Cochlear Dead Regions in Typical Hearing Aid Candidates: Prevalence and Implications for Use of High-Frequency Speech Cues

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Objectives: This study had two purposes. The first was to assess the prevalence of cochlear dead regions (DRs) among listeners with moderate to severe hearing loss that is typical of a large proportion of adult hearing aid wearers. The second was to determine whether subjects who tested positive for DRs differed from those without DRs in their ability to utilize high-frequency speech cues in a laboratory test.

Design: One hundred and seventy adults (307 ears) were tested for DRs at frequencies from 0.5 to 4 kHz using the threshold equalizing noise (HL) test. Speech recognition ability was measured for high-frequency emphasis (HFE) stimuli and for low-pass filtered HFE (HFE-LP) stimuli using the Quick Speech In Noise test. Results obtained from the HFE and HFE-LP conditions were compared to examine changes in word recognition when more speech cues were provided above 2.5 kHz. Possible effects of audiogram differences between DR-no and DR-yes groups were examined by estimating the change in audibility for the two Quick Speech In Noise conditions using calculated differences in Speech Intelligibility Index for each condition for every subject.

Results: Thirty-one percent of subjects (23% of ears) were found to have a DR at one or more test frequencies. Sixty-eight percent of subjects who tested positive for DR had DRs in one ear only. DRs were most prevalent at frequencies above 1.5 kHz. Comparison of word recognition scores obtained with the HFE and HFE-LP conditions revealed that, on average, both groups scored significantly better when more high-frequency cues were provided. The magnitude of the benefit was small for both groups, but the computed effect size was larger for listeners without DRs than for those with DRs. Further, subjects with contiguous DRs at 2 to 3 frequencies obtained less benefit than subjects with DRs at isolated frequencies. It was determined that the improved audibility of high-frequency cues in the HFE condition was significantly less for listeners with DRs, and this accounted for some, but not all, of the difference in effect sizes.

Conclusions: Although about one-third of listeners with flat or sloping moderate to severe hearing losses tested positive for at least one DR, there was no evidence to support a proposal for reducing high-frequency gain in hearing aid fittings for these types of listeners. Making high frequencies more audible was helpful, on average, regardless of DR status. It is recommended that field trials be undertaken in which subjects with and without DRs wear hearing aids in daily life. This type of study would produce higher level evidence about best practice in hearing aid fitting for patients with flat or sloping moderate to severe hearing loss who test positive for DRs.

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INTRODUCTION

For several decades, conventional wisdom based on published research (e.g., Killion & Tillman 1982; Skinner & Miller 1983) held that an important component of hearing aid fitting is the provision of ample high-frequency audibility, consistent with maintaining loudness comfort. Thus, conscientious practitioners attempted to provide significant high-frequency gain, despite associated difficulties with managing acoustic feedback and "tinny" or "shrill" sound quality. On the other hand, despite the prevailing view in favor of high-frequency emphasis, several early reports suggested that high-frequency gain might actually have minimal or even negative value for certain individuals with high-frequency impairment (e.g., Murray & Byrne 1986; Rankovic 1991). This topic gained momentum in 1998 with publication of reports by Ching et al. and Hogan and Turner. Ching et al. (1998) studied speech recognition abilities of hearing-impaired listeners as a function of extent of loss, frequency of speech cues, and sensation level. Their results showed wide variation across subjects in their ability to extract information from amplified speech at high frequencies. For many subjects with hearing loss greater than about 60 dB, audible high-frequency speech cues yielded no value or even degraded intelligibility. These results were bolstered by the report of Hogan and Turner (1998), whose data suggested that when high-frequency hearing loss exceeded about 55 dB, most listeners could not benefit from increased audibility in that frequency region. Other studies that support these types of findings have been reported (e.g., Byrne et al. 1990; Turner & Cummings 1999; Amos & Humes 2001). Taken together, these investigations suggested that it is sometimes inappropriate to provide the amount of high-frequency amplification called for by accepted prescriptive methods.

This body of literature precipitated a reconsideration of the role of high-frequency gain in hearing aid fittings. The evidence implied that there is considerable individual variation in optimal high-frequency amplification, at least for people whose high-frequency thresholds are worse than 60 dB HL. Moore (2001) offered an explanation for these data, pointing out that the inability to benefit from amplification in a frequency region where there is hearing loss could be a consequence of a cochlear "dead region" (DR). He noted that a DR occurs at a given frequency when there is loss of normal functioning of inner hair cells of the cochlea that are located at the region tuned to that frequency on the basilar membrane. He further suggested that hearing aid fitting success could be improved if practitioners were able to identify hearing aid patients for whom high-frequency amplification might be contraindicated due to the presence of DRs. See Moore (2001) for a review of this topic.

To facilitate clinical identification of cochlear DRs, Moore et al. (2000, 2004) developed a clinically applicable test. The

test is based on the assumption that tones falling within a DR are actually detected when the excitation spreads to a location on the basilar membrane that contains functioning inner hair cells and neurons. Thus, unmasked pure-tone thresholds for frequencies that fall in a DR are dependent on off-frequency listening. In such cases, a broadband noise will produce a greater masking effect than would be expected if the tones were detected via excitation at the maximally sensitive location in an undamaged cochlea. Administration of the test proposed by Moore requires measurement of thresholds for detecting pure tones that are masked by a threshold equalizing noise (TEN). The TEN is spectrally shaped so that, when used as a masker and presented via an appropriate transducer, it results in approximately equal pure-tone thresholds across a wide frequency range (at least 500 Hz to 4.0 kHz) for normal hearers. For hearing-impaired listeners without DRs, the TEN-masked thresholds are almost the same as masked thresholds for normal hearers, providing that the TEN intensity is sufficient to cause masking. For hearing-impaired listeners with DRs, the TEN-masked threshold corresponding to the affected frequency is elevated beyond that expected for normal hearers. Moore suggested the "standard" criterion for identifying a DR with the test, as follows: when the TEN-masked threshold is at least 10 dB higher than expected for normal hearers *and* 10 dB higher than the listener's unmasked threshold, this is indicative of a cochlear DR. The test is known as the TEN test.

