

# Dead Regions in the Cochlea at 4 kHz in Elderly Adults: Relation to Absolute Threshold, Steepness of Audiogram, and Pure-Tone Average

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## Abstract

The aims of this study were (1) to investigate the prevalence of dead regions (DRs) at 4 kHz in elderly people with hearing loss and (2) to determine the extent to which the presence/absence of a DR can be predicted from the absolute threshold, the slope of the audiogram, or the pure-tone average (PTA) hearing loss at 0.5, 1, and 2 kHz. DRs were assessed for 98 ears with absolute thresholds between 60 and 85 dB HL at 4 kHz using the threshold equalizing noise test. Thirty-six ears had a DR at 4 kHz. There was no statistically significant difference in the slope of the audiogram or PTA between ears with and without DRs. However, the mean absolute threshold at 4 kHz was significantly higher for the group with DRs than for the group without DRs. The prevalence of DRs exceeded 50% for hearing losses greater than 70 dB.

**Key Words:** Absolute threshold, audiogram, dead regions, elderly adults, TEN test

**Abbreviations:** BM = basilar membrane; DR = dead region; ERB = equivalent rectangular bandwidth; IHC = inner hair cell; OHC = outer hair cell; PTA = pure-tone average; PTC = psychophysical tuning curve; SNHL = sensorineural hearing loss; SNR(T) = signal-to-noise ratio at threshold; TEN = threshold-equalizing noise

## Sumario

Los propósitos de este estudio fueron (1) investigar la prevalencia de regiones muertas (DR) a 4 kHz en adultos mayores con hipoacusia y (2) determinar el grado en el que la presencia o ausencia de un DR puede predecirse a partir del umbral absoluto, de la pendiente del audiograma, o de la hipoacusia según el promedio tonal puro (PTA) a 0.5, 1 y 2 KHz. Las DR fueron evaluados en 98 oídos con umbrales absolutos entre 60 y 85 dB HL en 4 kHz, utilizando la prueba de ruido ecualizador del umbral. Treinta y seis oídos tenían un DR a 4 kHz. No existió diferencia estadísticamente significativa en la pendiente del audiograma o en el PTA entre los oídos con y sin DR. Sin embargo, el umbral absoluto medio a 4 kHz fue significativamente mayor en el grupo con DR que para el grupo sin DR. La prevalencia de DR fue mayor al 50% en hipoacusias mayores de 70 dB.

**Palabras Clave:** Umbral absoluto, audiograma, regiones muertas, adultos mayores, Prueba TEN

**Abreviaturas:** BM = membrana basilar; DR = región muerta; ERB = ancho de banda rectangular equivalente; IHC = células ciliadas internas; OHC = células ciliadas externas; PTA = promedio tonal puro; PTC = curva de afinamiento psicofisiológica; SNHL = pérdida auditiva sensorineural; SNR(T) = tasa señal/ruido en el umbral; TEN = ruido ecualizador de umbral

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Age-related hearing impairment is often associated with damage to the outer hair cells (OHCs) and inner hair cells (IHCs) in the cochlea, and to the neurons making up the auditory nerve (Schuknecht, 1993; Schuknecht and Gacek, 1993; Moore, 1998). In some cases, the IHCs and/or the associated neurons may be hardly functioning at all, leading to what has been called a dead region (DR). Moore defined a DR as “a region in the cochlea where IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening (i.e., the tone is detected at a place where the amount of basilar-membrane vibration is lower, but the IHCs and neurons are functioning more effectively)” (2004, p. 100). Such off-place listening can be identified using masking procedures, for example, psychophysical tuning curves (PTCs). APTC is measured using a signal that is fixed in frequency and usually presented at a level about 10 dB above the absolute threshold. The level of a narrowband masker required to mask the signal is determined as a function of the center frequency of the masker. When the tip of the PTC (the masker frequency at which the masker level at threshold is lowest) is shifted away from the signal frequency, this is taken to indicate a dead region at the signal frequency (Thornton and Abbas, 1980; Florentine and Houtsma, 1983; Turner et al, 1983; Moore and Alcántara, 2001; Kluk and Moore, 2005, 2006). Of course, it is possible to have regions of the cochlea where the IHCs are functioning poorly but are not completely nonfunctional. For example, they might function only at relatively high levels. However, the results of masking experiments suggest that if off-place listening occurs at levels just above the detection threshold, it also usually occurs at higher levels (Moore et al, 2000; Moore and Alcántara, 2001; Huss and Moore, 2003).

