J Am Acad Audiol 16:600–613 (2005)

# A Clinical Perspective on Cochlear Dead Regions: Intelligibility of Speech and Subjective Hearing Aid Benefit

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**Abstract**

Using the threshold equalizing noise (TEN) test, 49 subjects with at least two pure-tone thresholds per ear greater than 50 dB HL and none greater than 80 dB HL were evaluated for the presence or absence of dead regions. The purpose of this study was to (1) assess the prevalence of cochlear dead regions in this clinical population, (2) measure whether listeners with dead regions performed differently than listeners without dead regions on a speech intelligibility in noise test, and (3) determine whether cochlear dead regions are associated with reduced subjective hearing aid performance. The results showed that (1) twenty-nine percent of the subjects tested positive for dead regions, (2) listeners with dead regions had poorer sentence understanding in noise than listeners without dead regions and (3) listeners with dead regions perceived poorer subjective hearing aid performance in listening environments with reverberation or background noise as compared to those without dead regions.

**Key Words:** Cochlear dead regions, hearing aid performance, speech intelligibility

**Abbreviations:** AI = articulation index; ANCOVA = analysis of covariance; APD = auditory processing disorder; APHAB = abbreviated profile of hearing aid benefit; APHAP = abbreviated profile of hearing aid performance; AV = Averseness; BM = basilar membrane; BN = Background Noise; EC = Ease of Communication; ERB = equivalent rectangular bandwidth; HFDR = high-frequency dead region; IHC = inner hair cell; LFDR = low-frequency dead region; LMDR = low- or midfrequency dead regions; MFDR = midfrequency dead region; NoDR = no dead regions; NU-6 = Northwestern University Test No. 6; PTA = pure-tone average; PTC = psychoacoustic tuning curve; QuickSIN = Quick Speech-in-Noise test; RV = Reverberation; SNR = signal-to-noise ratio; SSI = synthetic sentence index; TEN = Threshold Equalizing Noise test; WDRC = wide dynamic range compression

**Sumario**

Utilizando el ruido ecualizador de umbral (TEN), se evaluó a 49 sujetos con al menos dos umbrales tonales por oído mayores de 50 dB HL, y ninguno por encima de 80 dB HL, buscando la presencia o ausencia de regiones muertas. El propósito de este estudio fue de (1) evaluar la presencia de regiones cocleares muertas en esta población clínica, (2) medir si los sujetos con regiones muertas funcionaban en una prueba de inteligibilidad de lenguaje en ruido diferente de aquellos sin regiones muertas, y (3) determinar si las

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Portions of this paper were presented at the American Auditory Society, Scottsdale, AZ, Mar. 2004, and the Academy of Rehabilitative Audiology Summer Institute, Saratoga Springs, NY, June 2004.

This project was funded by a Research Award from the University of Louisville School of Medicine.

regiones cocleares muertas estaban asociadas con una reducción subjetiva en el desempeño del auxiliar auditivo. Los resultados mostraron que: (1) el veintinueve por ciento de los individuos fueron positivos para la presencia de regiones muertas, (2) los sujetos con regiones muertas tuvieron una peor comprensión de frases en ruido que aquellos sin regiones muertas, y (3) los sujetos con regiones muertas tuvieron una percepción subjetiva más pobre del desempeño del auxiliar auditivo en ambientes de escucha con reverberación o con ruido de fondo, comparados con aquellos sin regiones muertas.

**Palabras Clave:** Regiones cocleares muertas, desempeño del auxiliar auditivo, inteligibilidad del lenguaje

**Abreviaturas:** AI = índice de articulación; ANCOVA = análisis de covarianza; APD = trastorno de procesamiento auditivo; APHAB = perfil abreviado de beneficio del auxiliar auditivo; APHAP = perfil abreviado de desempeño del auxiliar auditivo; AV = Aversión; BM = membrana basilar; BN = Ruido de Fondo; EC = Facilidad de Comunicación; ERB = ancho de banda rectangular equivalente; HFDR = región muerta de alta frecuencia; IHC = célula ciliada interna; LFDR = región muerta de baja frecuencia; LMDR = regiones muertas en las frecuencias bajas o medias; MFDR = región muerta de frecuencia media; NoDR = no región muerta; NU-6 = Prueba No. 6 de la Universidad Northwestern; PTA = promedio tonal puro; PTC = curva de afinación psicoacústica; QuickSIN = Prueba Rápida de Lenguaje en Ruido; RV = Reverberación; SNR = Tasa Señal/Ruido; SSI = índice de frases sintéticas; TEN = Prueba de Ruido Ecualizador de Umbral; WDRC = compresión de rango dinámico amplio

In normal cochlear functioning, different frequencies produce maximum displacement at different places along the basilar membrane (BM). The frequency that gives maximum response at a particular point along the BM is known as the "characteristic frequency" for that place. At the point of maximum BM displacement, deflection of the stereocilliary bundles of the inner hair cells (IHCs) gives rise to action potentials in the neurons of the auditory nerve (Moore, 2003). In sensorineural hearing loss, IHCs at certain places along the BM may be damaged or missing. In addition, the neurons innervating those IHCs may be nonfunctioning. "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). When a dead region is present, the "true" hearing loss at that frequency region is infinite and the measured pure-tone threshold should exceed the intensity limits of the audiometer (Moore, 2001, 2004). Due to the vibration pattern at the level of the basilar membrane, however, the audiometer tone can be detected by functioning IHCs and auditory neurons at a different place along the BM (Moore, 2001, 2004). When this "off-frequency" listening occurs, the audiogram can show thresholds as low as 40 dB HL at frequencies where cochlear dead regions exist (Moore, 2001).

### The TEN Test

A clinical test is now available that can identify dead regions along the basilar membrane (Moore et al, 2000): the Threshold Equalizing Noise (TEN) test. In this test listeners must detect sinusoids in the presence of a broadband noise that is designed to produce almost equal masked thresholds (in dB SPL) over a wide frequency range, for normal-hearing listeners and for listeners with hearing impairments but without dead regions. This broadband noise is referred to as equivalent rectangular bandwidth (ERB) noise. Listeners with dead regions show greater masking than expected from the TEN noise at frequencies where dead regions are located. In practical terms, in order to identify dead regions using the TEN test, pure-tone thresholds must be measured in quiet (approximately five minutes), then remeasured in the presence of the TEN noise (an additional five minutes). This can be done using a compact disc player routed to a conventional audiometer and transducers.