The validity of the TEN test has been examined by comparing its results with those yielded by psychophysical tuning curve (PTC) testing. PTCs are generally viewed as the gold standard for identifying cochlear DRs, but their measurement is technically demanding and time consuming (e.g., Kluk & Moore 2005). Thus, traditional PTC measurement is not feasible in clinical practice. Moore et al. (2000) compared TEN test and PTC test results for 14 subjects with a variety of sensorineural hearing losses (SNHLs). The results indicated very good agreement between the two measures. Moore and Alcantara (2001) also noted close correspondence between the two types of data. On the other hand, Summers et al. (2003) studied 17 subjects who all had steeply sloping high-frequency hearing losses and reported that for this group there was less satisfactory agreement between the results of the TEN test and PTC measures. The reliability of the TEN test also has been assessed. Cairns et al. (2007) and Markessis et al. (2009) found that TEN-masked thresholds were highly repeatable for listeners with SNHL ranging from mild to severe-profound who were retested within a few days. On the other hand, Munro et al. (2005) reported that repeatability was less satisfactory when listeners with severe-profound loss were retested after a year. Overall, the existing research is encouraging regarding the validity and reliability of the TEN test, although results with listeners having severe-profound hearing loss have been less positive than those with subjects having milder hearing losses.

Prevalence of Dead Regions

If the existence of cochlear DRs has important implications for the success of hearing aid fitting and the selection of high-frequency amplification, it is critical for practitioners to know how widespread the problem is. It has been reported that amplification of high frequencies well inside a DR usually does not yield benefit for speech understanding and may sometimes actually reduce it (e.g., Yanz 2002; Gordo & Iorio 2007; Moore

2009). These reports imply that if DRs are found in a high proportion of individuals whose high-frequency hearing loss exceeds, say, 60 dB, then practitioners should be prepared to prescribe less high-frequency amplification for a high proportion of patients with more than moderate high-frequency hearing loss. This would provoke a fundamental change in best-practice recommendations for hearing aid fitting. On the other hand, if DRs are relatively rare in hearing aid candidates, it would make sense for practitioners to follow current best-practice recommendations, which often call for sizeable high-frequency gain, unless DRs are demonstrated for a particular patient. Thus, it is important to determine the prevalence of DRs in hearing aid candidates.

Several estimates of the prevalence of DRs have been reported. Vinay and Moore (2007) tested a random sample of 308 adults with SNHL who attended an audiology clinic. Hearing losses ranged from mild to severe. Using the standard criterion to identify a DR, 57% of subjects (46% of ears) tested positive for a cochlear DR at one or more frequencies. Positive results were rare when thresholds were better than 60 dB HL. Aazh and Moore (2007) explored the prevalence of DRs at the single test frequency of 4 kHz for 63 subjects (98 ears) who had SNHL and thresholds of 60 to 85 dB at the test frequency. The TEN (HL) test revealed a DR at 4 kHz in 37% of the ears. Both Vinay and Moore and Aazh and Moore used the standard criterion recommended by Moore et al. (2000) to identify a DR. Hornsby and Dundas (2009) explored the prevalence of DRs over a wide frequency range in 59 subjects (117 ears) with SNHL ranging from mild to profound. These authors used a 5 dB step size in the TEN test, rather than the recommended 2 dB, and also used both a "lax" and a "strict" criterion for establishing the presence of a DR. The lax criterion was identical to the standard method proposed by Moore et al. (2000). The strict criterion required the masking noise to produce 15 dB of excess masking rather than the standard 10 dB. Using the lax/standard criterion, Hornsby and Dundas determined that 84% of participants had positive findings on the TEN test for at least one frequency. When the strict criterion was used, substantially fewer DRs were identified, especially at frequencies below 6 kHz. Finally, Preminger et al. (2005) used the TEN test to evaluate the presence or absence of DRs in 49 patients with SNHL, having at least some thresholds in the 50 to 80 dB HL range. All subjects were established users of bilateral hearing aids. These authors used a strict criterion to identify DRs: masked threshold at least 15 dB higher than expected for normal hearers and 15 dB higher than the listener's unmasked threshold. With this criterion, 29% of the group tested positive for DRs.

As this review illustrates, existing studies on the prevalence of DRs for listeners with SNHL do not present a consistent picture. Estimates of prevalence range from 29% to 84% of listeners. Estimates of prevalence using the standard identification criterion have tended to be greater than those obtained using a stricter criterion. In addition, the studies were designed to answer somewhat different questions, and their subject inclusion criteria were influenced by the investigation's essential purpose. Only one study determined DR prevalence in a random sample of hearing health care patients (Vinay and Moore 2007). The prevalence of 57% reported in that study would be even greater if patients who were not viable hearing aid candidates (those with normal hearing or a mild loss) were

eliminated from consideration. This suggests that DRs might be present in a large proportion of hearing aid candidates with moderate to severe hearing loss.

Dead Regions and Benefit of High-Frequency Speech Cues

What are the implications of DRs for hearing aid fitting? Several investigations have been reported that are relevant to this question. Vickers et al. (2001) and Baer et al. (2002) explored the benefit of high-frequency amplification for subjects with and without DRs. Subjects listened to shaped and filtered vowel-consonant-vowel syllables through headphones in quiet (Vickers et al.) and in noise (Baer et al.). In both studies it was seen that listeners with DRs obtained some benefit from additional high-frequency speech cues for frequencies up to about 70% above the lower edge of the DR. Above this point, additional high-frequency amplification was not helpful. However, these studies did not include a threshold-matched control group: the subjects with DRs tended to have severe-profound hearing losses, whereas the control group without DRs tended to have better hearing. It is possible that sufficient audibility was not achieved in the conditions presenting the highest frequencies to listeners with the greatest hearing losses.

Preminger et al. (2005) examined the effects of DRs (identified using a 15 dB criterion) in established hearing aid wearers with moderate to severe hearing loss. Subjects with DRs had poorer objective speech understanding in noise and poorer subjective speech understanding in noise than those without DRs. However, in this study, the group without DRs was found to have better hearing than the groups with DRs; therefore, differences in speech understanding might be attributable, at least in part, to audiogram differences. Perhaps more to the point, benefit from high-frequency speech cues did not differ across listeners with and without DRs.

In a study by Mackersie et al. (2004), a threshold-matched control group was used in a matched-pairs design. In this study, DRs were identified using the standard criterion; however, to be included in the group with DRs, listeners were required to have a DR that extended across three or more contiguous test frequencies. Four of the eight DR subjects had DRs extending upward from 2.0 kHz and the rest had DRs extending upward from 3.0 kHz. Subjects listened with hearing aids to monosyllabic words that were unfiltered or individually low-pass filtered for each subject based on their estimated DR location. The results indicated that subjects with and without DRs performed equivalently in quiet and low noise conditions. However, in high noise conditions, scores for the subjects with DRs reached an asymptote and failed to improve when high frequencies more than 100% above the edge of the DR were presented, whereas the subjects without DRs did improve in this condition.

