Providing audible amplified signals for listeners with severe high frequency hearing loss is somewhat controversial. Various strategies have been proposed for use in assessing hearing thresholds, and for providing full, limited, or no audibility for hearing levels in the severe to profound range. This chapter will review current knowledge on the efficacy of audibility in the high frequencies, testing for dead regions in the cochlea, and review current fitting strategies for providing amplification for severe high frequency hearing loss. Case studies will be used to illustrate test results where applicable.

Should High Frequencies be Made Audible?

Hearing aids provide audibility of sounds that would otherwise be inaudible due to the combined effects of hearing loss, input level, and distance. For spoken communication, hearing aids are intended to make speech sounds audible. Some hearing aid fitting approaches attempt to make a broad bandwidth of speech audible, and commonly used prescriptive formulae typically compute hearing aid targets to around 6000 to 8000 Hz. The term “high frequencies” in hearing aid fitting generally refers to the region between about 3000 Hz and the end of the hearing aid’s frequency response.

When hearing impairment is severe or profound, amplification for audibility in the high frequencies is both more difficult to attain, and more controversial. The following paragraphs will discuss this from two perspectives: the acoustic elements within high frequency speech, and research examining the utility of high frequency audibility for listeners with hearing loss.

Acoustically, conversational speech has the most energy between approximately 500 and 3000 Hz. This mid-frequency region is important for understanding speech, particularly speech that is meaningful such as words, sentences, or passages (Pavlovic 1987; Studebaker, Pavlovic and Sherbecoe 1987; Sherbecoe and Studebaker 2002). However, speech energy above 3000 Hz offers listeners important linguistic information. The standardized Speech Intelligibility Index (SII: ANSI 1997) allocates 27% of the importance of average speech to the 1/3 octave bands at 3150 Hz and above. For more difficult types of speech, such as nonsense syllables, the same high frequency region carries 31% of the importance in the speech signal. This high frequency importance makes good sense in terms of the acoustic properties of speech, because the high frequency region carries important speech cues. For example, the lowest spectral peak of /s/ is between 2.9 kHz and 8.9 kHz across genders (Boothroyd and Medwetsky 1992).

Research suggests that listeners require high frequency audibility in order to correctly understand /s/ cues, regardless of hearing status. One recent study demonstrated that listeners with moderate to moderately severe sensorineural hearing impairment needed an audible bandwidth to 5 kHz for male speech, 6 to 9 kHz for female speech, and 9 kHz for child speech in order to understand /s/ (Stelmachowicz, Pittman, Hoover.
and Lewis 2001). This suggests a need to provide hearing aid gain and output that is far in excess of what is normally provided today, if the spectral energy in /s/ is to be audible for hearing aid users (Stelmachowicz, Pittman, Hoover and Lewis 2004).

Some studies suggest, however, that providing audibility in the high frequencies may not be an effective strategy in all cases. Experiments using filtered speech have found discrepancies in expected and observed speech understanding performance in listeners with sensorineural hearing loss (Pavlovic 1984; Sherbecoe and Studebaker 2003). The expected performance levels are based on normal performance at specific levels of audibility. Discrepancies tend to be greatest in frequency regions with the most hearing loss. Essentially, this points to a reduction in the ability of the impaired ear to make use of the audible speech signal. Specifically, it has been suggested that individuals with hearing impairment may be less efficient at making use of amplified high frequency information (Ching, Dillon and Byrne 1998; Hogan and Turner 1998).

Ching et al. (1998) examined the relationship between audibility and speech recognition for listeners with sensorineural hearing losses ranging from mild to profound degrees. Mean results obtained using sentence stimuli as well as consonant (VCV) syllables suggested that speech recognition benefit was achieved across all degrees of hearing loss when level of speech audibility was up to and including approximately 20 dB sensation level (SL). Beyond 20 dB SL no additional benefit was conferred for listeners with severe to profound flat and/or sloping hearing losses. A small decrease in effectiveness of information, or rollover, in group performance was observed at high sensation levels (i.e. 36 dB SL) for the severe hearing loss groups. Re-analysis of these data suggested that, on average, little information can be extracted from an audible signal when hearing loss is greater than 80 dB HL at 4000 Hz (Ching, Dillon, Katsch and Byrne 2001).