A clinical test for the identification of a DR was presented by Moore et al (2000); for this test, levels were calibrated in dB SPL. A revised version with levels calibrated in dB HL was described by Moore et al (2004). The test is based on the detection threshold of a pure tone in the presence of a spectrally shaped broadband noise, designed to produce almost equal masked thresholds (in dB HL or SPL depending on the test) over a wide frequency range for normally hearing listeners and for listeners with hearing

impairment but without DRs. This noise is called “threshold-equalizing noise” (TEN), and so the test is called the “TEN(SPL)” test or the “TEN(HL)” test, depending on how levels are calibrated. The nominal level of the noise is specified as the level in a one- $ERB_N$  (equivalent rectangular bandwidth)-wide band centered at 1 kHz, where “ $ERB_N$ ” stands for the equivalent rectangular bandwidth of the auditory filter as measured using the notched-noise method for young normally hearing listeners at moderate sound levels (Glasberg and Moore, 1990; Moore, 2003). The value of  $ERB_N$  at 1 kHz is 0.132 kHz, so the noise level is effectively specified as the level in a 0.132-kHz-wide band centered at 1 kHz. The “normal” masked threshold of a pure tone in the TEN is approximately equal to the nominal noise level. For example, a level per  $ERB_N$  of 50 dB leads to a masked threshold of about 50 dB SPL in the TEN(SPL) test and to a masked threshold of about 50 dB HL in the TEN(HL) test.

A signal with a frequency falling in a DR will be detected by neurons/IHCs just outside the DR, and these will have characteristic frequencies different from the signal frequency. Given that the basilar membrane (BM) has some degree of tuning even in a poorly functioning ear, the amplitude of BM vibration at the place where the tone is detected will be less than the peak amplitude in the DR. Therefore, a broadband noise will mask the tone much more effectively than would normally be the case, as the noise only has to mask the reduced response at the remote place. Thus, if the threshold for detecting a tone in the TEN is markedly higher than normal, this indicates a DR. Comparison of the results of the TEN test with measurements of PTCs in the same participants showed that, for signal frequencies where the PTCs had shifted tips, indicating a DR, the signal threshold in the TEN was usually 10 dB or more higher than normal. Therefore, it was proposed that a DR is present at the signal frequency if the threshold in the TEN is 10 dB or more above the nominal TEN level and the TEN produces at least 10 dB of masking (Moore et al, 2000; Moore, 2001, 2004; Huss and Moore, 2005). It should be noted that, when the signal frequency falls only just inside a DR, the 10 dB criterion may not be met (Moore, 2001). Therefore, the TEN test is not suitable for revealing very restricted DRs.

The TEN test has been used in several studies to assess the prevalence of DRs in adults and teenagers (Moore et al, 2000, 2003; Munro et al, 2005; Preminger et al, 2005; Markessis et al, 2006). Moore et al (2000) used the TEN(SPL) test with TDH-50 earphones to assess 20 ears of 14 subjects with moderate to severe sensorineural hearing loss (SNHL). TEN levels of 30, 50, and 70 dB/ERB<sub>N</sub> were used. A DR was assumed to be present at a specific frequency when the masked threshold was at least 10 dB above the absolute threshold and 10 dB above the TEN level/ERB<sub>N</sub>. Sixty-eight percent of their subjects met these criteria, suggesting that DRs are relatively common in people with moderate to severe SNHL. Comparison of the individual audiograms and the TEN-test results in their study suggested that (1) DRs at high frequencies are often associated with steeply sloping losses; (2) a high-frequency DR can be present even at a frequency where the absolute threshold indicates only mild-to-moderate hearing loss; and (3) hearing losses greater than 70 dB at high frequencies are often associated with a DR. However, there were some cases with absolute thresholds of 70–80 dB with no diagnosed DR.