The results of these studies of the impact of DRs on benefit from high-frequency speech cues are not in agreement. Two studies suggest that provision of high frequencies more than 70% above the DR is not helpful in quiet or noise and might be detrimental (Vickers et al. 2001; Baer et al. 2002). One study found that provision of high frequencies in quiet and low noise was equally helpful for listeners with and without DRs but less helpful in higher noise levels (Mackersie et al. 2004). Another study did not find any difference between listeners with and without DRs in the benefit derived from high-frequency speech cues (Preminger et al. 2005).

Some of the existing research into the prevalence and perceptual implications of DRs has been carried out with listeners who have profound hearing loss (threshold >90 dB HL), and it appears that many of these do have DRs (e.g., Vickers et al. 2001; Baer et al. 2002; Moore et al. 2003). However, this might have little influence on the already established practice in fitting hearing aids for this group (Summers 2004; Venema 2005). Because individuals with moderate to severe hearing loss comprise a large proportion of adult hearing aid wearers, the status of this group with respect to DRs has particular significance for current clinical practice. The published studies about the prevalence and implications of DRs in listeners with moderate to severe hearing loss have not produced consistent results about either prevalence or implications. The present study was designed specifically to address this topic area. The goals were to determine the prevalence of DRs, using the standard identification criterion, in a large group of listeners with moderate to severe hearing loss and to explore the effect of these DRs on speech perception in a laboratory test. The following were the research questions:

1. Among listeners with some hearing thresholds in the 60 to 90 dB HL range, what is the prevalence of DRs indicated by the TEN test?
2. When individuals with impairment in the 60 to 90 dB HL range test positive for DRs, do they differ from those without DRs in the ability to utilize high-frequency speech cues?

MATERIALS AND METHODS

Participants

Potential subjects were identified at the University of Memphis Hearing Aid Research Laboratory and at the Memphis Veterans Affairs Medical Center. The goal at the Veterans Affairs Medical Center site was to test a complete consecutive sample of 100 individuals who presented for hearing evaluation, satisfied the inclusion criteria, and agreed to participate. At the Hearing Aid Research Laboratory site, all patients seen at the University clinic over the past 3 years who met the inclusion criteria were invited to participate. In addition, small consecutive samples from three private practices in Memphis were invited to participate.

Subject inclusion criteria were as follows: adult with bilateral flat or sloping sensorineural hearing impairment; thresholds of 60 to 90 dB HL in the better-hearing ear for at least part of the frequency range from 1 to 3 kHz, and thresholds no better than 25 dB HL in the better-hearing ear for frequencies <1 kHz. The requirement for low-frequency hearing loss was based on the observation that prevalence of hearing aid acceptance is very low among individuals who have normal low-frequency hearing (Flamme 2009). If both ears met these criteria, both were tested unless there was an asymmetry such that thresholds could not be obtained in the poorer ear without masking, in which case only the better ear was tested. In addition, subjects reported good physical and mental health, had literacy adequate to complete the consent form, and English as a primary language. Individuals with a history of ear surgery, chronic middle or outer ear pathology, evidence of retrocochlear involvement, and known psychiatric or neurologic disorder were excluded.

Four hundred and twenty-six potential subjects were identified and invited to participate. Of these, 170 subjects were
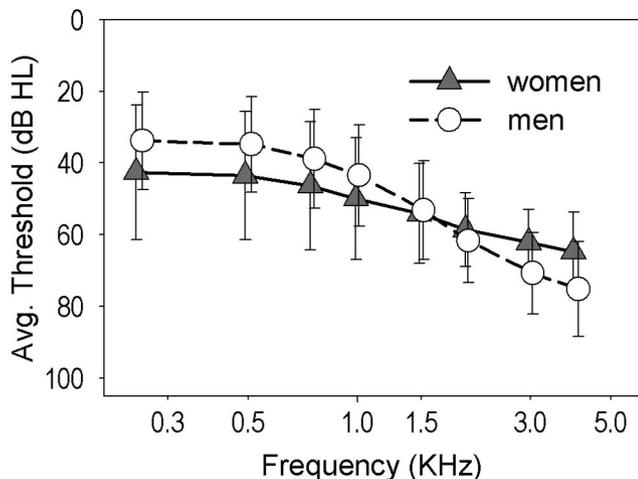
Fig. 1. Composite audiograms for men and women subjects. Bars indicate one standard deviation.

tested (98 men and 72 women). Although the participation rate of 40% was relatively low, there is no cause to believe that reasons for electing to participate were influenced by presence or absence of DRs. Ages ranged from 38 to 96 years, with a mean age of 74 years. Fifty-nine percent of subjects reported some experience with hearing aids (70% of women and 51% of men). Figure 1 depicts the composite audiograms for men and women.

Procedure

Each subject was tested for DRs using the TEN test. Next, speech recognition was measured for high-frequency emphasis (HFE) stimuli and for low-pass filtered HFE stimuli (HFE-LP) using the Quick Speech In Noise (QSIN) test (Killion et al. 2004). Finally, change in audibility for the two QSIN conditions was estimated. Details are provided below.

The TEN Test

The TEN (HL) version of the TEN test was used in this study (Moore et al. 2004). In this version, the threshold equalizing noise is somewhat band-limited to constrain potential loudness discomfort problems. With the TEN (HL), masked thresholds can be measured in the frequency range from 500 Hz to 4 kHz. The principles of the test have been described earlier. The method developed for administering the TEN (HL) test is described in Appendix A (see Supplemental Digital Content 1, Appendix A, http://links.lww.com/EANDH/A29). Stimuli were presented monaurally via an ER-3A earphone coupled to the ear with a compressible foam plug. Unmasked and TEN-masked thresholds were determined for pure tones at the following test frequencies: 0.50, 0.75, 1.0, 1.5, 2.0, 3.0, and 4.0 kHz. The standard threshold testing protocol with 5 dB ascending steps was used until the threshold zone was reached. Then the test was completed using 2 dB steps. The TEN (HL) test could not be applied at a given frequency under two conditions: (1) If the unmasked threshold was ≤10 dB below the maximum tone output for the frequency (maximum output values for test frequencies 0.5, 1.0, 2.0, 3.0, and 4.0 kHz were 105, 110, 115, 115, and 115 dB HL, respectively), or (2) If the subject could not tolerate the loudness of the TEN (HL) needed to perform the test at that frequency.

As shown in Supplemental Digital Content, Figure A1 (http://links.lww.com/EANDH/A29), there were three possible outcomes for the test at each frequency. These were defined as follows:

DR-no • The masked threshold was at least 10 dB worse than the unmasked threshold and <10 dB worse than the expected masked threshold for the TEN.

