

Cochlear Dead Regions in Adults and Children: Diagnosis and Clinical Implications

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ABSTRACT

The inner hair cells (IHCs) are the transducers of the cochlea; they convert mechanical vibrations to neural activity. When the IHCs and/or neurons are nonfunctioning over a certain region of the cochlea, this is referred to as a dead region. A dead region can be defined in terms of the characteristic frequencies of the IHCs and/or neurons immediately adjacent to the dead region. Dead regions can be detected, and their limits can be determined, using the threshold equalizing noise (TEN) test or by measurement of psychophysical tuning curves (PTCs). Both PTCs and the TEN test can be used to assess children as young as 7 years of age. The identification of dead regions can be helpful in determining the appropriate form of amplification. For both adults and children with restricted dead regions (“holes”), benefit is obtained from amplification of frequencies up to at least 4 kHz. For adults and children with extensive continuous dead regions starting at a relatively low frequency (≤ 1.5 kHz) there may be little or no benefit from amplification of high frequencies.

KEYWORDS: dead region, TEN test, psychophysical tuning curve, amplification, hearing aid

Learning Outcomes: As a result of this activity, the participant will be able to (1) describe what a dead region is and describe two methods for diagnosing a dead region for adults and children, and (2) list the implications of dead regions for speech perception and the fitting of hearing aids.

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A dead region is a region in the cochlea where the inner hair cells (IHCs) and/or the auditory neurons are functioning very poorly, if at all.¹⁻⁴ A sine wave that produces peak basilar membrane vibration in a dead region may not evoke sufficient neural activity within the dead region for that signal to be detected. However, if the signal is sufficiently intense, it may be detected via IHCs and neurons adjacent to the dead region. In other words, the signal may be detected via a place in the cochlea that is different from the place where that frequency would normally be detected. This is sometimes called “off-frequency listening” or “off-place listening.” Psychoacoustic tests for diagnosing a dead region are basically tests for detecting when off-place listening is occurring. Hence, a dead region can be defined operationally as a region in the cochlea where the IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening.⁴

Using a frequency-to-place map,⁵⁻⁷ the boundary of a dead region can be defined in terms of the characteristic frequency of the IHCs and/or neurons immediately adjacent to the dead region. This is referred to as the edge frequency (f_e).^{1,3} We can distinguish several types of dead regions:

1. A high-frequency (basal) dead region extends upward from f_e .^{2,8,9} When there is a dead region for all frequencies above f_e , the dead region is referred to as continuous.
2. A low-frequency (apical) dead region extends downward from f_e .^{10,11} When there is a dead region for all frequencies below f_e , the dead region is referred to as continuous.
3. A dead “hole” is a restricted dead region with lower and upper edge frequencies.^{12,13}
4. There may be a continuous dead region below a lower f_e and above an upper f_e , with a surviving “island” in between.¹⁴
5. There may be “patchy” dead regions (i.e., one or more dead holes with surviving regions in between).

DIAGNOSIS OF DEAD REGIONS

Psychophysical Tuning Curves

The “gold standard” for detecting dead regions is the psychophysical tuning curve (PTC). To

measure a PTC, the sinusoidal signal is fixed in level, usually at a low sensation level such as 10-dB sensation level. The masker is either a sinusoid or a narrowband noise. The masker level required just to mask the signal is measured as a function of the masker center frequency. For normally hearing subjects, the tip of the PTC (the frequency at which the masker level is lowest) usually lies close to the signal frequency.¹⁵⁻¹⁹ Thus, the masker is most effective when its center frequency is equal to the signal frequency. However, when hearing-impaired listeners are tested, PTCs have sometimes been found whose tips are shifted well away from the signal frequency.^{2,12,20-27} This happens when the signal frequency falls in a dead region. The masker is most effective when its center frequency coincides with the characteristic frequency at which the signal is being detected (via off-place listening). Thus, it is assumed that the tip of the PTC falls at the boundary of the dead region (i.e., at f_e).

There are several problems associated with the measurement of PTCs. One is that the results may be affected by the detection of combination tones produced by the interaction of the signal and masker.^{12,25} This can happen especially for a person whose hearing at low frequencies is much better than at high frequencies. If the masker and the signal both fall in a region of hearing loss, they may interact to produce a simple difference tone that falls in a region of better hearing. This difference tone may be heard even when the signal itself is masked. To avoid this problem, Kluk and Moore²⁵ recommended adding a fixed low-pass noise to the main narrowband masker. The noise level is chosen so that the low-pass noise does not mask the signal, but it does mask any combination tone produced by the interaction of the signal and the masker. A second problem with PTCs is that the results can be influenced by the detection of beats between the signal and the masker, even when the masker is a narrowband noise.^{12,25} To avoid this problem, Kluk and Moore²⁵ recommended the use of a relatively wide noise bandwidth, such as 300 Hz. Such a noise has inherent rapid amplitude fluctuations that make it difficult to detect beats between the signal and masker. However, the use of such a wide bandwidth is problematic for

low signal frequencies, where the normal auditory filters are relatively narrow.²⁸ When the noise bandwidth is larger than the auditory-filter bandwidth, this can result in a broadening of the tip of the PTC, making it more difficult to determine the exact frequency at the tip. For low frequencies, a bandwidth of 160 Hz may be a good compromise. If precautions are not taken to prevent beats and combination tones from being used as a cue, PTCs with two or even three tips may occur, which makes the interpretation of the results very difficult.^{19,24,25,29}

A practical problem for clinical applications is that the measurement of PTCs can be time consuming. The traditional method of obtaining PTCs is to measure the masker level required for threshold for several masker frequencies. Depending on how many masker frequencies are used and on the method that is used to estimate the masked threshold, it can take between 30 minutes and several hours to measure a PTC for a single signal frequency. A faster method is to use a masker that slowly sweeps in frequency, using a method resembling Békésy audiometry, to “track” the masker level required for threshold.^{24,30–32} The fast PTC method described by Sek et al.^{31,32} requires about 3 minutes to measure a PTC. However, subjects sometimes require a few practice runs before they give stable results.²⁶ Software for measuring fast PTCs can be downloaded from: <http://hearing.psychol.cam.ac.uk.htm>. The software runs on a PC with a good quality sound card.