Do these findings warrant the limitation of high frequency amplification in clinical practice? Three factors may be important to consider. First, current published prescriptive methods used to fit hearing aids would not recommend providing sensation levels in the range of 36 dB for severe to profound hearing losses. Therefore, at the levels representative of hearing aid use, rollover is not a concern, particularly for moderate-level speech signals when a prescriptive approach is used. Second, appropriate audibility provides clear, measurable benefit even for listeners with severe hearing loss. In the Ching et al. (2001) data, an audibility change from a low level (i.e., 12 dB) to a moderate level (i.e., 24 dB) increased scores from roughly 40% to roughly 70% for listeners with severe hearing loss, when listening to sentences with speech energy up to 5600 Hz. Therefore, this audibility increment produced approximately 30% benefit, despite the fact that the listeners had poorer-than-normal efficiency. Third, large individual variability is observed in listeners with hearing impairment. Some perform very efficiently, while others perform less efficiently. In the Ching et al. data, listeners with severe losses heard sentences filtered to have mid- to high-frequency energy (i.e., 1400 to 5600 Hz). At a moderate level of audibility (i.e., an SII of 0.4), their scores ranged from 0% to 70% correct. This remarkable range of individual performance underscores the need to evaluate the benefit of audibility on an individual basis in clinical practice, rather than removing audibility on the basis of the pure tone audiogram alone.

In summary, audibility may not be as effective for severe hearing losses as for milder losses; however, such listeners may still receive varying degrees of speech recognition benefit from high frequency audibility though amplification. Therefore, severe hearing loss can be related to reduced speech recognition performance; however, moderate levels of speech audibility do provide benefit. Efficacy of providing high frequency audibility should be determined on an individual basis. One recommended method for evaluating high-frequency candidacy is the assessment of dead regions in the cochlea (Baer, Moore and Kluk 2002). This will be discussed in the sections below.

Dead Regions in the Cochlea

New terminology has recently been introduced concerning audiometric evaluation of sensorineural hearing loss: this is the dead region in the cochlea. A dead region refers to an area on the basilar membrane that, when stimulated, gives rise to no neural activity in the associated auditory nerve fibres, presumably due to a lack of inner hair cell function (Moore, Huss, Vickers, Glasberg and Alcantara 2000). The existence of this type of cochlear damage has been reported and/or discussed previously in the literature, and has been related to both poor frequency resolution (Moore et al. 2000), altered patterns of loudness recruitment, and/or poor speech recognition abilities (e.g., Kilian 1995; see also Moore 2004 for a review of the history of this concept). The recent attention given to cochlear dead regions has...
arisen not because they are new (they are not), but rather because a new clinical test has been developed for their evaluation (Moore 2004; Moore, Glasberg and Stone 2004). The following section will summarize the background of this test and describe its use.

The degree of sensorineural hearing loss (SNHL) is, in most cases, related to the type of cellular damage underlying the impairment itself. That is, outer hair cell damage is typically responsible for SNHL of up to about 60 dB, due to reduction of their effects as the cochlear amplifier (Moore and Glasberg 2004). Above these levels, further SNHL is typically due to inner hair cell damage. Killion (1995) termed these two types of SNHL as Type I and Type II, respectively.

Type I losses have better frequency resolution than do Type II hearing losses. The concept of frequency resolution is essential to the understanding of dead region testing. Frequency resolution, as measured by a psychometric tuning curve, is the ability to detect a target tone in the presence of masking tones at nearby frequencies. The normal cochlea allows the listener to do this very well, resulting in sharp tuning curves with low threshold levels. Type I hearing loss results in a loss of the sharpest portion of the tuning curve (due to the loss of outer hair cell function, and therefore the loss of the nonlinear cochlear amplifier). The resulting tuning curves have raised thresholds and are broader (i.e., frequency resolution is poorer). In Type II hearing losses, the tuning curves have still higher thresholds and still broader tuning. For the person with SNHL, poor frequency resolution is associated with poor abilities to understand speech in competition, such as speech in noise. In fact, individual abilities to understand speech in different types of noise have been shown to relate to the specific shape and width of their tuning curves (Stelmachowicz, Jesteadt, Gorga and Mott 1985).