DR-yes • The masked threshold was at least 10 dB worse than the unmasked threshold and at least 10 dB worse than the expected masked threshold for the TEN.

Inconclusive • The masked threshold for the highest TEN level was <10 dB worse than the unmasked threshold.

The QSIN Test

The QSIN test provides a measure of the recognition of words in sentences against a competition of four-talker babble. Each list consists of six sentences, with each sentence presented at a progressively poorer signal-to-noise ratio (SNR) across the nominal SNR range of 25 dB (very easy) to 0 dB (very difficult). There are 30 key words per list, five in each sentence. The first step in scoring a list of six sentences is to note the total number of key words (out of 30) correctly repeated. Because the goal in this study was to determine the listener's ability to recognize words in sentences presented with noise, the QSIN score we report is the number of keywords correctly repeated. Note that, in clinical settings, the score for QSIN words correctly repeated is often further manipulated to produce a value for "SNR loss," which is the extent to which the listener's speech understanding in noise is worse than that of normal-hearing listeners. This clinical application was not used in our research.

The QSIN materials were especially appropriate for this research because the test includes 12 lists of sentences recorded with high-frequency emphasis (HFE), beginning at 1 kHz and reaching an asymptote of 32 dB of gain at about 4 kHz. In addition, the same 12 lists are recorded with the high-frequency emphasis followed by brickwall low-pass filtering (HFE-LP) beginning at 2.0 kHz. Figure 2 illustrates the amplification and filter shapes applied to HFE and HFE-LP lists. The HFE lists are amplified substantially above 2.5 kHz, whereas the HFE-LP lists
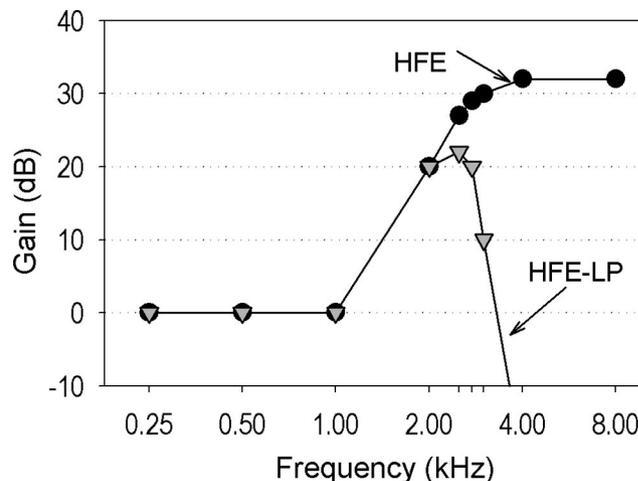

Fig. 2. Amplification and filter shapes applied to high-frequency emphasis (HFE) and high-frequency emphasis low-pass filtered (HFE-LP) lists of the Quick Speech In Noise (QSIN) test.
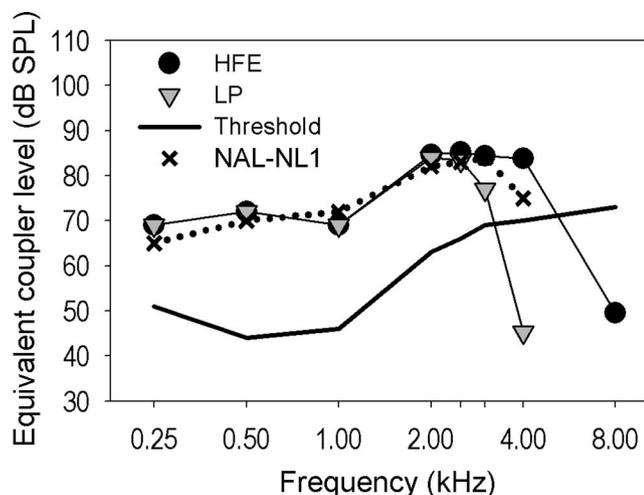
Fig. 3. QSIN listening levels for the average subject compared to amplification targets for loud speech prescribed by the NAL-NL1 prescription procedure.

TABLE 1. Distribution of cochlear dead regions across the test frequencies

Test Frequency (kHz)	Percent of Ears With Positive Results (N = 307)
0.5	1.6
0.75	2.3
1.0	2.0
1.5	2.3
2.0	7.2
3.0	7.8
4.0	13.0

Although the circumstances for individual subjects would vary somewhat from this average, these data imply that the listening conditions experienced by the subjects were rather similar to those of persons wearing competently fitted hearing aids.

Computing Audibility

Because many subjects had sloping high-frequency hearing loss that would limit reception of high-frequency sounds, and because the QSIN speech stimuli were filtered equally for all subjects, it was relevant to determine the extent to which the HFE condition supplied additional high-frequency cues compared with the HFE-LP condition for each individual. To estimate the audibility difference between the HFE and HFE-LP conditions for each subject, the Speech Intelligibility Index (SII) was computed for each condition for each subject and the difference ($SII_{HFE} - SII_{HFE-LP}$) was determined. SII calculations were performed using the online procedure based on ANSI S3.5–1997 (ANSI 1997). Thresholds in dB HL and 1/3 octave band levels of the QSIN speech in quiet (in 2 cm^3 coupler levels) were used for the computation. The level of noise introduced as the QSIN test proceeds was not included in the computation.

RESULTS

Prevalence of Dead Regions

Of the 170 subjects tested, 53 (31%) were found to have a DR for one or more test frequencies. Of the 307 ears tested, 70 (23%) were found to have a DR for one or more test frequencies. Among the 53 subjects who tested positive for DR, 17 had DRs in both ears, 18 had DRs in the left ear only, and 18 had DRs in the right ear only. At least one DR was detected at every test frequency, but they were most prevalent at frequencies above 1.5 kHz. Table 1 gives the distribution of DRs across frequency. Most subjects who were positive for DRs were positive at only one test frequency, but several subjects were positive at two or more frequencies. Within these subjects, some had DRs at contiguous frequencies and some did not. Table 2 describes the distribution of DRs across ears. Considering all frequencies, DRs were detected in 34% of the men and 28% of the women. The mean age of those who tested positive for DRs (DR-yes) was 73 (range: 38–91) years. The mean age of those who tested negative for DRs (DR-no) was 74 (range: 49–96) years. Neither differences in gender nor differences in age were statistically significant when DR-yes and DR-no groups were compared ($p > 0.05$ for both variables).

For some subjects, the TEN (HL) test could not be performed at some frequencies. This happened when the un-

have much less gain in this frequency range. Thus, a comparison of scores obtained with the HFE and HFE-LP lists allows an examination of changes in speech intelligibility when more speech cues are provided above 2.5 kHz.