The Threshold Equalizing Noise Test

The threshold equalizing noise (TEN) test was developed as a simple and quick method for diagnosing dead regions in the clinic.^{2,33} The test involves measuring the threshold for detecting a pure tone presented in a background noise called *threshold equalizing noise*. The signal level is adjusted to determine the masked threshold, while the TEN level is fixed. The noise spectrum is shaped in such a way that the threshold for detecting a pure tone in the noise is approximately the same over a wide range of tone frequencies for people with normal hearing and for people with hearing loss but without any dead regions. The masked threshold is approx-

imately equal to the nominal level of the noise, specified as the level in a 132-Hz-wide band centered at 1000 Hz. The value of 132 Hz corresponds to the equivalent rectangular bandwidth of the auditory filter, as determined using young, normally hearing listeners, which is denoted ERB_N .³⁴ When the signal frequency falls in a dead region, the signal will only be detected when it produces sufficient basilar-membrane vibration at a remote region in the cochlea where there are surviving IHCs and neurons. Because of the tuning of the basilar membrane, the amount of vibration at this remote region will be less than in the dead region, and so the noise will be very effective in masking it. Thus, the signal threshold is expected to be markedly higher than normal. A masked threshold that is 10 dB higher than normal is usually taken as indicating a dead region.^{2,33} For a positive diagnosis, the masked threshold of the signal in the TEN is also required to be 10 dB or more above the absolute threshold (i.e., the TEN must produce at least 10 dB of masking). If the TEN level/ ERB_N is set equal to or 10 dB above the absolute threshold at the test frequency, the second criterion is automatically satisfied when the first criterion is satisfied.

In the first version of the TEN test,² all levels were calibrated in decibels sound pressure level (SPL) and the spectrum of the TEN was broad, so that the test could be used for a wide range of signal frequencies (0.125 kHz to 10 kHz); this version is referred to as the TEN (SPL) test. In a later version of the test,³³ all levels were calibrated in dB hearing level (HL) and the spectrum was made narrower to reduce the loudness of the TEN; this version is referred to as the TEN(HL) test. The TEN(HL) test can be used for signal frequencies in the range 0.5 to 4 kHz, and has to be used with specific headphones, namely Telephonics TDH39, TDH49 and TDH50 headphones (Telephonics; Farmingdale, New York). Recently, a version of the TEN test suitable for use with Etymotic Research ER-3A (Etymotic Research; Elk Grove Village, Illinois) insert earphones has been developed.³⁵ This is called the TEN(ER3) test.

One drawback of the TEN test is that it does not give a precise estimate of the value of f_e . If the criteria for diagnosis of a dead region are not met at a given test frequency but are met

at the next higher test frequency, this suggests that the value of f_e lies somewhere between the two test frequencies. Thus the precision in estimating the value of f_e depends on the spacing of the test frequencies that are used. Also, the criteria for positive diagnosis of a dead region may not be met when the test frequency falls only a little above f_e . Thus, in general, it is desirable to confirm the results of the TEN test, and to estimate the value of f_e more precisely, using PTCs.

The Audiogram

To assess whether dead regions could be diagnosed from the audiogram, Aazh and Moore³⁶ and Vinay and Moore³⁷ attempted to predict the presence of dead regions based on the audiogram. They compared the diagnosis with that obtained using the TEN(HL) test.³³ They showed that it was not possible to achieve both high sensitivity and high specificity when attempting to predict the presence/absence of a dead region from the audiogram. However, Vinay and Moore³⁷ showed that, for each test frequency from 0.5 to 4 kHz, 59% or more of ears had a dead region when the absolute threshold was above 70 dB HL. Thus, a hearing loss of 70 dB or more is suggestive of a dead region. However, a dead region can be present at a given test frequency when the audiometric threshold at that frequency is 55 dB or less,^{2,37,38} whereas a dead region may be absent when the hearing loss is 85 dB or more.^{2,37} Thus, there is a large range of uncertainty. A very steep slope of the audiogram, with thresholds worsening rapidly with increasing frequency, is suggestive of a high-frequency dead region but does not provide a reliable diagnostic method.^{37,39}

IMPLICATIONS OF DEAD REGIONS FOR THE CHOICE OF AMPLIFICATION CHARACTERISTICS FOR ADULTS

There have long been reports suggesting that people with moderate to severe hearing loss at high frequencies often do not benefit from amplification of high frequencies, or even perform more poorly when high frequencies are

amplified.^{40–45} It has been assumed in many of these studies that the subjects who did not benefit from amplification of high frequencies had reduced function or complete loss of function of IHCs and/or neurons, but no direct test for the presence of dead regions was conducted.

In two studies, adult subjects were tested for the presence of dead regions using both PTCs and the TEN test.^{8,9} All subjects had high-frequency hearing loss, but some had high-frequency dead regions and some did not. The dead regions, when present, appeared to be continuous rather than patchy (i.e., they extended from f_e upward, without any surviving “islands” of function). Also, the values of f_e were rather low, so the dead regions were extensive. Generally, the subjects with dead regions had more severe high-frequency hearing losses than those without dead regions. The speech stimuli were vowel-consonant-vowel nonsense syllables, using one of three vowels (/i/, /a/, and /u/) and 21 different consonants. The stimuli were subjected to the frequency-gain characteristic prescribed by the “Cambridge” formula,⁴⁶ which is roughly equivalent to a half-gain rule for midrange frequencies. The level of the input speech, before any amplification or filtering was applied, was 65 dB SPL.