Hearing losses with dead regions present with a different profile. Unlike Type II loss, no hair cell function remains in a dead region. Therefore, a tuning curve measured in the vicinity of a dead region should not show any ability to discriminate between frequencies in that area of the cochlea. This concept provides the cornerstone for the development, validation, and continuing research on dead regions in the cochlea.

Dead regions in the cochlea have importance for clinical audiometry, whether or not they are routinely evaluated. In performing conventional audiometry within a dead region, the clinician will likely use high presentation levels to attain threshold. The physiological levels will be high without producing a neural response arising from the presumed test place in the cochlea. Recall that the Organ of Corti is tonotopically organized, and also that the traveling wave on the basilar membrane spreads activation from the peak level of stimulation to other areas. This high level of basilar membrane activity (at the test frequency place) will therefore also create activation at other frequency places, possibly places with enough function to result in neural firing. This by-product response may be enough to cause the listener to respond during audiometry by indicating that a sound was heard. This type of false response will occur at a lower test level than would be associated with true threshold.

The prevalence of SNHL with off-frequency listening (or dead regions) is not definitively known, but one study reported an incidence of 29% in a clinical sample of adults with moderate to severe hearing impairment (Preminger, Carpenter and Ziegler 2005). Prevalence estimates in the severe to profound population may be higher, with one study of 22 teenagers showing an incidence of dead regions in 70% of participants, in at least one ear (Moore, Killen and Munro 2003). The existence of dead regions is not entirely predictable from the audiogram (or a test would not be necessary), although the test developers suggest that it may be associated with high-frequency thresholds greater than 90 dB HL, and/or losses with slopes greater than 50 dB per octave. However, a clinical study with the Threshold Equalization in Noise (TEN) test showed a greater likelihood of dead regions in patients presenting with an audiometric slope from 500 and 2000 Hz steeper than 19 dB/octave, for listeners with thresholds 85 dB HL and better (Preminger et al. 2005). This suggests that testing for dead regions may be indicated for some listeners with severe hearing loss.

The TEN test has been proposed as a method for determining whether dead regions exist in a given ear (Moore et al. 2000). The TEN test uses a specially developed masking noise, which is administered to the test ear (i.e., ipsilaterally). This is done to prevent either upward or downward spread of activation from producing off-frequency listening. Essentially, the testing process determines whether pure tone thresholds are made much poorer when the TEN noise is present: if they are,
then the tester concludes that they were false thresholds due to off-frequency listening when the tones were presented in isolation. In short, a dead region has been found. The process for conducting TEN testing will be described in the next section.

**Dead Regions: Administering the TEN Test**

The TEN test is a masking procedure in which both masker and test signal are presented to the same ear. Conventional audiometric masking is used when the test signal is strong enough to send signals from the test ear to the non-test ear. This is a very different masking purpose in comparison to masking for off-frequency listening in the test ear. Therefore, the procedures are somewhat different.

In conventional masking, the masker level is selected based on the presumed crossover level of the test stimulus and the non-test ear thresholds. Masking noise is administered to the non-test ear. A plateau of masked responses is measured to determine that appropriate masking levels have been administered. In contrast, TEN masking is administered to the test ear, at a level sufficient to mask upward and/or downward spread of activity arising from the test tone. No masking plateau is measured. Instead, evidence of masking is determined when the better-hearing thresholds in the test ear shift to the masker level. An example of this is shown in figure 1. For this audiogram, unmasked thresholds were measured at severe to profound hearing levels. These high test levels may have been associated with downward spread of activity in which the 2000 and 4000 Hz thresholds may have been due to activity at 1000 Hz, as shown by the dashed lines. The downward spread of activity estimates were determined by plotting a 50 dB/octave line from each threshold point. This line provides visual assistance in determining regions of the audiogram that have approximate slopes that warrant an evaluation of dead regions (Moore 2004). In this example, masking is needed to prevent the 1000 Hz region from responding while the 2000–4000 Hz region is tested. Once this masking is in place, the thresholds in the 2000–4000 Hz region will either remain at or within 10 dB of their unmasked levels (i.e., pass result, no dead region), or may increase by 10 dB or more (i.e., fail result, dead region).