There has been some disagreement regarding the validity of the TEN test. Moore et al (2000) validated the TEN test in 19 ears of 14 subjects using psychoacoustic tuning curves (PTCs) as the gold standard. A PTC is a curve showing the level of a narrowband or tone masker required to mask a fixed tone signal, plotted as function of masker frequency. The PTC is thought to provide an estimate of the ear's frequency selectivity ability at the frequency location of the test tone. When a dead region was defined as a frequency location where the masked threshold in the TEN was at least 10 dB higher than normal, and the TEN produced at least 10 dB of masking, there was good agreement between the TEN test results and the PTC configuration (Moore et al).

A more recent study by Summers et al (2003) measured the validity of the TEN test, also using PTCs as the gold standard, in 18 ears. Using the definition of dead regions as described by Moore et al (2000), Summers et al found that the results of the TEN test and PTC evaluation agreed in only 56% of the cases. When Summers et al adjusted the definition of dead regions to include masked thresholds that were at least 14 dB above the absolute threshold and 14 dB above the level/ERB of the TEN, the consistency of agreement between the TEN test and PTCs improved to 89%. Moore (2004) reviewed the Summers et al data and proposed that PTCs may not be the most appropriate test to confirm the presence or absence of dead regions because the PTC measurement paradigm may introduce audible beats or combination tones that can then lead to altered PTC configurations. Moore (2004) did conclude, however, that it may be appropriate to utilize a stricter criterion requiring threshold in the TEN to be at least 15 dB higher than normal. Based on the results of Moore et al (2000), Summers et al (2003), and the recent discussion of Moore (2004), it does appear that the TEN test is valid. When using a 14 or 15 dB threshold shift criterion, the clinical audiologist can feel fairly confident that a positive TEN test result indicates the presence of a cochlear dead region.

## Dead Regions in Listeners with Moderate and Severe Hearing Loss

Moore (2001, 2004) has suggested that dead regions are likely at frequencies where thresholds are greater than 90 dB HL in the high frequencies and greater than 80 dB HL in the low frequencies. Audiologists would also expect listeners with thresholds greater than 80 dB HL to have poor speech intelligibility due to the severity of the hearing loss and the limited audibility of the aided speech signal regardless of whether the listener has cochlear dead regions. The impact of dead regions in subjects who have moderate to severe hearing loss is less clear.

There are no available data regarding the prevalence of dead regions in individuals with sensorineural hearing loss between 50 and 80 dB HL. If dead regions are extremely rare in this population, then it is probably not worth the time to use the TEN test routinely in patients with an audiogram that meets these criteria. If dead regions are prevalent (if they have an impact on communication, and if effective differential treatment can be developed for individuals who have dead regions), then it should be worth the time to measure them. One purpose of this study was to measure the prevalence of cochlear dead regions in a typical clinical population with sensorineural hearing loss between 50 and 80 dB HL.

## Dead Regions and Intelligibility of Speech

Since cochlear dead regions indicate dysfunction along a portion of the BM, speech intelligibility will likely be poorer than expected. An articulation index (AI; ANSI, 1969) can be used to test this hypothesis. Based on pure-tone thresholds, an AI calculation can be performed in order to predict speech intelligibility scores (Halpin, 2002); if a dead region is present, then we would expect the speech intelligibility score to be poorer than predicted by the AI.

A few recent studies have investigated whether there is a direct association between the presence of cochlear dead regions and speech recognition ability (Vickers et al, 2001; Baer et al, 2002; Vestergaard, 2003). Baer et al and Vickers et al investigated speech intelligibility in subjects with dead regions at thresholds that were 80 dB HL or greater; dead regions were measured with PTCs and confirmed with the TEN test (10 dB definition). They found that listeners with high-frequency hearing loss with no dead regions had improved speech recognition ability for low-pass filtered speech as the low-pass cutoff increased from 800 to 7500 Hz (i.e., as progressively more high-frequency information became audible). Baer et al and

Vickers et al also showed that listeners with high-frequency dead regions did not benefit to the same extent as the listeners without dead regions when high-frequency speech information became available. Baer et al and Vickers et al concluded that the AI may overpredict the speech recognition abilities for listeners with dead regions. This conclusion is based on listeners with dead regions for auditory thresholds greater than 80 dB HL. It is still not clear whether dead regions for thresholds less than 80 dB HL are associated with poorer than expected speech intelligibility. The second purpose of this study was to determine whether listeners with dead regions perform differently than listeners without dead regions on a clinical speech intelligibility task.

### Dead Regions and Subjective Hearing Aid Benefit

It is also important to consider the impact of cochlear dead regions on hearing aid benefit. Relatively poor subjective hearing aid performance is expected in listeners with profound hearing loss because it is typically not possible to provide sufficient speech audibility at frequencies with thresholds exceeding 90 dB HL. Conversely, amplification should provide ample audibility of speech and result in better subjective performance for listeners with pure-tone thresholds between 50 and 80 dB HL. This may not be the case in hearing aid users with cochlear dead regions because it is possible that at frequencies where a dead region is present, those individuals will not receive usable speech cues despite "sufficient" aided gain. In theory, cochlear dead regions present several obstacles to successful amplification. First, the infinite degree of "true" sensorineural hearing loss at a frequency corresponding to a dead region renders audibility at that frequency impossible, except by off-frequency listening. Second, attempts to provide amplification in the frequency range of a dead region may introduce distortion or result in the masking of adjacent frequencies through spread of excitation along the basilar membrane. Third, listeners with dead regions are believed to have a very limited usable dynamic range for frequencies within the dead region (Moore, 2001). This may require the limitation of audibility in order to preserve comfort. The third purpose of this study was to determine whether cochlear dead regions are associated with reduced subjective hearing aid performance.

To summarize, the purpose of the present study was to (1) measure the prevalence of cochlear dead regions in a typical clinical population with sensorineural hearing loss between 50 and 80 dB HL; (2) determine whether listeners with dead regions perform differently than listeners without dead regions on a typical clinical speech intelligibility task; and (3) determine whether cochlear dead regions are associated with reduced subjective hearing aid performance.