Subjects were tested using broadband stimuli (upper frequency limit 7.5 kHz) and stimuli that were low-pass filtered with various cutoff frequencies. Changes in performance with cutoff frequency can be used to infer the extent to which information was being extracted in different frequency regions. In one experiment,⁸ the stimuli were presented in quiet. In another experiment,⁹ the stimuli were presented in steady speech-shaped noise, using a speech-to-noise ratio chosen to give a moderate reduction in performance relative to that measured in quiet. The general pattern of results was similar for the two experiments, and we describe here only the results of the second experiment.

For subjects without dead regions, performance improved progressively with increasing cutoff frequency. This indicates that these subjects were able to make use of high-frequency information. The mean score for the broadband stimuli was 79%. For subjects with dead regions, scores tended to increase with

increasing cutoff frequency up to $1.5f_c$ to $2f_c$. For higher cutoff frequencies, scores tended to remain nearly constant or to decrease slightly. These results indicate that the subjects with dead regions extracted little or no information from frequencies that were well inside the dead regions. Generally, the best scores for the subjects with dead regions were well below those obtained by the subjects without dead regions when listening to broadband stimuli.

A study of Vestergaard⁴⁷ provided data broadly consistent with the findings previously summarized. He tested experienced users of hearing aids. He used the TEN(SPL) test to diagnose dead regions. He also measured speech intelligibility using low-pass filtered word lists, while subjects listened through their own hearing aids, all of which provided substantial amplification at frequencies where there was hearing loss. To analyze his results, the ears tested were divided into those showing high-frequency dead regions with f_c in the range 0.75 to 1.5 kHz, and ears showing either no dead regions or dead regions with f_c at 3 kHz or above. Ears showing evidence of dead "holes" were excluded from the analysis.

For the subjects with no dead regions or dead regions starting at 3 kHz or above, performance tended to improve progressively with increasing low-pass filter cutoff frequency; the highest mean percent correct (86%) was achieved for the widest bandwidth. For the subjects with f_c in the range 0.75 to 1.5 kHz, the pattern was less consistent, but the mean scores showed no clear trend with increasing cutoff frequency above 1 kHz, and the mean score for the widest bandwidth was only 58%.

Overall, these results support the idea that subjects with extensive continuous high-frequency dead regions do not make as effective use of audible speech information at high frequencies as subjects without such dead regions. The subjects tested by Vestergaard⁴⁷ all had experience using hearing aids that provided substantial high-frequency amplification. This suggests that the failure of the subjects with extensive high-frequency dead regions to benefit from the audibility of high frequencies was not due to lack of experience in hearing those frequencies.

Preminger et al³⁹ investigated speech intelligibility and subjective hearing aid benefit using 49 experienced hearing aid users, with audiometric thresholds poorer than 50 dB HL for at least two frequencies and no audiometric thresholds poorer than 80 dB HL. They used the TEN(SPL) test to diagnose dead regions, but using a 15-dB masked-threshold criterion rather than the 10-dB criterion recommended by Moore et al.² They measured speech intelligibility using two versions of the Quick SIN (signal in noise) test (Etymotic Research, Elk Grove Village, Illinois), one of which had increased gain above 1 kHz, with about 20 dB and 30 dB of gain at 2 kHz and 3 kHz, respectively. Subjects with dead regions had poorer understanding of speech in noise than those without dead regions. However, both groups showed a benefit from increased high-frequency gain. It should be noted that the same frequency-gain characteristic was used for all participants, unlike the studies of Vickers et al⁸ and Baer et al,⁹ where the frequency-gain characteristic was tailored for each participant, based on their audiogram. The data of Preminger et al are not inconsistent with the idea that, for participants with extensive continuous dead regions, there is benefit from providing gain for frequencies up to about $1.7f_c$, but no benefit from providing gain at higher frequencies.

In some studies conducted more recently, dead regions were diagnosed using the TEN (SPL) test⁴⁸ or a modified version of the TEN (HL) test.^{49,50} The subjects tested in those studies mostly had less severe hearing loss than the subjects studied by Vickers et al,⁸ Baer et al,⁹ and Vestergaard.⁴⁷ Also, the subjects had restricted dead regions (holes) rather than extensive continuous dead regions. The results generally showed that subjects both with and without dead regions benefited from the application of gain at high frequencies.

Overall, the results suggest that, for adult subjects with continuous high-frequency dead regions with f_c at 1.5 kHz or below, there is benefit from amplification of frequencies up to about $1.7f_c$, but no benefit of amplifying higher frequencies. However, for subjects with dead holes, patchy high-frequency dead regions, or continuous dead regions with f_c at 2 kHz or above, amplification over the widest bandwidth possible may be most beneficial.

DIAGNOSIS OF DEAD REGIONS IN CHILDREN

Malicka et al.⁵¹ assessed whether it is possible to measure PTCs reliably for school-age children. They used a fast method, similar but not identical to the method of Sek and coworkers, as described earlier.^{31,32} Twelve normal-hearing children (7 to 10 years old) and five adults were tested. Fast PTCs were measured for 1- and 4-kHz signals. The center frequency of the narrowband noise masker either started below the signal frequency and was swept upward or started above the signal frequency and was swept downward. Both upward and downward sweeps were used for each subject and each signal frequency. The estimated tip frequency of the PTC tends to be above the signal frequency when the masker frequency sweeps upward and below the signal frequency when it

sweeps downward.^{31,51} Measurements were repeated on a separate day to assess test-retest variability.