Each subject responded to four randomly selected HFE lists alternated with four different randomly selected HFE-LP lists. The QSIN test was presented monaurally via an ER-3A earphone coupled to the ear with a compressible foam plug. The test ear was determined using the following method: (1) If TEN (HL) results suggested the presence of a DR in only one ear, that ear was selected as the QSIN test ear; (2) If no DR was present for either ear or DRs were present for both ears, the subject's preferred ear for a hearing aid was used as the test ear. The QSIN was presented at a level that the participant considered to be "loud, but OK," determined using a loudness category scale and a bracketing procedure. Presentation levels ranged from 75 to 113 dB HL, with an average of 95 dB HL. Two unfiltered practice lists were administered before the test lists.

In this research, we were specifically interested in the implications of cochlear DR for individuals with the moderate to severe hearing loss that is typical of a large proportion of adult hearing aid wearers. Although the subjects were not individually fitted with hearing aids when listening to the QSIN test materials, the level of speech was individually adjusted for each subject to a "loud but OK" level, as described earlier. It is of interest to assess the extent to which the resulting listening conditions were similar to those experienced by hearing aid wearers with fittings that are representative of current practice. This is illustrated in Figure 3 for the average subject. Speech was delivered through an ER-3A earphone. All data have been transformed to equivalent 2 cm^3 coupler 1/3 octave band levels. The figure shows thresholds, National Acoustics Laboratories, Non-Linear, version 1 (NAL-NL1) targets (Byrne et al. 2001) for loud (75 dB SPL) speech, and the presentation levels for the HFE and HFE-LP conditions. It can be seen that the correspondence between presentation levels for the QSIN conditions and the NAL-NL1 amplification targets was very close for all frequencies up to 2.5 kHz. At higher frequencies, the HFE condition provided somewhat more gain than the target, and the HFE-LP condition provided less gain than the target.

TABLE 2. Distribution of cochlear dead regions across subject ears (N = 307)

Number of Frequencies Positive for DR	Number of Ears	Number of Ears With All DRs at Contiguous Frequencies
0	236	
1	45	
2	14	10
3	10	6
4	2	0

Fig. 5. Mean scores for high-frequency emphasis (HFE) and high-frequency emphasis low-pass filtered (HFE-LP) lists for subjects without dead regions (DR-no) and for subjects with dead regions (DR-yes). Bars indicate one standard deviation.

masked threshold was 10 dB or less below the maximum tone output for that frequency (14 occurrences), or when the subject could not tolerate the loudness of the TEN needed to complete the test (4 occurrences). Of the 2131 tests that were performed, there were 71 inconclusive results in 57 ears (2 at 0.75 kHz, 1 at 1.5 kHz, 7 at 2.0 kHz, 25 at 3.0 kHz, and 36 at 4.0 kHz). Subjects with any inconclusive or unmeasurable results who also tested positive for DR at other frequencies were classified as DR-yes overall. Otherwise they were classified as DR-no overall.

Figure 4 illustrates the mean audiograms of tested ears separated by their DR results. It is obvious that the audiograms for the two results (DR-yes and DR-no) are essentially identical up to 1.0 kHz. Above this frequency, mean thresholds were poorer for the ears that tested positive for DR. A mixed-model analysis of variance (SPSS GLM, version 14) was performed on these data (DR group versus test frequency) to explore the statistical significance of differences in thresholds between ears with and without DR. This test revealed a significant interaction between test frequency and DR group ($F_{[2.4, 734.1]} = 4.9$, $p = 0.005$). Post hoc univariate tests revealed that mean thresholds for the DR-yes group were significantly poorer than those for the DR-no group at 2.0, 3.0, and 4.0 kHz ($p < 0.005$ for all three comparisons).

Dead Regions and Benefit of High-Frequency Speech Cues

Each QSIN condition (HFE and HFE-LP) was scored using the mean number of key words correct across four lists. Thus, the possible scores ranged from 0 to 30. As a result of a procedural error, the QSIN test was performed on the DR-no ear instead of the DR-yes ear for two subjects who tested positive for DR in one ear and negative for DR in the other ear. Thus, in the data for Figures 5 and 6, there are 119 ears in the DR-no group and 51 ears in the DR-yes group. Figure 5 depicts the mean scores for HFE and HFE-LP lists for DR-no and DR-yes subjects. For both groups, the mean HFE-LP score was poorer than the mean HFE score, but the absolute differences were small: 1.76 words for the DR-no group and 0.94 words for the DR-yes group. A mixed-model analysis of variance (DR group versus QSIN condition) was performed to explore the statistical significance of differences in the HFE and HFE-LP means for the DR-yes and DR-no groups. There was a
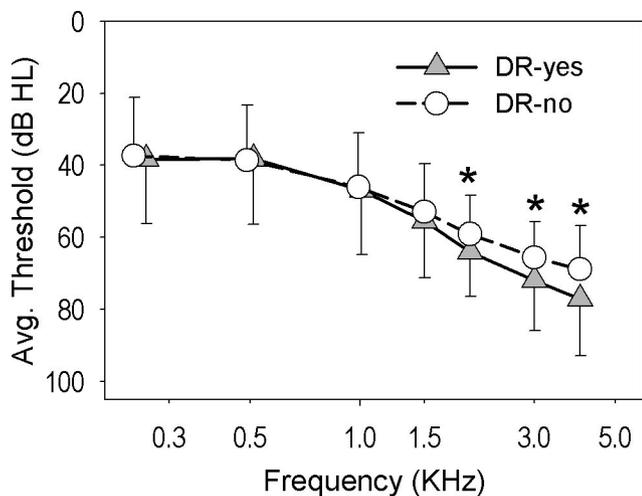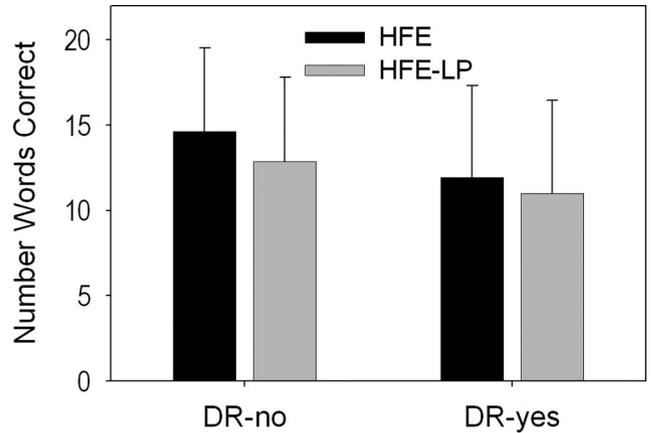