## METHOD

### Subjects

Patients of the private practice associated with the University of Louisville Program in Audiology were invited to participate in a research project on hearing. Only potential subjects who met the following criteria were invited to participate:

1. Individuals were between 21 and 75 years of age (all subjects were screened for auditory processing disorders [APD], as described below, and it was expected that patients older than 75 years would have a higher prevalence of APD; Stach et al, 1990).
2. Individuals had at least two pure-tone thresholds (per ear) greater than 50 dB HL and no pure tone thresholds greater than 80 dB HL. Subjects had to have thresholds of at least 50 dB HL to increase the likelihood of having cochlear dead regions. Subjects with thresholds greater than 80 dB HL were excluded because we would expect to see dead regions in severe and profound hearing loss. We were interested in evaluating the prevalence of dead regions and their impact in subjects in whom it was not clear if dead regions were present based on the audiogram alone.
3. Individuals had at least six months experience with binaural hearing aids.
4. All prospective subjects were

screened for APD using the synthetic sentence index (SSI) and the NU-6 word list. Subjects were considered APD positive if the difference between the NU-6 word score and the SSI score was greater than 20% (Stach et al, 1990) or if the SSI score was "disproportionately poor," i.e., less than the empirically derived lower boundary of SSI scores as a function of pure-tone average (Yellin et al, 1989). The SSI was administered after two practice lists were completed, and then scores were averaged across two lists. Subjects who were classified as APD positive were excluded from the study.

5. All prospective subjects were screened with tympanometry (226 Hz). Only subjects who had no indication of middle ear pathology were invited to participate.

Forty-nine individuals with hearing loss participated in this study. Their ages ranged from 23 to 75 years with a mean age of 62.5 years (standard deviation = 11 years). Fourteen of the subjects were female. Hearing aid information was available for 26 of the 49 subjects. Sixty-nine percent of the subjects were fit with nonlinear wide dynamic range compression (WDRC) hearing aids, and 31% were fit with linear hearing aids with output limiting compression. Twelve percent were fit with digital hearing aids, and 8% were fit with directional microphones.

## Evaluation Materials

### *TEN Test*

The TEN test was used to measure the presence or absence of dead regions in the cochlea. The test CD consists of pure tones at octave and interoctave frequencies between 500 and 10,000 Hz, and noise known as "threshold equalizing noise" (TEN). This noise is spectrally shaped so that masked thresholds in dB SPL are approximately the same for all audiometric test frequencies for people with normal hearing and for listeners with hearing loss and no dead regions (Moore et al, 2000). For an individual with a hearing loss and well-functioning IHCs and neurons associated with elevated thresholds, it is expected that thresholds in TEN would be only slightly higher than normal (2–3 dB, Moore et al, 2000). When a dead region is present, off-place listening occurs, resulting in thresholds in TEN that would be markedly higher than normal (at least 10–15 dB; Moore, 2004).

### *QuickSIN*

Speech intelligibility was measured with the Quick Speech-in-Noise test (QuickSIN; Killion and Niquette, 2000; Niquette et al, 2001). This is a typical clinical evaluation measure of speech understanding in noise that was used by 50% of dispensing audiologists surveyed by the *Hearing Review* in 2003 (Strom, 2004). The purpose of this test is to determine a speech reception threshold (SRT) by varying the signal-to-noise ratio (SNR). In other words, the test identifies the SNR at which the subject correctly repeats 50% of the key words. The QuickSIN consists of sentence lists that have six sentences per list and five key words per sentence. Performance is scored based on the percentage of key words repeated correctly. The sentences are presented at prerecorded signal-to-noise ratios that decrease in 5 dB steps from 25 (very easy) to 0 (extremely difficult). The noise on the CD is a four-talker babble.

Two types of QuickSIN sentences were used in this study: standard lists and high-frequency lists. The standard lists are unfiltered, whereas the high-frequency lists have increased gain above 1000 Hz, with approximately 20 dB of gain at 2000 Hz and 30 dB of gain above 3000 Hz.

### Abbreviated Profile of Hearing Aid Benefit (APHAB)

Subjective hearing aid performance was measured with the APHAB (Cox and Alexander, 1995). This is a 24-item questionnaire consisting of four subscales: Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV). These subscales assess the benefit derived from hearing aid use with respect to communication under ideal listening conditions (low noise/reverberation with visual cues available), communication under quiet, but poor, listening conditions (e.g., reverberation, soft speech, and visual cues unavailable), communication in noisy situations, and negative reactions to environmental sounds. Examples include "When I am having a quiet conversation with a friend, I have difficulty understanding" and "I have trouble understanding the dialogue in a movie or at the theater." Possible responses range on a seven-point scale from "Always" (1) to "Never" (7). When scored, the responses are expressed in terms of percent problems. That is, the percentage of instances in which the listener experiences difficulty for each type of listening situation addressed by the questionnaire.

## Procedures

### *TEN Test*

The TEN test was administered according to the instructions outlined by Moore (2001); all testing was conducted monaurally under insert earphones. First, thresholds were measured for the tones generated by the TEN CD in quiet; thresholds were measured at 250, 500, 1000, 1500, 2000, 3000, and 4000 Hz. Then, thresholds were measured for the TEN test tones in the TEN. The level of the TEN was determined by the severity of the hearing loss. If at least one of the thresholds in quiet was less than or equal to 60 dB SPL, then the TEN was set to 70 dB/ERB. If all thresholds in quiet were 60 dB SPL or higher, then the TEN was set to the lowest (best) threshold in quiet plus 10 dB. Thresholds were measured using a standard clinical technique (Stach, 1998). After the test tone was heard initially, threshold search followed with a "down 10 dB and up 5 dB" rule. Threshold was considered to be the lowest level at which the listener responded to the test tone for either two out of three or three out of five test runs. The presence of a cochlear dead region at a particular frequency was indicated by a masked threshold that was at least 15 dB above the absolute threshold and 15 dB above the level/ERB of the TEN (Moore et al, 2004).

### *QuickSIN*

The QuickSIN was administered unaided using insert earphones so that ability was measured separately for each ear. The presentation level was selected based on the instructions provided with the CD (Niquette et al, 2001). For ears with a pure-tone average (PTA, for 500, 1000, and 2000 Hz) less than or equal to 45 dB HL, the presentation level was set at 70 dB HL. For ears with PTAs greater than 45 dB HL, the level of the QuickSIN was set based on the loudness of a practice list of QuickSIN sentences. The level of the practice sentences was adjusted until subjects rated the loudness of the speech as "loud but OK." All subsequent sentence lists were presented at this level. In order to improve the reliability of the test, subjects completed one practice list presented to each ear before data collection began. Four lists of six sentences were then presented to each ear for each sentence condition (Standard and High Frequency); the final results were averaged across the four lists.

