hearing loss. To reduce the overall level of the TEN, the bandwidth of the noise was reduced so that only thresholds from 500 to 4000 Hz could be tested. In addition, the crest factor of the TEN (HL) was reduced, limiting the peak levels of the noise. These changes allow the TEN (HL) to be presented at higher levels than the TEN (SPL) without distortion and with less loudness discomfort. This may help reduce the number of inconclusive outcomes due to an inability to create at least 10 dB of excess masking (Moore et al, 2004).

Another factor that may have affected test results in the current study was the use of a 5 dB, rather than 2 dB, step size during TEN (SPL) threshold measures. The use of 5 dB step size, particularly when measuring thresholds in quiet, may have led to an increase in inconclusive results when compared to studies using a 2 dB step size (e.g., Vinay and Moore, 2007a). Recall that the majority of inconclusive results (221 of 263 cases) in the current study occurred when masked thresholds were not 10 dB, or more, greater than threshold in quiet. The use of a 2 dB step size could have potentially lowered quiet thresholds enough to meet this criterion, at least in some cases. At the same time, the use of a 2 dB step size may result in an increase in the number of "borderline" cases where confidence in the relationship between a positive TEN

finding and the presence of a dead region may be reduced. For example, Aazh and Moore (2007) found that over 30% of the individuals identified as having dead regions on the TEN (HL) met the criteria by only 1-2 dB. For these individuals masked thresholds were 10-11 dB above the level of the noise (a 10 dB threshold shift was the criterion for a positive result). Likewise 18% of individuals with negative results (no suspected dead region) would have had a positive result if thresholds were 1-2 dB higher (i.e., masked thresholds were 8-9 dB above the level of the TEN [HL]). Data from Cairns et al (2007) suggests that TEN outcomes (positive or negative) based on differences of this magnitude should be viewed cautiously. These authors examined test-retest reliability of the TEN (HL) and found that in four out of five cases where a test outcome changed on retest (from positive to negative or vice versa), TEN test criteria had been met by only 1 or 2 dB. Thus the reliability of test outcomes for these “borderline” cases is not clear.

Along these lines, Cairns et al (2007) noted that in all but one of the cases where TEN test outcomes changed between test sessions, positive findings were observed at only one test frequency. The functional impact of these isolated, or patchy, positive results is unknown. It is reasonable to expect, however, that the impact of positive test findings is likely related to the range of frequencies affected, with greater functional impact associated with larger affected frequency regions. In this study, although a high percentage of ears had positive TEN results, the majority of these cases were limited to one or two isolated results (see Fig. 6 and Table 3). In other words, “patchy” rather than contiguous regions of positive test results were quite common. It is important, however, to view these results with caution given the high proportion of inconclusive results in this study. If higher noise levels could have been presented it is possible that a larger proportion of positive adjacent findings may have been observed.

SUMMARY

In summary, participants with a wide range of hearing losses were recruited to examine the effects of degree and configuration of hearing loss on TEN (SPL) outcomes. Consistent with past research, TEN test outcomes (positive or negative) were not well predicted based on audiometric characteristics alone. Thresholds were generally higher (poorer) for participants with positive results; however, substantial overlap was observed. Some participants with relatively mild hearing loss had positive test results while others with more severe hearing loss had negative test results. Likewise, although persons with steeply sloping losses were more likely to have *fewer* negative TEN results, there was no difference in the number of positive test results observed as a function of slope. Several findings from the current study, however, suggest that drawing firm conclusions about underlying cochlear status based on results of the TEN (SPL) should be done with caution, at least with the protocol used in this study (i.e., 5 dB step size and using ER-3A insert earphones). Specifically, the presence of a high proportion of positive findings in individuals with relatively mild losses is suggestive of false positive findings. In addition, the large number of inconclusive results, particularly in the high-frequency regions, makes it difficult to draw firm conclusions about cochlear status over a wide frequency range for many of the study participants. The large number of inconclusive results, coupled with the potential for false positive results, makes it difficult to estimate the true prevalence of positive, or negative, findings on the TEN (SPL) in persons with hearing loss, particularly in the high-frequency regions.

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Abbreviations

DR, dead region; IHC, inner hair cell; PTA, pure-tone average; PTC, psychophysical tuning curve; SNHL, sensorineural hearing loss; SPL, sound pressure level; SPMSQ, Short Portable Mental Status Questionnaire; TEN, Threshold Equalizing Noise test.