Fig. 4. Composite audiograms of subjects separated by their results on the TEN (HL) test for subjects without dead regions (DR-no) and for subjects with dead regions (DR-yes). Bars indicate one standard deviation. Asterisks denote frequencies, where the two groups were significantly different on average.
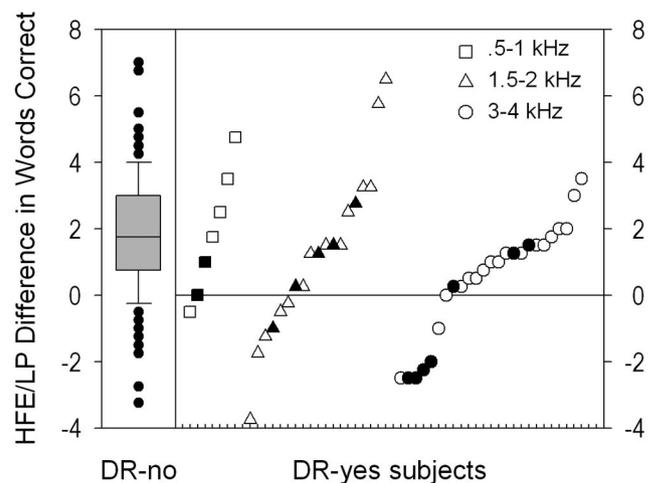

Fig. 6. The left panel shows a box plot of the differences between the high-frequency emphasis (HFE) and high-frequency emphasis low-pass filtered (HFE-LP) lists for subjects without dead regions (DR-no). The right panel of the figure gives the difference score for each subject with dead regions (DR-yes). The symbol used for each subject indicates the frequency region of the lowest DR detected in that subject. Closed symbols were used for subjects who had contiguous DRs at two or three frequencies.

significant main effect of QSIN condition ($F_{[1, 168]} = 71.13$, $p < 0.001$) and a significant main effect of DR group ($F_{[1, 168]} = 7.60$, $p = 0.006$). Of greater interest for this study, a significant interaction was seen between DR group and QSIN condition ($F_{[1,168]} = 6.50$, $p = 0.012$). Post hoc tests revealed a statistically significant difference between scores for the HFE condition and the HFE-LP condition for both the DR-no group ($F_{[1,168]} = 100.5$, $p < 0.001$), and the DR-yes group ($F_{[1,168]} = 12.37$, $p = 0.001$). Effect sizes (Cohen's d: Cohen 1988) were computed to quantify the impact of providing additional high-frequency cues. The computed effect size for the DR-no group was 0.357 (a small effect) and for the DR-yes group was 0.173 (a very small effect). These results, taken together, indicate that the addition of high-frequency speech cues in the HFE condition was helpful for speech recognition for both DR groups. Although the extra high-frequency information resulted in greater gains for the DR-no group than for the DR-yes group, the gains for both groups were small for the QSIN test materials.

As illustrated in Figure 4, subjects who were positive for DR tended to have somewhat poorer high-frequency thresholds than those who were negative for DR. Because of this, it was possible that there was less difference in audibility between the HFE and HFE-LP conditions for the DR-yes group than for the DR-no group, and this could partially explain the smaller difference between HFE and HFE-LP scores seen for the DR-yes group. To examine this issue, as noted earlier, estimates of SII were computed for each subject in the HFE and HFE-LP conditions. For the DR-no group, mean $SII_{HFE} = 0.6129$ (SD = 0.14) and mean $SII_{HFE-LP} = 0.5336$ (SD = 0.13). For the DR-yes group, mean $SII_{HFE} = 0.5611$ (SD = 0.16) and mean $SII_{HFE-LP} = 0.4963$ (SD = 0.15). The difference in SII between the two conditions was computed for each subject yielding a variable called SIIdiff (SIIdiff = SII_{HFE} − SII_{HFE-LP}). For the DR-no group, mean SIIdiff = 0.0793 (SD = 0.03). For the DR-yes group, mean SIIdiff = 0.0649 (SD = 0.04). A t-test was performed to assess the significance of the differences in SIIdiff between the DR-yes and DR-no groups. The test indicated that the mean SIIdiff was significantly smaller for the DR-yes group ($t_{[82.5]} = 2.497$, $p = 0.014$). This result confirmed our suspicion that the additional high-frequency cues available in the HFE lists were provided more effectively for individuals in the DR-no group than for those in the DR-yes group.

It is well known that audibility is a primary predictor of speech recognition scores (e.g., Humes 2007). Therefore, we expected that this difference in audibility of high-frequency cues would account for some of the differences in QSIN scores between DR-no and DR-yes groups. For this study, it was important to know whether the presence of a DR provided additional independent information about differences in QSIN scores. To explore this question, a multiple regression analysis was performed in which the difference between HFE and HFE-LP scores (QSINdiff) was predicted using SIIdiff (entered first) and DR group (entered second, coded DR-no = 0, and DR-yes = 1). The results indicated that audibility differences accounted for 5.8% of the variation in QSINdiff scores ($p = 0.002$). DR group accounted for an additional 2.2% of the variation in QSINdiff scores ($p = 0.049$). In other words, both variables made very small but statistically significant independent contributions to the prediction of the differences between

HFE and HFE-LP scores. This analysis yielded the following regression equation:

QSINdiff = 12.439(SIIdiff) − 0.636(DR group) + 0.770.

As shown in Table 1, most of the DRs detected in these subjects occurred at 2.0, 3.0, or 4.0 kHz, but some occurred at lower frequencies. Nonetheless, all subjects were exposed to the same spectral filtering in the HFE and HFE-LP conditions. It was of interest to assess any possible differences in benefit from added high-frequency cues among the DR-yes subjects based on the frequency region at which the DRs were detected. This was explored in Figure 6. The left panel of the figure is a box plot of the differences between the HFE and HFE-LP scores for the DR-no subjects. The shaded box gives the range from the 25th to 75th percentiles with the median score indicated. The whiskers above and below the box extend to the 90th and 10th percentile scores, and the outlying scores are shown individually. The right panel of the figure gives the difference score for each DR-yes subject. The symbol used for each subject indicates the frequency region of the lowest DR detected in that subject. Filled symbols were used for subjects who had contiguous DRs at two or three frequencies. Open symbols were used for all other subjects. Based on the proposition that listeners with DRs are likely to profit from additional speech cues only at frequencies up to about 70% above the edge of the DR, it could be hypothesized that the subjects in the 3.0 to 4.0 kHz group would obtain some benefit from the HFE condition, whereas those in the 1.5 to 2.0 kHz group would obtain less or no benefit. It is not clear what would be expected in the 0.5 to 1.0 kHz group. A visual assessment suggests that there are no obvious differences among the three groups of DR-yes subjects in the size of the QSIN score differences. To explore this issue in greater detail, a t-test was run to compare the mean QSIN score differences for subjects with lowest DRs below 3.0 kHz with those for subjects with lowest DRs at and above 3.0 kHz. The results indicated that the mean difference between the two groups (0.9 words correct) was not statistically significant ($t_{[49]} = 1.556$, $p = 0.126$), which confirmed the visual assessment. Also in Figure 6, subjects with contiguous DRs are scattered throughout the distributions, and it is not obvious whether they obtained less benefit than subjects with other DR patterns. To further explore the latter issue, a t-test was run to compare the mean QSIN score differences for subjects with and without contiguous DRs. The results indicated that the mean difference between the two groups (1.34 words correct) was statistically significant ($t_{[49]} = 2.116$, $p = 0.039$). In other words, subjects who tested positive for DR at one or more isolated frequency regions were more able to benefit from high-frequency cues than those whose DRs were found at contiguous frequency regions.