### APHAB

Typically, the APHAB questionnaire is administered before treatment (such as fitting hearing aids or an assistive listening device) and again following the treatment. These responses may then be compared for a measurement of benefit from the treatment (Cox and Alexander, 1995). Because all subjects in the present study had worn hearing aids for at least six months prior to taking part in this research, the APHAB was administered only in the aided condition, yielding a measurement of aided performance rather than benefit from amplification. It is not necessary to complete the APHAB for both the unaided and aided conditions in order to evaluate the success of a hearing aid fitting (Cox, 1996). Normative data for the questionnaire are available for both "benefit" (aided minus unaided performance) and "performance" (aided performance alone; Cox and Alexander, 1995). Other research has used the APHAB in this fashion, referring to the questionnaire as the Abbreviated Profile of Hearing Aid Performance (APHAP) (Purdy and Jerram, 1998). In order to differentiate between "benefit" and "performance," the evaluation measure will be referred to as the "APHAP" for the remainder of this paper.

The APHAP questionnaire was administered in pencil-and-paper format. In cases where an item was not applicable, subjects were instructed to make an estimation of how well they thought they would understand speech or how aversive sounds might be in that situation.

## RESULTS

### Prevalence of Dead Regions in a Clinical Population

The first purpose of this investigation was to determine the prevalence of cochlear dead regions in an adult clinical population with thresholds between 50 and 80 dB HL. Of the 49 individuals evaluated, 14 (29%) tested positive for dead regions. Six individuals had dead regions in only one ear, and eight subjects had binaural dead regions. The individuals with binaural dead regions, however, did not always have dead regions at the same frequency locations in each ear.

Subject age did not appear to be associated with the presence or absence of dead regions. The mean ages of subjects without dead regions (M = 62.3, SD = 11.2 years) and of subjects with dead regions (M = 62.9, SD = 10.2 years) were not significantly different ($t = .731$, $df = 47$, $p = .86$). There also appeared to be no association between gender and dead region. While 31% of males had dead regions, and 21% of females had dead regions, a chi-square analysis showed these percentages were not significantly different ($\chi^2 = .49$, $df = 1$, $p = .48$).

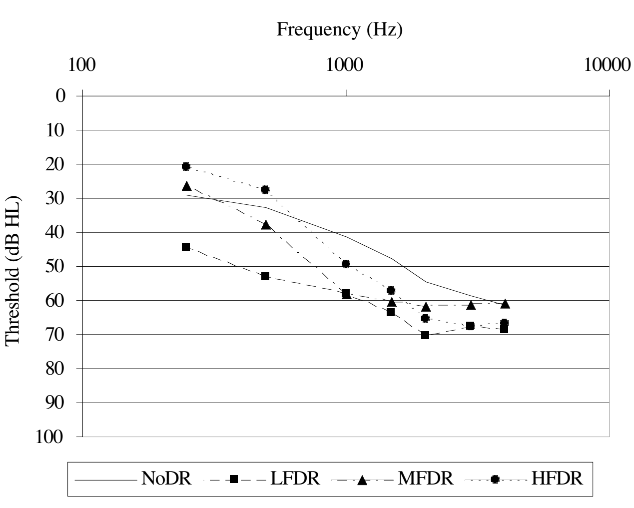


**Figure 1.** Mean audiograms for the four dead-region classification groups. The mean audiogram for the dead-region negative group (NoDR) is shown with the solid line; the mean audiogram for the subjects classified as having low-frequency dead regions (LFDR) is shown with the squares; the mean audiogram for the subjects classified as having midfrequency dead regions (MFDR) is shown with the triangles; and the mean audiogram for the subjects classified as having high-frequency dead regions (HFDR) is shown with the circles.

### Dead Regions and Audiometric Configuration

In order to examine the impact of dead regions on speech intelligibility and on subjective hearing aid performance, it is helpful to consider the frequency location(s) of the dead regions. Subject ears were classified as dead region positive or negative and separated into four groups: (1) low-frequency dead-region subjects (LFDR) had at least one dead region at 250 and/or 500 Hz (n = 5 ears); (2) high-frequency dead-region subjects (HFDR) had at least one dead region at 3000 and/or 4000 Hz (n = 13 ears); (3) midfrequency dead-region subjects (MFDR) had at least one dead region not including 250, 500, 3000, and 4000 Hz (n = 4 ears); and (4) no-dead-region subjects (NoDR) tested negative for dead regions at all frequencies (n = 76 ears).

Mean audiograms for each subject group are shown in Figure 1. It is apparent that the mean audiograms are quite similar across the four groups. This is primarily due to the fact that a strict threshold criterion was used to allow subjects into this study. Subjects had to have at least two thresholds poorer than 50 dB HL and no threshold poorer than 80 dB HL in order to participate. Closer examination of the audiograms reveals some distinction between them. For example, subjects in the LFDR and HFDR groups had the poorest high-frequency thresholds, but these two groups had distinctly different low-frequency thresholds. Subjects in the MFDR group had poorer thresholds at 1000 Hz compared to subjects in the NoDR group.

Examination of the mean audiograms in Figure 1 suggests that the difference in audiograms between groups may be explained by the slope between 500 and 2000 Hz. For subjects in the NoDR group, the mean threshold dropped from 32.9 dB HL at 500 Hz to 54.8 dB HL at 2000 Hz, a mean change of 21.9 dB (11 dB/octave). The mean audiogram for the HFDR group demonstrated a mean threshold of 27.7 dB HL at 500 Hz dropping to 65.5 dB HL at 2000 Hz, a mean change of 37.8 dB (18.9 dB/octave). An ANOVA analysis was used to compare the mean change between the two groups; this showed a statistically significant mean difference of 15.9 dB, F(1,94) = 11.71, p = 0.001. This does not appear to be a difference of clinical importance; however, 4 of the 13 ears with HFDR had slopes less than 19 dB/octave between 500 and 2000 Hz. In addition, 16 of the 76 ears with NoDR had slopes greater than 19/octave between 500 and 2000 Hz.