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Figure 1.
Histogram of thresholds, across all frequencies, in a given range.

Figure 2. Percent of cases of positive (using a lax criterion; *top panel*), negative (No DR; *middle panel*), and inconclusive (*bottom panel*) TEN (SPL) test results as a function of range of hearing thresholds.

Figure 3.

Relative occurrence of TENG (SPL) test results as a function of threshold frequency. The top panel shows the percentage of test results that were negative (No DR; black bars) or inconclusive (for any reason; white bars) as a function of threshold frequency. The bottom panel shows the percentage of positive results (suggestive of a DR) using both a lax (white bars) and strict (striped bars) criterion as a function of threshold frequency.

Figure 4.
Average audiograms for each participant group.

Figure 5.

Effect of hearing loss slope (steep, moderate, or flat) on negative, positive (lax criterion), and inconclusive (for any reason) TEN (SPL) results in high-frequency (3000-8000 Hz) regions. DR = dead region.

Figure 6. Percentage of ears with positive TEN (SPL) findings at zero (no positive findings) to eight test frequencies (250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz).

Table 1
Number of Various Test Findings as a Function of Threshold across All Frequencies

Threshold (dB HL)	Total	No DR	DR Lax	DR Strict	Inc. All	Inc. 1	Inc. 2	Inc. 3
5	0	0	0	0	0	0	0	0
10	2	2	0	0	0	0	0	0
15	4	4	0	0	0	0	0	0
20	24	23	1	1	0	0	0	0
25	23	23	0	0	0	0	0	0
30	31	28	3	3	0	0	0	0
35	49	43	6	2	0	0	0	0
40	44	38	6	1	0	0	0	0
45	47	38	9	5	0	0	0	0
50	53	35	17	6	1	1	0	0
55	47	29	16	7	2	2	0	0
60	80	44	31	11	5	5	0	0
65	76	38	22	9	16	16	0	0
70	78	30	31	17	17	17	0	0
75	71	35	11	10	25	25	0	0
80	72	15	26	6	31	31	0	0
85	67	10	17	7	40	36	4	0
90	54	8	12	6	34	33	1	0
95	36	3	11	7	22	19	3	0
100	23	0	2	1	21	20	1	0
105	14	0	4	4	10	8	2	0
110	4	0	1	1	3	3	0	0
115	4	0	1	1	3	2	1	0
120-130	3	0	0	0	3	3	0	0
NR	30	0	0	0	30	0	0	30
Sum	936	446	227	103	263	221	12	30

Note: Total = total number of thresholds in a given range. DR = dead region. Inc. = inconclusive. Inc. 1 = thresholds in noise were not ≥ 10 dB above quiet threshold but noise levels were too low to create 10 dB of masking. Inc. 2 = quiet thresholds were 5 dB or less than the maximum output at a given frequency and no response was obtained in noise. Inc. 3 = no response to tones in quiet.

Table 2

Audiometric categorization

Group	Slope	Mean/median high-frequency loss	Hearing loss slope (dB)	N	Ears
1	Steep Moderate Flat	85(85) dB	>45 16-45 ±15	21	37
2		75(74) dB		32	47
3		70(65) dB		19	24
Total					108

Note: Mean high-frequency loss is the average (in dB) of thresholds at 3, 4, and 6 kHz. Median values are also shown in parentheses. Slope refers to the difference (in dB) between mean thresholds at 3, 4, and 6 kHz and 0.25, 0.5, and 1 kHz. N = the number of individuals with hearing loss that fit into a given group. Ears = the number of ears that fit into each group. The total number of individuals (N) is >53 as some individuals had threshold configurations that were subtly different between ears. Thus, it was possible for one individual to be classified into two groups and thus be counted twice.

Table 3
Number of Ears with Positive Findings Observed at Adjacent Frequencies as a Function of Starting Frequency (in Hz)

Starting Frequency (Hz)	Number of Ears with Adjacent Positive Findings (Lax Criterion)						
	Two Adjacent Frequencies	Three Adjacent Frequencies	Four Adjacent Frequencies	Five Adjacent Frequencies	Six Adjacent Frequencies	Seven Adjacent Frequencies	
250	3	3	1	0	0	0	
500	7	4	2	2	1	0	
1000	19	8	7	5	2		
2000	13	11	8	4			
3000	13	9	5				
4000	18	10					
6000	22						