A final consideration regarding Figure 6 is the scatter of scores for individual subjects above and below zero on the "HFE/ HFE-LP difference" axis. Scores for most subjects lie above zero indicating that the score was higher in the HFE condition. However, some subjects yielded scores below zero indicating that the score was lower in the HFE condition. It might be tempting to assume that subjects with negative scores in Figure 6 were significantly penalized by the additional high-frequency cues in the HFE condition, but the data do not support that assumption. The 95% critical difference for the

QSIN scores used in this study is about three words (unpublished data from our laboratory). Thus, if the HFE/HFE-LP difference score from an individual subject is within ± 3, it cannot be concluded that the HFE and HFE-LP conditions yielded significantly different scores for that person. In Figure 6, there are two scores lower than −3, one in the DR-no group and one in the DR-yes group. Given the number of individual HFE/HFE-LP differences evaluated, either of these scores might have occurred due to measurement error. Thus, there is no evidence that individuals were penalized by the additional high-frequency cues in the HFE condition.

DISCUSSION

In this investigation, the goals were to explore the prevalence and potential implications of cochlear DRs in hearing-impaired listeners with the types of audiograms frequently considered to be optimal for hearing aid use. We recruited consecutive samples of individuals, from several clinical sites, who had moderate to severe hearing loss similar to the impairment of a large proportion of hearing aid wearers.

Prevalence of Dead Regions

Using the TEN (HL) test, 31% of these individuals were found to test positive for a DR at one or more test frequencies. This prevalence result is rather similar to the 29% reported by Preminger et al. (2005) for a small sample of hearing aid wearers. Two procedural differences between the studies could affect observed prevalence. Preminger et al. used a strict criterion (15 dB excess masking) to identify a DR and limited subjects' high-frequency thresholds to 80 dB or better. In contrast, we used the standard criterion (10 dB excess masking) to identify a DR and accepted subjects with thresholds poorer than 80 dB. Both differences would be expected to lead to a lower prevalence in the Preminger et al. study.

Our prevalence rate is considerably lower than those reported in several studies that used the same identification criterion as we used (10 dB excess masking). Vinay and Moore (2007), whose subjects included some with milder hearing losses than those in our study, reported a prevalence of 57%. As noted earlier, if the mildly impaired subjects were removed from consideration, the prevalence of DR reported by Vinay and Moore would be even >57%. Aazh and Moore (2007) reported a prevalence of 37% for subjects tested only at 4 kHz. The comparable prevalence in our study was 13% (Table 1). Because Vinay and Moore, Aazh and Moore, and our study all used the standard procedures and a criterion of 10 dB excess masking to identify a DR, it seems unlikely that procedural discrepancies can account for the differences in reported prevalence. Hornsby and Dundas (2009) reported a DR prevalence of 84% using the standard criterion, but their use of a 5 dB step size, rather than the recommended 2 dB, might have contributed to this high prevalence.

Differences in hearing loss etiology and audiological characteristics of subjects might have contributed to different prevalence estimates. The subjects of Hornsby and Dundas (2009) included some with more extensive impairment, and this might partially explain the greater prevalence rate they found, since it has been noted that DRs are very commonly seen in listeners with more severe hearing losses (e.g., Moore et al. 2000). The subjects of Aazh and Moore (2007) were

specifically chosen to have sloping audiograms, which was not the case in other studies. Several studies have shown that audiogram slope plays a role in DR identification (e.g., Vinay & Moore 2007; Hornsby & Dundas 2009), so perhaps this difference could account for some of the disparity in observed prevalence of DR at 4 kHz between our study and Aazh and Moore. Another noteworthy difference is the requirement in our study for a threshold no better than 25 dB HL below 1.0 kHz. This requirement was specified because the prevalence of hearing aid use is low among individuals with normal low-frequency hearing. Since most of our subjects were older, most of them would be expected to have sensory, metabolic, or sensory+metabolic presbycusis as a primary etiology (Schmiedt 2009). Our exclusion of individuals with normal low-frequency hearing could have increased the proportion of metabolic presbycusis in our subjects' hearing losses compared with subjects in previous studies, some of whom had normal low-frequency thresholds.

Although the prevalence of DRs was lower in our subject group than in some previous investigations, the trends in our findings echoed those reported in previous studies. For the most part, DRs were observed at frequencies >1.5 kHz (Table 1), but there were a number of positive findings for the lower test frequencies (e.g., Vinay & Moore 2007). There was no difference in prevalence of DRs between men and women, and there was not a significant difference in age between those with and without DRs (Preminger et al. 2005; Vinay & Moore 2007; Aazh & Moore 2007). In agreement with Hornsby and Dundas (2009), most ears of our subjects in the DR-yes group were positive for DR at only one frequency, and a relatively small number displayed a pattern of DR at two or more frequencies (Table 2).

Even though the range of subjects' audiograms in this study was intentionally limited to those typically exhibited by hearing aid wearers, we still found that listeners with DRs had significantly poorer average high-frequency thresholds than listeners without DRs. This is consistent with several previous reports showing that greater hearing loss is associated with a higher likelihood of DR detection (e.g., Preminger et al. 2005; Vinay & Moore 2007; Aazh & Moore 2007). Nevertheless, our data also were consistent with others in showing substantial overlap in audiograms between listeners with DRs and those without.