The LFDR and MFDR groups showed mean changes of 17.5 (8.8 dB/octave) and 24.3 dB (12.3 dB/octave), respectively, from 500 to 2000 Hz. The slope for the LFDR group was shallower than the slope for the NoDR group; however, this difference was not statistically significant (F[1,94] = .42, p = 0.518). The mean slope in the MFDR group was not compared to the mean slope in the NoDR group because they were quite similar (12.3 dB/octave and 11 dB/octave, respectively).

## Dead Regions and Speech Intelligibility

QuickSIN data were available for 96 of the 98 ears shown in Figure 1. Subjects heard the QuickSIN sentences at different presentation levels ranging from 70 to 100 dB HL (Niquette et al, 2001). To control for presentation level and configuration of hearing loss, an AI was calculated for each ear (Pavlovic, 1989). The AI calculations were based on subject thresholds, the speech spectrum of the QuickSIN speaker (Fikret-Pasa, 1993), the presentation level of the QuickSIN, and band importance functions for sentences (DePaolis et al, 1996). AI calculations should also take into account the level of the noise, but due to the variable SNR for the QuickSIN sentences, noise levels were not entered into the calculations. The open bars in Figure 2 show the SNR that yielded 50% correct (i.e., SRT) for the Standard (unfiltered) sentences adjusted by AI. The black bars show the SNR for 50% correct for the High-Frequency QuickSIN sentences.

An Analysis of Covariance (ANCOVA) was performed to assess if a statistical mean difference existed on the Standard QuickSIN and for the High-Frequency QuickSIN for ears with and without dead regions when adjusted for AI calculations. The results for the Standard sentences showed a significant effect between the dead-region and no-dead-region groups, F(1,93) = 41.19, p < 0.001. For the High-Frequency QuickSIN, a significant effect also existed between dead-region and no-dead-region groups, F(1,93) = 31.37, p < 0.001. These differences can be seen in Figure 2; subjects with dead regions had greater difficulty understanding sentences in noise than subjects without dead regions.

An ANCOVA analysis was also performed to assess if a statistically significant effect

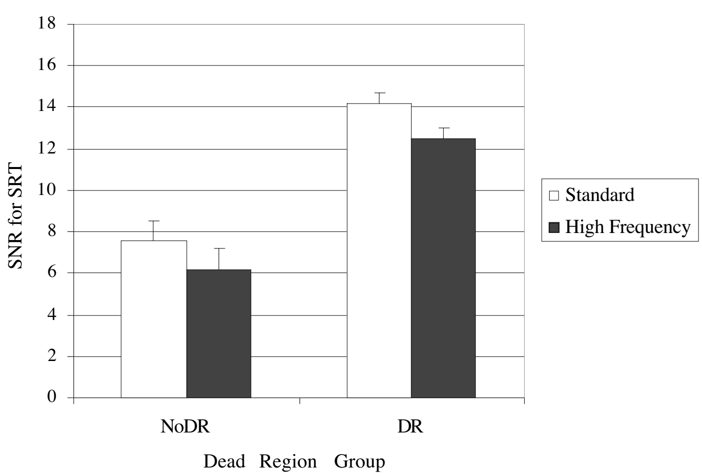


**Figure 2.** Mean signal-to-noise ratio (SNR) for 50% correct for the QuickSIN test. The open bars show the results for the standard QuickSIN sentences, and the black bars show the results for the high-frequency QuickSIN sentences. The bars on the left are for subjects without dead regions (NoDR), and the bars on the right are for subjects with dead regions (DR). Error bars represent +1 standard deviation. A lower SNR indicates better speech understanding than a higher SNR.

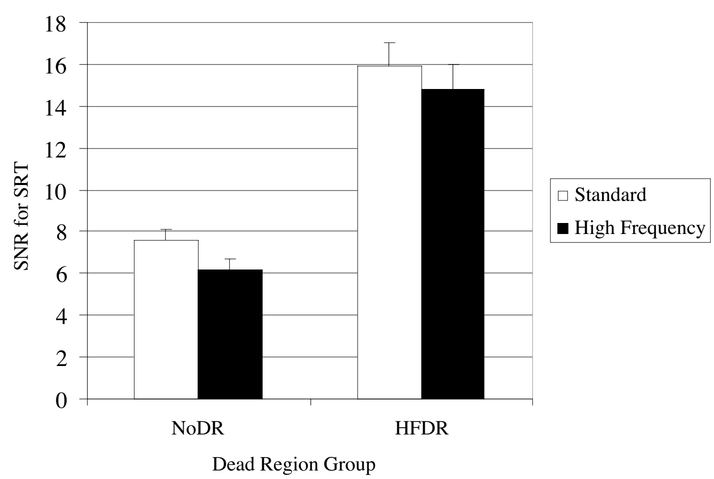


**Figure 3.** Mean signal-to-noise ratio (SNR) for 50% correct for the QuickSIN test. The open bars show the results for the standard QuickSIN sentences, and the black bars show the results for the high-frequency QuickSIN sentences. The bars on the left are for subjects without dead regions (NoDR), and the bars on the right are for subjects with high-frequency dead regions (HFDR). Error bars represent +1 standard deviation. A lower SNR indicates better speech understanding than a higher SNR.

**Table 1. ANOVA/ANCOVA Results of Omnibus F Statistics, F (2,46), for the APHAP Subscales Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV)**

| EC | RV | BN | AV |
|---|---|---|---|
| 4.10 * | 16.58 ** | 11.63 ** | 0.13 |

*p < 0.05, **p < 0.01

existed between the NoDR (n = 76) and HFDR (n = 13) groups. In the analysis of the Standard QuickSIN sentences, a significant effect existed between the two groups, $F(1,84) = 45.89$, $p < 0.001$. Similarly, for the High-Frequency sentences, statistical significance also existed between the two groups, $F(1,84) = 40.72$, $p < 0.001$. These results are shown in Figure 3; this figure shows large differences in mean QuickSIN scores between the NoDR and HFDR groups for both the Standard sentences (8.3 dB difference) and the High-Frequency sentences (8.6 dB difference).