A clinical example of this type of testing is shown in figure 2. This patient presented with a moderately-severe sensorineural hearing loss bilaterally. Thresholds in the high frequencies were in excess of 90 dB HL, motivating the evaluation of dead regions in the cochlea. Unmasked thresholds for the TEN tones (tested with supra-aural headphones) were within 5 dB of audiometric thresholds (tested with insert phones), except at 3000 Hz, where the difference was 10 dB. This is a
rather large difference in the context of the 10 dB pass/fail criterion of the TEN test procedure. For this reason, TEN test interpretation was made based on the TEN tone unmasked thresholds rather than the audiometric thresholds, as recommended by Moore et al. (2004). TEN masking was introduced at 65 dB HL. In the presence of the masker, thresholds from 500 through 1500 Hz were within 10 dB of the masker level, indicating that low frequency masking was successful. Masked thresholds at 2000 and 3000 Hz were within 10 dB of the unmasked thresholds, indicating no evidence of a dead region at those frequencies. The masked threshold at 4000 Hz was beyond the limits of the audiometer (at 110 dB HL) despite an unmasked threshold of 100 dB HL. This is taken as evidence of a dead region at 4000 Hz. Current recommendations for amplification include providing audibility of high frequency energy to one octave above the cutoff frequency of the dead region (Moore 2004), and/or discounting the results of any TEN test that produces a dead region result at only a single frequency (Mackersie, Crocker and Davis 2004). For this patient, either of these criteria would indicate that amplification of high-frequency speech energy is indicated.

**Dead Regions Research: Validity and Psychometric Properties**

The TEN test was developed and validated by comparing TEN results in groups of patients with and without dead regions, as diagnosed by psychometric tuning curves (Moore et al. 2000). In patients without dead regions, masked thresholds were within 10 dB of the masker level and/or the unmasked thresholds (whichever was higher). In patients with dead regions, the TEN masker shifted thresholds to be more than 10 dB poorer, evidence that off-frequency listening likely played a role in the testing of the unmasked threshold (i.e., that a dead region was present). Further experiments evaluated the effects of dead regions on speech recognition in quiet and in noise. In one study, listeners with dead regions demonstrated poorer speech recognition in quiet than the listeners without dead regions (Vickers, Moore and Baer 2001). In the majority of listeners with dead regions, the benefit of providing additional high frequency information ceased when filtering was 50 to 100% (i.e., up to an octave) above the edge frequency of the dead regions. In most cases, this occurred as a plateau in performance; however, rollover was observed in two listeners when the speech band extended beyond the one octave range above the edge frequency of the dead regions. In contrast, listeners without dead regions (and moderate to severe high frequency hearing loss) continued to benefit from the addition of high frequency speech energy up to 7500 Hz. A few procedural factors are important to consider when interpreting these data. Of the seven listeners in this study with dead regions, five had extensive dead regions that began at or below 2 kHz. Furthermore, the listeners without dead regions had, on average, better hearing than the listeners with dead regions. In a different study, a different group of patients with better hearing and dead regions that began in the 2–3 kHz region were evaluated (Mackersie et al. 2004). Patients with dead regions had performance in quiet that was equivalent to that of audiometrically matched patients without dead regions (Mackersie et al. 2004). It appears, therefore, that speech recognition in quiet may not be substantially affected by a dead region, more so than would be expected based on the audiogram alone.

Speech recognition in noise also has been investigated in listeners with dead regions. Baer et al. (2002) found that listeners with dead regions performed best with broadband speech (i.e., to 7500 Hz). However, some of their listeners demonstrated rollover (as in the Vickers et al. 2001 study), so they concluded that amplification of high frequencies to 50 to 100% of the dead region edge frequency may be an effective strategy. A clinical study of patients with hearing losses between 50 and 80 dB HL found that listeners who had dead regions had a greater degree of hearing loss, a higher reported rate of listening difficulty in real world environments, and poorer unaided speech recognition in noise than did listeners without dead regions (Preminger et al. 2005). Neither of these studies factored out the differential contributions of greater hearing loss versus dead regions. Mackersie et al. (2004), using a matched-pairs design, found that listeners with dead regions performed more poorly in high levels of background noise than their matched counterparts. These results demonstrate that listeners with dead regions can be expected to have significant listening difficulties in some real world environments.