All children were able to perform the task. Examples of some of the PTCs are shown in Fig. 1. Results are shown for upward frequency sweeps for signal frequencies of 1 kHz (top row) and 4 kHz (bottom row). The fast PTCs were smoothed by taking a two-point moving average of the masker levels at the turn points, and the smoothed PTCs were used to estimate the frequency at the tip. The frequency at the tip was well defined for only 87% of the fast PTCs; for the other cases the PTCs had a flat region around the tip or had two or more tips. The variability in the estimated tip frequency was higher for the children than for the adults, but the difference was not statistically significant. The absolute value of the difference

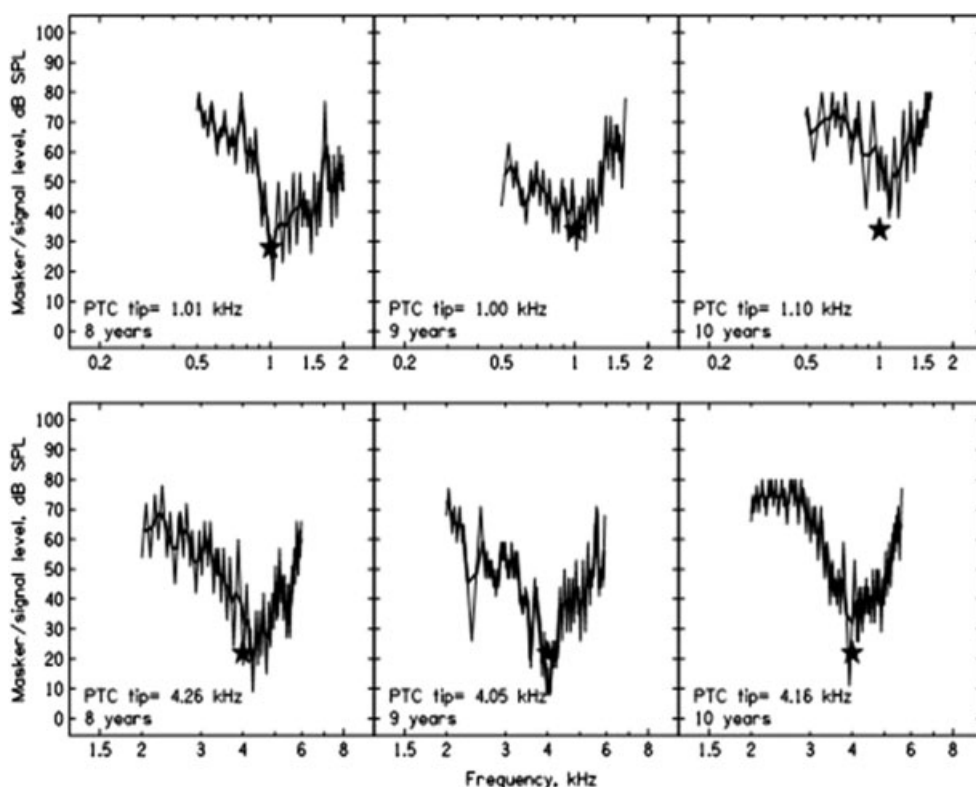


Figure 1 Examples of fast PTCs obtained from children with normal hearing. The age of the child is indicated in each panel. The top and bottom rows show results for signal frequencies of 1 and 4 kHz, respectively. The signal frequency and level for each PTC are indicated by the position of the filled star. The thin lines are the raw fast PTCs, and the thicker lines are two-point moving averages. The tip frequencies estimated from the moving averages are shown in each panel. The data are from Malicka et al.⁵¹ Abbreviations: PTC, psychophysical tuning curve; SPL, sound pressure level.

between the estimated tip frequencies for test and retest was about 14% at 1 kHz and 10% at 4 kHz. When the masker frequency was swept upward, the estimated tip frequency had a mean value that was shifted upward from the signal frequency by about 11% at 1 kHz and 8% at 4 kHz. When the masker frequency was swept downward, the estimated tip frequency had a mean value that was shifted downward from the signal frequency by about 8% at 1 kHz and 7% at 4 kHz.

There were only a few cases for children where the tip frequency was shifted down by more than 20% or up by more than 25%, relative to the signal frequency. These values can therefore be used as limits that can be expected for most children without dead regions. Shifts in the tip frequency outside this range can be taken as indicating the presence of a dead region at the signal frequency.

Malicka et al.²⁷ assessed the extent of correspondence between results from the TEN(HL) test and fast PTCs. They also assessed whether the TEN(HL)-test criteria for diagnosing a dead region should differ for children and adults. They tested eight normal-hearing children (16 ears) and 12 hearing-impaired children (21 ears), aged 7 to 13 years. For the normal-hearing children, masked thresholds in the TEN(HL) were measured for five TEN(HL) levels (30, 40, 50, 60, and 70 dB/ERB_N). For the hearing-impaired children, the level of the TEN was selected sepa-

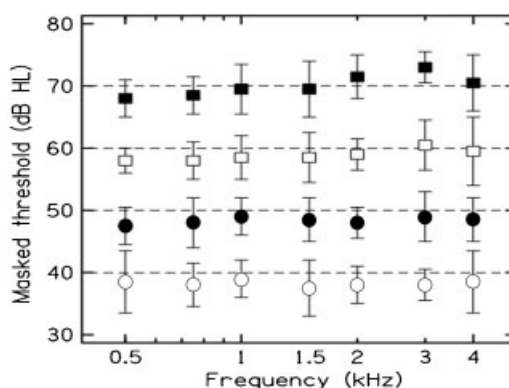


Figure 2 Mean TEN(HL) test results for normal-hearing children for TEN(HL) levels of 40, 50, 60, and 70 dB/ERB_N. The data are from Malicka et al.²⁷ Abbreviations: dB hearing level (HL); ERB_N, equivalent rectangular bandwidth of the auditory filter, as determined using young, normally hearing listeners; TEN(HL), threshold equalizing noise with a spectrum chosen to produce equal masked thresholds in dB HL.

rately for each ear based on the highest acceptable level minus 5 dB.