The LFDR group had only five ears, and the MFDR group had only four ears. These small numbers made it infeasible to compare speech intelligibility scores with these two subject groups (e.g., LFDR vs. NoDR, MFDR vs. NoDR). The possibility of making a Type II error (failing to show statistical significance when statistical significance actually exists) is greatest when the sample size is small and, thus, the power of the study is low. In other words, the results of the study would probably not be able to demonstrate a statistical difference between the LFDR group and any other group, or the MFDR group and any other group due to the small sample size.

## High-Frequency Benefit for the QuickSIN

It is interesting to consider the results for the High-Frequency QuickSIN compared to the results for the Standard QuickSIN sentences. Subjects in the NoDR group had sloping hearing losses and would be expected to benefit from the high-frequency gain above 2000 Hz provided in the High-Frequency QuickSIN sentences as compared to the Standard sentences. It also might be expected that listeners in the HFDR group would not benefit from this high-frequency amplification, because the applied gain was in the area of their dead regions. The benefit of high-frequency amplification for subjects in the NoDR group and the HFDR group can be observed by comparing the difference in heights across the gray bars (Standard sentences) and the black bars (High-Frequency sentences) in Figure 3. Both groups showed benefit for the high-frequency sentences; the mean SNRs were lower for the High-Frequency sentences compared to the Standard sentences, indicating that the high-frequency emphasis improved speech intelligibility. There was no significant difference in benefit, however, across the two dead-region classification groups ($t = 2.76$, $df = 85$, $p = 0.33$).

## Subjective Hearing Aid Performance

All subjects in this study wore hearing aids in both ears, so the APHAP results reflected binaural aided performance. Accordingly, we analyzed the APHAP results by *subject* and not by *ear*. Six individuals had dead regions in only one ear, and eight subjects had binaural dead regions. Subjects were considered dead-region positive whether they had monaural or binaural dead regions.

Subjects with dead regions were classified based on the frequency locations of their dead regions. Those with dead regions below 2000 Hz were placed in the low- or midfrequency dead-region group (LMDR, n = 6). Subjects with dead regions above 1000 Hz were placed in the high-frequency dead-region group (HFDR, n = 8). Subjects without dead regions were placed in the no-dead-region group (NoDR, n = 35). One subject had dead regions at different frequency locations across ears; he had low- or midfrequency dead regions in one ear (at 250, 500, and 1000 Hz) and a high-frequency dead region in the other ear (3000 Hz). This individual was placed in the LMDR group because he had three low- or midfrequency dead regions but only one high-frequency dead region.

The results of the APHAP were submitted to an Analysis of Variance (ANOVA) to determine whether a statistical mean difference existed at the 0.05 level of significance on the EC, RV, BN, and AV subscales across dead-region groups. The results of these analyses are presented in Table 1 and in Figure 4. Figure 4 shows the mean scores of the dead-region groups for the four APHAP subscales. The analysis showed a significant main effect on the EC, RV, and BN subscales. The results for these three subscales were submitted to the Tukey post hoc test to identify dead-region group mean

**Table 2. Tukey Post Hoc Test Results by Dead-Region Group for the APHAP Subscales Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV)**

| EC | RV | BN | AV |
|---|---|---|---|
| NoDR-HFDR* | NoDR-HFDR*<br>NoDR-LMDR* | NoDR-HFDR*<br>NoDR-LMDR* | – |

*Note:* Significantly different pairs of dead-region groups are listed together within each column.
*p < 0.05

differences. These post hoc test results are shown in Table 2 and described below.

### *Ease of Communication*

This subscale measures subjective communication performance for low-noise and low-reverberation conditions when visual cues are available. For these ideal listening situations, a statistical mean difference existed between the NoDR and the HFDR groups. No statistical difference was found between the LMDR group and any other group.

### *Reverberation*

This subscale measures communication for quiet, but poor, listening conditions. This includes situations with reverberation or soft speech, and situations when visual cues are unavailable. For these less than ideal listening situations, Tukey post hoc testing showed that individuals with high-frequency dead regions and those with low- or midfrequency dead regions perceived more difficulty understanding speech in reverberant situations than those without dead regions.

### *Background Noise*

This subscale measures subjective performance for communication in noisy situations. As in reverberant environments, speech understanding in background noise was significantly poorer for those with high-frequency dead regions and those with low- or midfrequency dead regions when compared to subjects without dead regions.

### *Aversiveness*

This subscale measures negative reactions to environmental sounds. The hypothesis investigated in this study was that cochlear dead regions are associated with reduced hearing aid benefit, primarily through reduced speech intelligibility. We supposed that, due to reduced dynamic range at the frequency of dead regions, there was also some possibility that dead regions could result in increased susceptibility to loudness discomfort. However, there was no evidence of such a relationship. The effect of dead-region group on the AV subscale failed to reach significance.

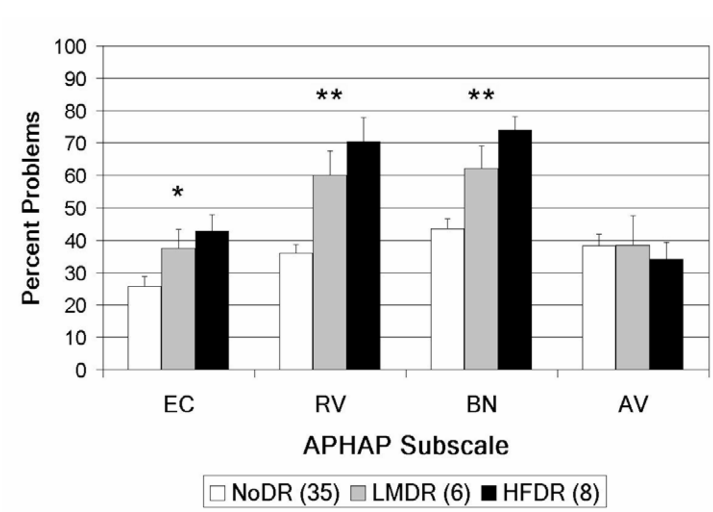


**Figure 4.** APHAP subscales as a function of dead region group. Dead region groups: no dead regions (NoDR), low- or midfrequency dead regions (LMDR), and high-frequency dead regions (HFDR). APHAP subscales: Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV). The numbers in parentheses indicate the number of subjects in each group. Error bars represent one standard error. Groups of bars significantly different at the .05 level are shown with a single asterisk, and groups of bars significantly different at the .01 level are shown with a double asterisk.