These studies provide evidence that the phenomenon of dead regions is of clinical importance, particularly when they are extensive. However, some caution may remain. The original validation of the TEN test approach was conducted on a relatively small sample of patients, many of whom had extensive dead regions. One study attempting to replicate the validation found relatively poor agreement between the tuning curve results and the TEN.
findings, calling the validity of the test into question (Summers et al. 2003). However, this poor agreement may be attributable to two factors. One, the TEN test sometimes produces a “fail” result at an isolated frequency – in essence a dead region surrounded by alive regions. This type of test result has the poorest agreement with tuning curve tests across studies, leading some to recommend that isolated “dead regions” be disregarded (Mackersie et al. 2004). Second, poor agreement between tuning curves and TEN results in the Summers et al. paper may have been affected by procedural issues in tuning curve evaluation rather than a limitation of the TEN test itself (Moore 2004). Overall, testing for dead regions using the TEN procedure is likely valid, but the results may not change the goals for hearing aid audibility in many patients.

A common clinical finding, in our experience and in one study of a clinical sample (Preminger et al. 2005) is that of dead regions that are at 3000 Hz and/or higher. Patients with this type of high frequency dead region, along with patients who have single-frequency dead regions require no modification in clinical treatment, by any recommendation that currently exists in the literature (Mackersie et al. 2004; Moore 2004). Specifically, some authors recommend amplifying sound up to one octave beyond the starting frequency of a high frequency dead region (Moore 2004). For a dead region beginning at 3000 Hz, this would result in amplification (if possible) to 6000 Hz. This is not typically exceeded by the bandwidth limitations of today’s hearing aids. Therefore, conventional hearing aid goals would not be altered by the results of dead region testing for many patients who have them. However, for those patients with extensive dead regions, different goals for amplification may be an important consideration. Specifically, these patients would not be expected to have good aided speech recognition with conventional hearing aids and likely would have significant problems in noise. Reduction of high-frequency amplification (i.e., frequencies greater than one octave above the start of the dead region) may allow a hearing aid fitting with reduced feedback, and may prevent rollover in some listeners (Baer et al. 2002). However, reduction of high frequency amplification is not likely to improve speech recognition. Alternative signal processors and/or enhancement of signal-to-noise and/or signal-to-reverberation (e.g., via a personal FM system), along with high-quality aural rehabilitation, are important considerations for patients with extensive dead regions.

**Clinical Example of High Frequency Amplification**

The following case example features a 60 year old male patient (WH) who had received several trials with amplification, but had not become a successful hearing aid user. He presents with a normal hearing loss in the low frequencies, steeply sloping above 1000 Hz to profound levels in the high frequencies. His air conduction

![Figure 3](image3.png)  
*Figure 3. Air conduction thresholds as a function of frequency in dB HL.*

![Figure 4](image4.png)  
*Figure 4. Unmasked and masked threshold obtained from TEN test for the left ear.*
pure tone thresholds, as measured with insert earphones coupled to personal earmolds, are shown in Figure 3. The hearing loss is sensorineural in nature, as confirmed by bone conduction thresholds and tympanometry. The hearing loss is believed to be congenital. Based on results from the TEN test (Moore et al. 2004) dead regions were found at 3000 Hz and above on the left side and at 4000 Hz and above on the right side. He commented during completion of the TEN that when listening for the tone on the left side at 3000 Hz and above he could not hear the tones, but rather felt their presentation. Figures 4 and 5 display the results obtained from the TEN from both the left and right ears respectively.

WH was fitted with bilateral behind-the-ear hearing aids using wide-dynamic-range compression adjusted according to the DSL v5.0 prescriptive method (Scollie et al. 2005). The hearing aids were further adjusted according to listener preference; he preferred to have more audibility in the high frequencies than was prescribed by the adult targets in DSL 5.0 (figures 6 and 7). Given that his loss is congenital in nature, one could argue that the pediatric targets (which are higher) could have been applied. These targets would have been closer to his preferred settings in the high frequencies, particularly for his better (right) ear. His stated preference, and indeed his motivation to pursue amplification, was to have audibility of high frequency environmental sounds, particularly sounds of nature, and speech sounds to ease the difficulty of communication. The fitting provided high frequency audibility up to, or slightly above, 4000 Hz in the left ear, and to 6000 Hz in the right ear. Therefore, the bandwidth of this fitting is within the recommended one octave range above the dead region edge. This illustrates the important concept that the presence of dead regions does not necessarily confine audibility to below the dead region. As shown in this case, the preferred hearing aid response included audibility within the dead region.