The mean TEN(HL)-test results for the normal-hearing children for TEN(HL) levels of 40, 50, 60 and 70 dB/ERB_N are shown in Fig. 2. The mean masked thresholds were usually slightly below the TEN level/ERB_N and were never more than 5 dB above it. The results resemble those found for adults.^{2,33,35}

All hearing-impaired children were able to perform the TEN test and fast PTCs. Examples of PTCs for two hearing-impaired children are

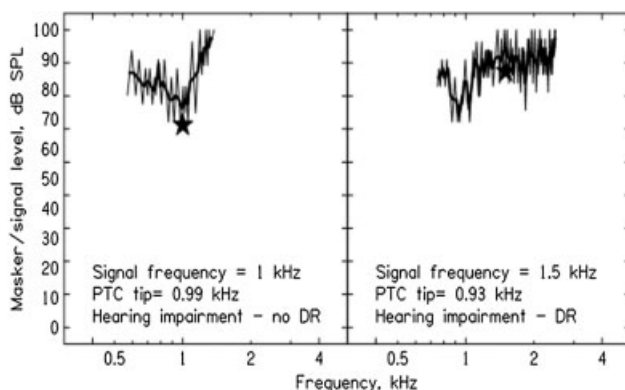


Figure 3 Examples of fast PTCs for two hearing-impaired children, one without a dead region at the signal frequency (left) and one with a dead region at the signal frequency (right). The thin lines are the raw fast PTCs, and the thicker lines are two-point moving averages. Abbreviations: DR, dead region; PTC, psychophysical tuning curve; SPL, sound pressure level.

shown in Fig. 3. For the case shown in the left panel, the tip frequency of the PTC (0.99 kHz) was close to the signal frequency (1 kHz) indicating that there was no dead region at the signal frequency. For the case shown in the right panel, the tip frequency of the PTC (0.93 kHz) was shifted well below the signal frequency (1.5 kHz) indicating that there was a dead region at the signal frequency.

Examples of the correspondence between the PTCs and the TEN(HL)-test results are shown in Fig. 4. Eight ears showed no dead region on the TEN(HL) test and no dead region using PTCs. An example is shown in the leftmost column of Fig. 4. The masked threshold in the TEN (open squares) was always less than 10 dB above the TEN level

of 60 dB/ERB_N. The PTCs, determined using signal frequencies (filled symbols) of 1, 2, and 4 kHz, all had tips (open symbols) close to the signal frequency.

Nine ears showed a dead region on the TEN(HL) test that was confirmed using PTCs. An example is shown in the second column of Fig. 4. The TEN-test criteria for a dead region were met for signal frequencies of 0.5, 0.75, and 1 kHz, as indicated by the area with diagonal shading. For signal frequencies of 1.5 kHz and above, the absolute threshold was too high for the TEN(HL) test to be performed (as indicated by the cross-hatched area), but it seems very likely that a dead region was present. The PTC determined using a signal frequency of 0.25 kHz (middle panel)