## DISCUSSION

### Audiometric Configuration

In the current data set, subjects had flat or sloping hearing losses with at least two thresholds greater than 50 dB HL and no thresholds greater than 80 dB HL. Moore (2001) has commented that while dead regions cannot be predicted from the audiogram, there are certain hearing loss configurations that are commonly associated with dead regions. For example, high-frequency dead regions would be expected in sharply sloping hearing loss where thresholds drop more than 50 dB/octave with increasing frequency. None of the subjects in the present study had hearing losses with slopes greater than 50 dB/octave. There were, however, significant differences in the slope of the audiogram between 500 and 2000 Hz for those classified as HFDR compared to those classified as NoDR. The current results suggest that an audiogram slope between 500 and 2000 Hz steeper than 19 dB/octave raises the possibility of a high-frequency dead region. However, due to the variability in slopes across the two groups (NoDR and HFDR), it is unlikely that the presence or absence of high-frequency dead regions can be predicted by audiogram slope in individuals with pure-tone thresholds less than 85 dB HL.

Moore (2001) also suggested that low-frequency dead regions may be suspected with (1) a hearing loss of 40–50 dB HL at low frequencies with near-normal hearing at mid- and higher frequencies or (2) a hearing loss greater than 50 dB HL at low frequencies with somewhat less hearing loss at higher frequencies. We did not find any subjects in the first group due to the pure-tone threshold criterion to enter this study. In addition, no audiograms described in the second group were found in the current data set. The five subjects with low-frequency dead regions had either flat or sloping hearing losses. Based on these results, it is important for the audiologist to note that both low- and high-frequency dead regions may be present in a variety of audiometric configurations.

### QuickSIN Classification System

The results for the QuickSIN demonstrated that listeners with dead regions had poorer speech understanding in noise than listeners without dead regions. To better understand the impact of cochlear dead regions on the intelligibility of speech, we can look at the current data set in a typical clinical fashion. The creators of the QuickSIN developed a classification system in order to interpret the test results; this is shown in the first two columns of Table 3 (Niquette et al, 2001). The remaining columns in Table 3 show the numbers of subject ears from each dead-region classification group that fell into each SNR category while subjects listened to the Standard sentence lists. The majority of ears (88%) in the NoDR group fell into the mild or moderate SNR loss groups. Very small percentages of the NoDR group were classified with a normal or near-normal SNR loss (7%) or a severe SNR loss (5%).

None of the ears with dead regions were ever classified with a normal or near-normal SNR loss, and only one ear (out of 22) fell into the mild SNR loss category. The majority of ears with dead regions were classified with either a moderate or severe SNR loss. For example, in the HFDR group, 69% fell into the severe SNR group. These results demonstrate that listeners with measured dead regions, especially those with high-frequency dead regions, have difficulty understanding speech in noise. Niquette et al (2001) have proposed hearing aids with directional microphones or array microphones for individuals classified with a moderate SNR loss; they also proposed hearing aid use in conjunction with FM systems for individuals classified with a severe SNR loss. These same

**Table 3. QuickSIN Interpretation Guidelines from Niquette et al (2001) and Numbers of Ears from Each Dead-Region Classification Group That Fell into Each Category for the Standard Sentence Lists**

| SNR Loss | Degree of SNR Loss | NoDR | LFDR | MFDR | HFDR |
|---|---|---|---|---|---|
| 0–2 dB | Normal, Near Normal | 5 | 0 | 0 | 0 |
| 2–7 dB | Mild SNR Loss | 31 | 0 | 1 | 0 |
| 7–15 dB | Moderate SNR Loss | 34 | 4 | 2 | 4 |
| >15 dB | Severe SNR Loss | 4 | 1 | 1 | 9 |

recommendations are appropriate for listeners with cochlear dead regions.

## APHAP Results: Comparison with Normative Data

The results for the APHAP demonstrated that listeners with dead regions reported poorer speech understanding in difficult listening conditions than listeners without dead regions. To better understand the impact of cochlear dead regions on subjective hearing aid performance, we can compare the current data set to normative APHAP data. Cox and Alexander (1995) presented normative data for the APHAP subscales in a group of "successful" hearing aid users with mild-to-moderate sloping or flat sensorineural hearing loss. Figure 5 compares the mean aided APHAP subscale scores from the normative data (solid line) to the mean APHAP subscale scores of the three dead-region groups in the present study (dashed lines).

There are three notable features in Figure 5. First, those with high-frequency dead regions reported more frequent communication difficulty in reverberation or background noise than those in the Cox and Alexander study. Second, the mean hearing aid performance reported by subjects in the NoDR group was remarkably similar to the normative data across the communication subscales (EC, RV, and BN). In other words, the group that most closely resembled the "successful" hearing aid users from the normative data in terms of subjective hearing aid performance was the NoDR group. (Because the scores for this group so closely overlie those of the normative group, error bars for the NoDR group were removed to make the graph easier to interpret.) Third, scores for all three subjects groups were lower on the AV subscale than the mean value from the normative data. This means that subjects in the present study reported fewer negative reactions to environmental sound.

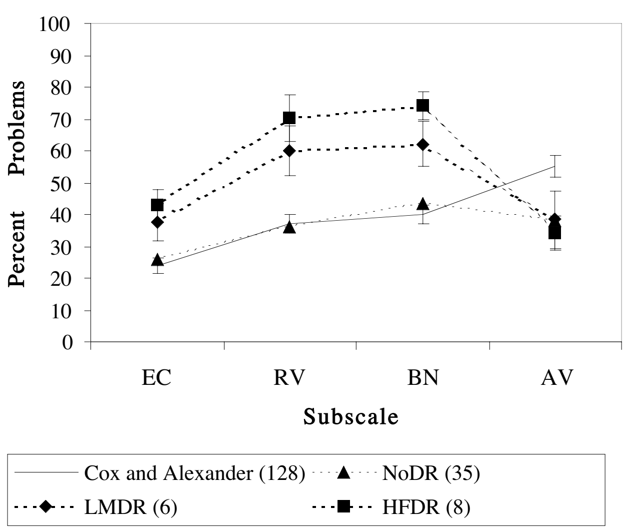


**Figure 5.** Mean APHAP subscale scores of three auditory dead-region groups (shown with dashed lines) compared to mean aided APHAB scores of "successful" hearing aid users as reported in Cox and Alexander (1995; shown with solid line). Dead-region groups: no dead regions (NoDR), low- or midfrequency dead regions (LMDR), and high-frequency dead regions (HFDR). APHAP subscales: Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV). The numbers in parentheses indicate the number of subjects in each group. Error bars represent ±1 SE.