Dead Regions and Benefit of High-Frequency Speech Cues

One goal of the study was to assess, in a preliminary way, the possible implications of DRs for the selection of hearing aid frequency-gain function. All subjects with at least one DR were treated as a single group to explore the benefit obtained from high-frequency speech cues. Although individuals were not fitted with hearing aids in this research, the listening conditions were typically quite similar to those experienced by hearing aid wearers, as shown in Figure 3. The results of speech recognition testing indicated that, on average, subjects with DRs did perform better when more high-frequency cues were available in the HFE condition, but listeners without DRs gained even more benefit from the HFE condition. Although these differences were statistically significant, the size of the effect was small for the DR-no group and very small for the DR-yes group, and it is premature to draw any conclusions about the clinical importance of these small effects. Further, measures of

SII revealed that the difference in audibility between the HFE and HFE-LP conditions was somewhat larger for listeners without DRs than for those with DRs. This could have increased the apparent advantage seen for the HFE condition in the DR-no subjects. As a result, it was not clear whether, or how much, the presence of DRs in the DR-yes group contributed to this pattern. A multiple regression analysis was used to clarify the separate contributions of audibility differences and DR differences. This analysis showed that each variable made a significant independent contribution to explaining the differences between HFE and HFE-LP scores. At the same time, although the results were statistically significant, each variable accounted for only a very small percentage of the variation across subjects. Clearly, other variables (such as underlying pathology, audiogram characteristics, psychoacoustic abilities, procedural issues, cognitive functioning, and so on) also were important in determining the differences in speech understanding between the HFE and HFE-LP conditions for each subject.

Because we found high frequencies to be helpful for both DR-yes and DR-no listeners on average, our results might seem to be at variance with those reported by Vickers et al. (2001) and Baer et al. (2002). However, it should be noted that there were potentially important differences between their studies and ours. Some of their experimental subjects had essentially normal low-frequency hearing, which was not the case in our subjects. In addition, the subjects in the studies by Vickers et al. and Baer et al. had more severe high-frequency hearing losses and more extensive DRs than the subjects in our study. Most of their experimental subjects had DRs that were contiguous across several octaves. Such extensive DRs were not seen in any of our subjects; however, we did observe that subjects with contiguous DRs in two to three frequency regions obtained less benefit from high frequencies, on average, than subjects with isolated DR(s). As noted earlier, differences in high- and low-frequency threshold sensitivity could point to differences in hearing loss etiology, which might be associated with the impact of DRs. Further, Vickers et al. (2001) and Baer et al. (2002) used controlled filtering conditions that were customized for each subjects' DR location; the widest bandwidth extended to 7500 Hz; and the speech tokens were nonsense syllables, whose recognition depends on purely auditory cues. In our study, we presented conditions that were more similar to those experienced by hearing aid wearers: the maximum bandwidth extended to about 4500 Hz (similar to hearing aids) and the speech tokens were meaningful sentences (similar to daily life). These variables could have contributed to the different results obtained in our study compared with the studies of Vickers et al. and Baer et al.

The results of our study are quite similar to those reported by Mackersie et al. (2004) and Preminger et al. (2005) in investigations with small groups of subjects. These studies were analogous to our study in that the maximum audible bandwidth was limited to that of hearing aids, and the subjects had similar audiograms. Preminger et al. observed benefit from high-frequency gain in listeners with and without DRs, and there was not a significant difference in benefit between the groups. Mackersie et al. determined that listeners with and without DRs obtained similar benefit from high-frequency gain in quiet and low noise conditions, whereas in higher noise conditions, subjects with DRs gained some benefit but not as much as those without DRs. It is noteworthy that the DR-yes

subjects of Mackersie et al. were required to have positive DR results in three or more contiguous frequency regions on the assumption (supported in our study) that these individuals would show greater disruption in performance than those with only one positive DR frequency. A positive DR finding in three contiguous frequencies was very rare in our study. As shown in Table 2, fewer than 5% of our subjects had DRs that were contiguous at two or three test frequencies.

Our study did not produce support for a recommendation to reduce high-frequency hearing aid gain for amplification candidates with moderate to severe hearing loss who test positive for DRs using the TEN (HL) test. Although individuals with DRs seem to be less able than those without DRs to exploit high-frequency speech cues, some benefit from those cues is typically obtained, even in the presence of DRs. In a recent work, Vinay and Moore (2007) suggested a relatively limited role for identification of DRs in hearing aid fitting. They noted that, because of the limited bandwidth of hearing aids and the potential usefulness of amplification at frequencies up to 70% above the DR edge, the presence of a DR at 3 kHz or higher would not be expected to impact hearing aid fitting. They recommended that, when hearing aid fitting is the goal, the TEN(HL) test should be used at lower frequencies (0.5 to 2 kHz) and only when the audiometric threshold exceeds 60 dB HL.

CONCLUSIONS

When the TEN(HL) test was administered to a large group of listeners who had moderate to severe hearing losses similar to those of many hearing aid wearers, almost one-third of the individuals (almost one-quarter of ears) tested positive for a DR at one or more frequencies. This prevalence rate is similar to that reported in one previous small-scale study but less than that reported in several other previous studies. Although there are some reasonable explanations for different results among the studies, there remains considerable uncertainty about the prevalence of DRs among typical hearing aid candidates.

When additional high-frequency speech cues were provided for listeners with DRs and without DRs, both groups showed small improvements in performance, on average. The group with DRs gained less from the high-frequency boost than those without DRs, and individuals with DRs at contiguous frequencies gained less than individuals with isolated DR(s). Although audibility limitations accounted for part of the disadvantage seen for the listeners with DRs, there also was a separate independent contribution attributable to the positive DR finding. These results are consistent with a conclusion that individuals with DRs are less able than those without DRs to exploit high-frequency speech cues when those cues are equally audible for both groups. Nevertheless, on average, listeners with DRs did obtain some benefit from high-frequency speech cues.

Although there are plausible arguments to support the proposition that provision of amplification at frequencies within a high-frequency cochlear DR can be detrimental for speech recognition, there is no evidence in this or any of the reviewed published investigations that the predicted problems actually occur in listeners with moderate to severe hearing loss. This statement rests on analysis of group data and does not preclude the possibility that some specific individuals might be negatively impacted by amplification at frequencies inside a

DR. Further research is needed to determine if such individuals exist, and how they might be identified. It is premature to draw any firm conclusions from this study about the clinical relevance of additional high-frequency cues in daily life for patients with and without DR. Field trials with patients wearing hearing aids will be needed to provide this type of evidence and to suggest the most effective approach to managing cochlear DRs in hearing health care. In the meantime, it is suggested that practitioners continue to follow best-practice recommendations when fitting hearing aids for patients with moderate to severe hearing impairment. These recommendations include the goal of providing high-frequency gain according to evidence-based prescriptive methods.

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