Various subjective and objective outcome measures were administered to assess hearing aid performance. High frequency audibility was measured using a modified version of the Distinctive Features Differences Test (DFD: Cheesman and Jamieson 1996), which assesses recognition of consonants occurring in a fixed, word-medial context (i.e., /CII/). The subset of 10 consonants tested includes: /ch, d, f, j, k, s, sh, th, z/. Results suggest that WH could hear and recognize many high frequency consonants at a soft presentation level of 50 dB SPL. Figure 8 displays phoneme recognition as a function of number of correct responses for six presentations of each phoneme. He experienced the most difficulty recognizing the highest frequency phonemes; this is consistent with the fitting providing little audibility, particularly for soft speech, above 4000 Hz. Loudness growth also was assessed using a modified version of the contour test (Cox, Alexander, Taylor and Gray 1997). The task was computerized and the listener chose from responses presented on a computer monitor in the sound booth. Results suggest loudness growth at the lower end of the normal range (figure 9). Lastly, the Abbreviated Profile of Hearing Aid Performance (APHAP) was used to assess subjective performance in adverse listening conditions (Cox and Alexander 1995). The responses were compared to the 20th to 80th percentile range of problems with aided performance reported by successful users of linear hearing aids (Cox and Alexander 1995). Results suggest no significant problems in any listening condition evaluated, with the best performance occurring in the ease of communication scale (figure 10).

Overall, this case displays an example of provision of high frequency audibility for a listener with severe high frequency hearing loss and the presence of bilateral cochlear dead regions. The fitting was considered
Figure 6. Hearing aid fitting for the right ear of the audiogram shown in figure 3. Displayed variables are plotted in ear canal sound pressure level, and include thresholds (○), targets for speech at an input level of 65 dB SPL (Adult target: /dialogue/ , Pediatric target: - ), targets for a 90 dB pure tone (†), and predicted upper limits of comfort (*)\textsuperscript{6}. Measured hearing aid responses include the maximum power output (†) and the aided RMS levels of speech (—), surrounded by the peaks and valleys of aided speech (vertical hatched area).

Figure 7. Hearing aid fitting for the left ear of the same patient as shown in figure 6. Format follows that of figure 6, except threshold levels are indicated for the left ear (○).
both wearable and beneficial by this listener, and provided acceptable loudness, speech recognition, and self-reported outcomes. For listeners with high frequency dead regions, this suggests that providing high frequency audibility may not be necessarily detrimental to hearing aid performance and speech recognition. In the case described above, the listener preferred the hearing aids set above DSL v5.0 targets specifically in the high frequencies to maximize high frequency audibility. This setting provided audibility to within an octave of the dead region edge frequency. We did not test this patient with additional high frequency information, in part because the bandwidth limitations of conventional hearing aid technology would not allow us to do so. This is a common result in patients with dead regions: the dead regions themselves are at fairly high frequencies, meaning that the audibility goals of the fitting are not functionally different than they would be if dead regions were not present.

Conclusions

In this chapter, we have reviewed studies evaluating whether speech audibility is beneficial for listeners with severe sensorineural hearing loss. In addition, we have considered whether dead region testing provides useful additional information for these patients. It is difficult to arrive at a meaningful single conclusion of best practice for this population, because individuals with severe hearing loss vary substantially in their ability to derive meaning from an audible speech signal. Using the TEN (HL) test to evaluate patients for extensive dead regions is likely helpful in understanding the underlying reasons for some patients who have extraordinary difficulties. Such testing may help clinicians and patients to consider additional technologies and/or strategies to help in difficult communication situations. However, the literature reviewed here and the case study presented illustrate that high frequency dead regions (i.e., above about 3000 Hz) may have little impact on the clinical fitting of amplification. It is recommended that high frequency benefit be evaluated on an individual basis, as even listeners with poor speech discrimination abilities may benefit from increased bandwidth. The inclusion of the TEN test, in addition to objective or subjective measures of speech recognition in quiet and in noise may provide a clearer picture of listener specific auditory function and amplification needs.
References