A possible reason for the improved results on the AV subscale for subjects in the present study may be differences in hearing aid technology. For example, some of the subjects in the current study wore hearing aids with multiple memories or noise cancellation circuitry that may have improved listening comfort in noisy situations for the current subjects. These technologies were not available to the subjects reported by Cox and Alexander. All of those subjects wore conventional, nonprogrammable hearing aids. More importantly, WDRC was not in common use at the time of the Cox and Alexander study, whereas 69% of those in the current study (for whom hearing aid information was available) wore WDRC hearing aids. It is likely that on average, because of WDRC, subjects in the current study received relatively less gain for high-intensity inputs compared to those in the norms. This would reduce discomfort for loud sounds and is probably the primary reason for the difference on the AV subscale between the current study results and the norms.

The pattern of reduced hearing aid performance in those with cochlear dead regions is evident in the individual subject data as well as in the group data. Figure 6 shows the individual APHAP results for the eight subjects in the HFDR group. The scores are plotted over the 20th to 80th percentile range of the "successful" hearing aid users reported by Cox and Alexander. On the RV subscale, seven of the eight subjects with high-frequency dead regions scored above

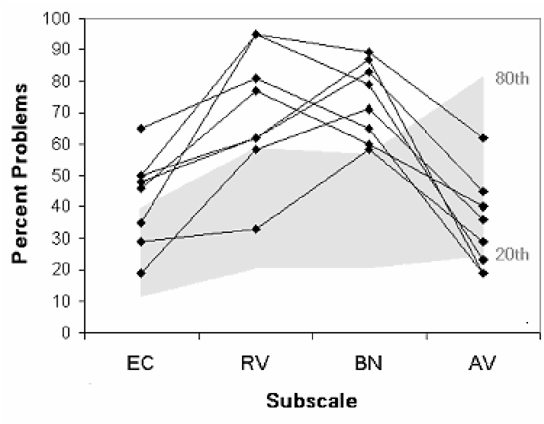


**Figure 6.** APHAP subscale scores of the eight subjects in the HFDR group. The shaded region represents the 20th to 80th percentile hearing aid performance of "successful" hearing aid users as reported by Cox and Alexander (1995). APHAP subscales: Ease of Communication (EC), Reverberation (RV), Background Noise (BN), and Aversiveness (AV).

the 80th percentile (indicating greater than average percent problems), and on the BN subscale all subjects scored above that point. It is clear that these listeners with high-frequency dead regions perceived more problems understanding speech in difficult listening situations than the typical hearing aid user. The conclusions based on the APHAP results are consistent with the conclusions based on the QuickSIN results: hearing aids with directional microphones, array microphones, and/or FM systems should be considered for listeners with dead regions, especially those with high-frequency dead regions.

## Clinical Use of the TEN Test

As discussed at the beginning of this article, there is some concern about the validity of the TEN test (Summers et al, 2003; Moore, 2004). The results of the current study lend support to the validity of the TEN test as a predictor of dead regions using a 15 dB threshold shift criterion. Previous studies have used both PTCs and the TEN test in order to identify listeners with dead regions and then demonstrated that these listeners had poorer than expected intelligibility of speech in both quiet and in noise (Vickers et al, 2001; Baer et al, 2002). Using only the TEN test to identify dead regions, the results of the current study demonstrated significantly poorer intelligibility of speech in noise for listeners with dead regions compared to those without dead regions. In addition, using only the TEN test to identify dead regions, the results of the current study demonstrated that 21 of all 22 ears identified with dead regions were classified (Niquette et al, 2001) as having a "moderate" or "severe" SNR loss on the QuickSIN test for the Standard sentences.

Is it worthwhile to use the TEN test in the clinic? This depends upon the questions that the clinician is asking. The results from the present experiment show that listeners with dead regions perform poorer than average on tests of speech intelligibility and subjective hearing aid performance. Individuals with hearing loss may demonstrate unexpectedly poor intelligibility of speech or unexpectedly poor hearing aid performance for a variety of reasons. For example, Gates et al (2003) suggested that unexpectedly poor word-recognition scores may be caused by age-related auditory neuropathy. The TEN test can be used as a part of a test battery in order to examine the possible causes of poor speech recognition skills.

The primary limitation to the utility of testing for cochlear dead regions in a clinical environment is the lack of effective hearing aid treatment options specific to those with dead regions. Some current ideas for ways to uniquely approach this problem include limitation of gain beyond 1.7 times the edge frequency of the dead region (Moore 2001, 2004), frequency compression hearing aids (McDermott and Knight, 2001), and hybrid hearing aid/cochlear implants (Gantz and Turner, 2003). Recent work by Preminger (2004) has shown that reduction of hearing aid gain in the frequency range of dead regions may be desirable in some listeners who have them. However, this conclusion is based on a limited data set, and more research in this area is needed. Until effective treatment alternatives become available, there may not be a practical reason to test for dead regions in the clinical environment. While it is important to identify patients at risk for poor hearing aid outcomes, at present, measures of speech intelligibility in background noise probably serve that function better.

## CONCLUSIONS

In a sample of 49 experienced hearing aid users from a clinical population with at least two thresholds greater than 50 dB HL and no thresholds greater than 80 dB HL, 71% had no cochlear dead regions, 16.5% had high-frequency dead regions, and 12.5% had low- or midfrequency dead regions. When the 98 ears (rather than individuals) were classified as dead-region positive or negative, 78% of the ears had no cochlear dead regions, 13% had high-frequency dead regions, and 9% had low- or midfrequency dead regions.

Subjects with dead regions had poorer speech understanding than those without dead regions. In addition, listeners with dead regions perceived poorer subjective hearing aid performance in listening environments with reverberation or background noise as compared to those without dead regions. These results indicate that unexpectedly low scores on a speech-in-noise test and/or unexpectedly poor subjective hearing aid performance may be due to cochlear dead regions.

**Acknowledgments.** The authors wish to thank Elizabeth Everett, Eric Korsgaard, Richard Luekenga, Elizabeth Mosier, and Emily Schauwecker for assistance with data collection.

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