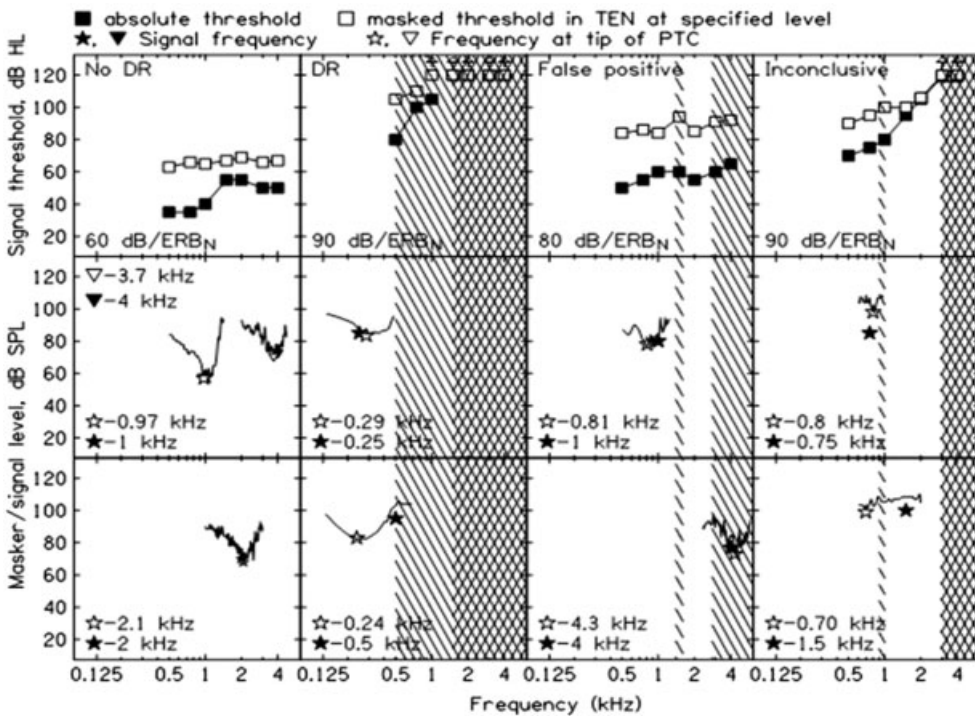


Figure 4 Examples of results from hearing-impaired children who were tested using the TEN(HL) test and fast PTCs. In each column, the top panel shows results for the TEN(HL) test. Filled squares show absolute thresholds and open squares show masked thresholds in the TEN(HL). The TEN(HL) level is indicated in each panel. Diagonally shaded areas indicate frequency regions where the TEN(HL) test results suggested the presence of a dead region. Cross-hatched areas indicate frequency regions where the absolute threshold was too high for the TEN(HL) test to be performed. The other panels show two-point moving averages of the fast PTCs. Solid symbols indicate the signal frequency, and open symbols indicate the estimated tip frequency of the PTC. The data are from Malicka et al.²⁷ Abbreviations: ERB_N, equivalent rectangular bandwidth of the auditory filter, as determined using young, normally hearing listeners; PTC, psychophysical tuning curves; SPL, sound pressure level; TEN(HL), threshold equalizing noise with a spectrum chosen to produce equal masked thresholds in dB HL.

did not show a clearly shifted tip, whereas the PTC determined using a signal frequency of 0.5 kHz (bottom panel) showed a downward-shifted tip.

Three ears showed a dead region on the TEN(HL) test that was not confirmed using PTCs; the PTCs did not show shifted tips when the signal frequency fell in a region identified as dead by the TEN(HL) test. An example is shown in the third column of Fig. 4. The findings for these three ears suggest that the TEN(HL) test can sometimes give false-positive results with children. This also sometimes occurs with adults.²

For one ear, the TEN(HL)-test results suggested a restricted dead region (hole) around 1 kHz, and probably a dead region above 3 kHz. However, at 3 kHz the absolute threshold was so high that the TEN(HL) did not raise the masked threshold above the absolute threshold, so the result must be regarded as inconclusive. These results are shown in the fourth column of Fig. 4. For a PTC measured with a signal frequency of 1.5 kHz (bottom panel in the fourth column of Fig. 4), the PTC was very "flat," but the tip did appear to be shifted downward to about 0.7 kHz. This result might indicate that even the frequency region between 1 and 3 kHz was dead. However, because the PTC is so flat, this result too must be regarded as inconclusive.

Overall, Malicka et al²⁷ concluded that dead regions usually can be detected reliably in children using the fast-PTC technique and the TEN(HL) test. The most appropriate criteria for diagnosing a dead region using the TEN(HL) test are those recommended for adults. For cases where the masked threshold in the TEN(HL) is 10 to 15 dB above the TEN level/ERB_N, the diagnosis of a dead region should be confirmed via measurement of fast PTCs, because false positives can occur when using the TEN(HL) test alone.

BENEFIT OF AMPLIFICATION AT HIGH FREQUENCIES FOR CHILDREN WITH DEAD REGIONS

Malicka et al⁵² investigated the benefit of high-frequency amplification for children with various degrees of high-frequency hearing loss,

with and without dead regions. Dead regions were diagnosed using both the TEN(HL) test and fast PTCs, as described by Malicka et al.²⁷ The children, aged 8 to 13 years, were divided into two groups according to the severity of their hearing loss. Group MS had moderate to severe loss (nine ears without dead regions and three ears with dead regions). For this group, the dead regions, when present, were restricted to the range 1.5 to 2 kHz. Group SP had severe to profound hearing loss (seven ears with high-frequency dead regions and one ear without a dead region). For this group, the dead regions, when present, were extensive and continuous, with estimated values of f_e between 0.75 and 1.5 kHz. The stimuli were vowel-consonant-vowel nonsense syllables. They were subjected to the frequency-gain characteristic prescribed by the Desired Sensation Level fitting method⁵³ for 65 dB SPL speech, and presented via headphones. The gains provided were similar to those used in the children's own hearing aids. However, the children were fitted with multi-channel compression hearing aids, whereas only linear amplification was used in the laboratory study.

The stimuli were either broadband or were low-pass filtered with various cutoff frequencies. For ears with a dead region, the cutoff frequencies were selected to cover the range from up to one octave below to well above the estimated value of f_e . For ears without a dead region, the cutoff frequencies were chosen to be in the range between 1 and 4 kHz, usually 1, 2, and 4 kHz and optionally 1.5 and 3 kHz. The number of conditions varied between four and six per ear.

The results for group MS are shown in Fig. 5. Consonant identification scores are plotted as a function of low-pass filter cutoff frequency. For all ears, the scores improved with increasing cutoff frequency up to ~ 4 kHz and tended to flatten above that frequency. There was a significant difference between scores for cutoff frequencies of 1 and 2 kHz, and 2 and 4 kHz, but there was no significant difference between scores for the cutoff frequency of 4 kHz and the broadband condition. Thus, benefit was obtained for amplification of frequencies up to 4 kHz, but not for higher frequencies.

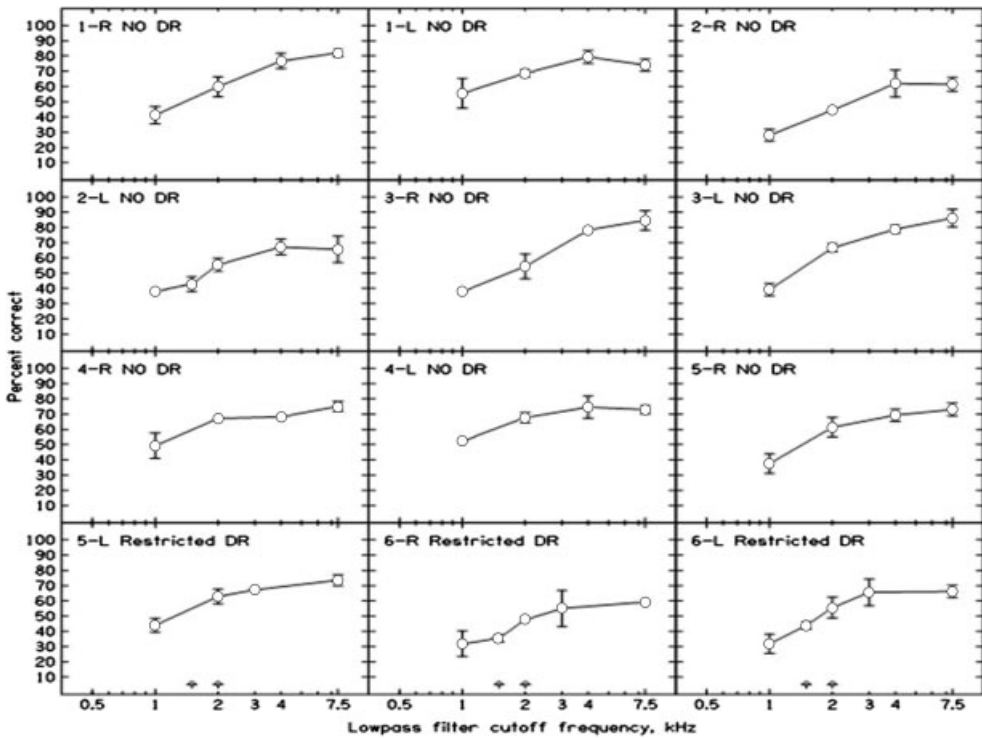


Figure 5 Consonant identification scores for individual subjects from group MS (group with moderate to severe loss), plotted as a function of low-pass filter cutoff frequency. Error bars represent \pm one standard deviation. The three upper rows show the results for the nine ears without dead regions, and the bottom row shows results for the three ears with restricted dead regions. The edges of the dead regions are indicated by the arrows close to the abscissa. The data are from Malicka et al.⁵² Abbreviation: DR, dead region.

The results for group SP are shown in Fig. 6. For the one ear without any dead region (7-L), performance was relatively poor, but it did improve with increasing cutoff frequency. Scores for the cutoff frequencies of 1, 2, and 4 kHz were 33, 39, and 42%, respectively. For the ears with dead regions, performance generally did not improve monotonically with increasing cutoff frequency. Mean scores for the ears with dead regions were 27, 31, and 30%, for the cutoff frequencies of 1, 2, and 4 kHz, respectively. There was no significant effect of cutoff frequency across these three values. Thus the results provide no evidence for a benefit of presenting high-frequency speech components. For two ears (7-R and 11-L) performance worsened somewhat when the cutoff frequency was increased above 2 kHz.

To assess whether the changes in speech score with cutoff frequency were related to the

values of $f_{\hat{e}}$, scores for speech low-pass filtered at $f_{\hat{e}}$ were compared with scores for speech that was low-pass filtered at one octave and two octaves above $f_{\hat{e}}$. The analysis was based on six ears (ear 8-L was excluded due to the large discrepancy between the frequency at the tip of the PTC, and the value of $f_{\hat{e}}$ estimated from the TEN(HL) test, leading to uncertainty as to the true $f_{\hat{e}}$). There was no significant effect of cutoff frequency. Thus, there was no benefit of amplified frequency components above $f_{\hat{e}}$.

Summers⁵⁴ has argued that the most appropriate amplification for subjects with a severe sloping hearing loss can be selected based on the audiogram, and that a test for diagnosing dead regions is not required. He proposed, following common clinical practice, that amplification should be provided only for frequencies where hearing thresholds were better than 90 dB HL. However, this rule would not work

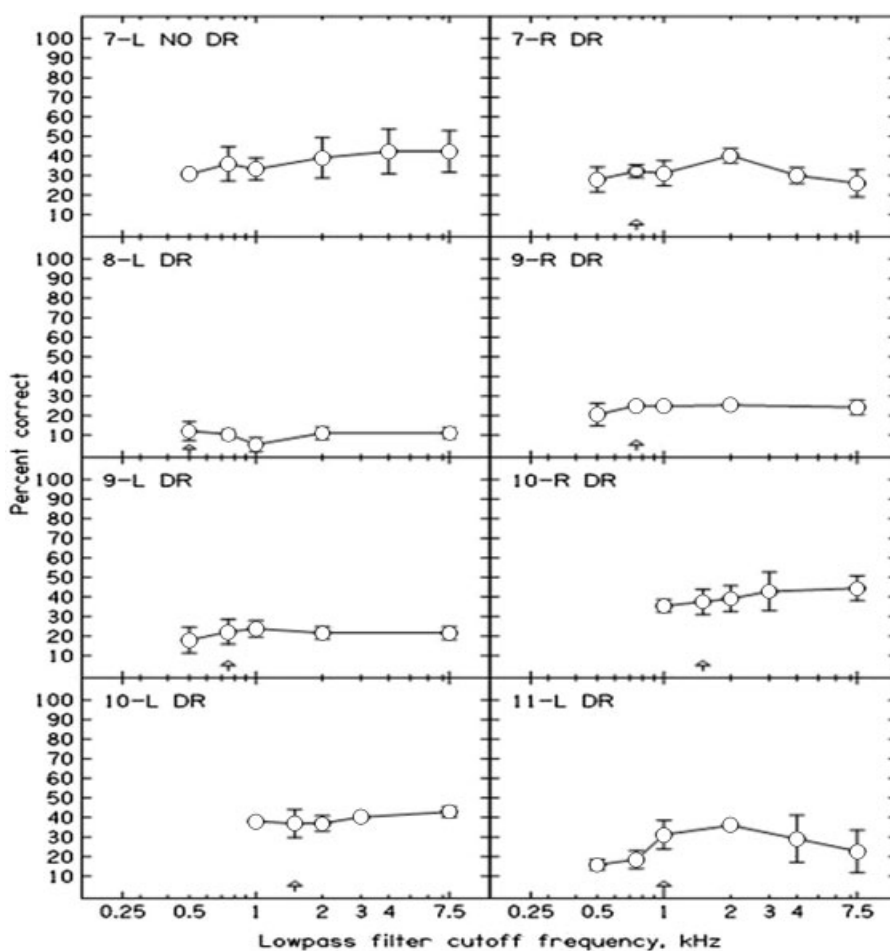


Figure 6 As Figure 4, but for group SP (with severe to profound loss). All ears except 7-L had extensive continuous dead regions with edge frequency at 1.5 kHz or below. The data are from Malicka et al.⁵² Abbreviation: DR, dead region.

well for all of the children studied by Malicka et al.⁵² For example, for ear 7-R (Fig. 6), Summer's rule would lead to no amplification for frequencies above 0.5 kHz, whereas 7-R actually showed a benefit of amplifying frequencies up to 2 kHz.

The speech intelligibility index (SII)⁵⁵ was used to assess the effectiveness with which the children made use of audible speech components. The SII represents the proportion of the speech spectrum that is audible for a given speech material (with a weighting function representing the relative importance of different frequencies). The SII is calculated from the spectrum of the speech signal and the subject's hearing thresholds. The SII has a value between

0 (none of the speech signal is audible) and 1 (the speech signal is fully audible). The SII includes "corrections" to account for the self-masking of speech and distortions that can occur at high listening levels. The SII values calculated by Malicka et al.⁵² were based on the actual gains used for each ear.

To convert SII values to predicted speech scores, a transfer function relating scores to the SII needs to be estimated. The transfer function was derived by fitting a linear regression line to the results for children with hearing impairment but without dead regions. This line is shown in both panels of Fig. 7. The symbols in Fig. 7 show the percentage of correct responses for speech plotted against the

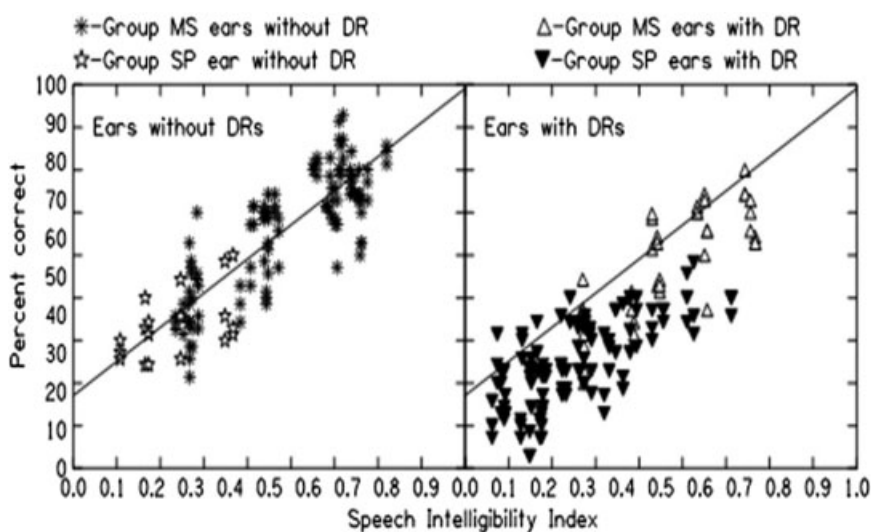


Figure 7 The symbols show percent correct scores for consonants plotted against the corresponding speech intelligibility index value. Each point represents one test condition and one ear. The left panel shows data for ears without dead regions (group MS, with moderate to profound loss asterisks; group SP, with severe to profound loss, open stars). The right panel shows data for ears with dead regions (group MS, open triangles; group SP, filled down-pointing triangles). The line in each panel is a linear regression line fitted to the data for all ears without dead regions. The data are from Malicka et al.⁵² Abbreviation: DR, dead region.

corresponding SII value. Each point represents one test condition and one ear. The left panel shows results for ears without dead regions (group MS—asterisks, group SP—open stars). The points are scattered roughly equally above and below the line, as expected. The scatter reflects individual differences in proficiency and random errors of measurement. It is noteworthy that the deviations of obtained scores from the line are similar for group MS and for the single participant in group SP who did not have a dead region.

The right panel of Fig. 7 shows the data for the ears with dead regions. Most of the points fall below the line, indicating that obtained speech scores were lower than predicted from the SII. This was especially the case for group SP, who had continuous rather than restricted dead regions. The deviations from the line are greatest for higher values of the SII, which correspond to cases where the cutoff frequency was relatively high. The results indicate that the children with dead regions made less efficient use of audible speech components than the children without dead regions.

CONCLUSIONS

The results obtained with children are broadly consistent with those obtained using adults. Children with moderate to severe hearing loss, without dead regions, or with restricted dead regions, showed a benefit from the provision of amplification for frequencies up to 4 kHz. However, there was no significant difference in scores for the broadband condition and the condition with low-pass filtering at 4 kHz. For children with severe to profound hearing loss, those with extensive continuous dead regions showed reduced benefit from high-frequency amplification, and there was little benefit, or even a degradation, when amplification was provided for frequencies above $2f_c$. The single participant in group SP who did not have any dead region showed a benefit from providing amplification for frequencies up to 2 to 4 kHz.

The results may have important clinical implications for fitting hearing aids to children with severe to profound hearing impairment and extensive dead regions ($f_c \leq 1.5$ kHz). The results suggest that it may be appropriate to

provide amplification only for frequencies up to about $2f_c$.

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