Moore et al (2003) applied the TEN(SPL) test to teenagers with long-standing severe to profound SNHL. The subjects had a mean age of 14 years, and there were 13 females and 20 males. The stimuli derived from the TEN-test CD were routed via a GSI-16 audiometer and a power amplifier to Sennheiser HD580 earphones. A DR was assumed to be present at a specific frequency when the masked threshold was at least 10 dB above the absolute threshold and 10 dB above the TEN level/ERB<sub>N</sub>. For the majority of ears, the results were inconclusive at some frequencies due to the maximum output of the system being reached when measuring the absolute or masked threshold. However, for 70% of subjects the criteria were met at medium or high frequencies in at least one ear. The results suggested that DRs are relatively common among teenagers with a long-standing severe to profound SNHL.

Preminger et al (2005) studied the prevalence of DRs in 49 individuals (mean age = 62 years) for whom pure-tone absolute thresholds for at least two frequencies were above 50 dB HL and no thresholds were above 80 dB HL. They performed the

TEN(SPL) test using insert earphones. If at least one of the absolute thresholds was less than or equal to 60 dB SPL, then the TEN level was set to 70 dB SPL/ERB<sub>N</sub>. If all absolute thresholds were 60 dB SPL or higher, then the TEN level was set to the lowest threshold in quiet plus 10 dB. Ears for which the masked threshold was 15 dB above the absolute threshold and 15 dB above the TEN level were considered to have DRs at the test frequency. Twenty-nine percent of their subjects tested positive for DRs. The slope of the audiogram was found to be significantly higher for ears with high-frequency DRs (18.9 dB/octave) than for ears with no DR (11 dB/octave). However, there was a considerable overlap between the audiogram slopes for subjects with and without DRs, so the slope did not appear to be useful as a tool for predicting the presence or absence of a DR.

Markessis et al (2006) performed the TEN(SPL) test using TDH-50P headphones on 35 adults (40–89 years old) with moderate to severe SNHL. Their audiograms had a slope of more than 20 dB/octave over at least one octave from 1 to 8 kHz. The TEN-level was 80 dB SPL/ERB<sub>N</sub>. Ears with a masked threshold exceeding both the absolute threshold and the TEN level by 10 dB were considered to have DRs at the test frequency. Overall, 87% of the ears met the criteria for a DR for at least one test frequency. The proportion of ears meeting the TEN-test criteria was highest at 4 kHz, being 52% of 69 tested ears. Absolute thresholds at 4 kHz were between 65 and 90 dB HL. The reduced proportion of ears meeting the criteria at frequencies above 4 kHz can be attributed to the difficulty in making the TEN sufficiently intense at these high frequencies.

It is not clear from the published data how well the presence or absence of a DR at a specific frequency can be predicted from the absolute threshold at that frequency, the slope of the audiogram, or the pure-tone average (PTA) hearing threshold. The aims of the present study were: (1) to investigate the prevalence of DRs in hearing-impaired elderly adults (63 years and older); (2) to determine the extent to which the absolute threshold, slope of the audiogram, or PTA at 0.5, 1, and 2 kHz provide an indication of the presence/absence of a DR; and (3) to assess what proportion of subjects would be correctly classified in terms of the presence/absence of a DR based on the value of the absolute

threshold and to determine the optimum threshold criterion for classifying subjects in this way. We assessed the presence/absence of DRs only at 4 kHz. This was done since previous studies have shown a relatively high prevalence of DRs at this frequency (Preminger et al, 2005; Markessis et al, 2006), the effect of aging on hearing is largest at high frequencies (Davis, 1995), and 4 kHz is the highest frequency included in the TEN(HL) test.

## METHODS

### Subjects and Sample Size

Results are presented only for subjects with a sloping SNHL and an absolute threshold of 60–85 dB HL at 4 kHz; in preliminary tests, no DRs were found at 4 kHz when the absolute threshold was 60 dB HL or better. Given the method used to set the noise level (see below for details) and the output limitations of the audiometer, the TEN(HL) test could not be applied when the hearing loss was greater than 85 dB. Subjects with a conductive component to their hearing loss (as indicated by an air-bone gap of more than 10 dB) were not included. For subjects with more than a 35 dB difference in threshold between two ears, the worse ear was not included. People with Alzheimer's disease, learning difficulties, or mental retardation were excluded from the study. People with decreased tolerance to loud sounds were also usually excluded, since the TEN(HL) test requires relatively high sound levels when the hearing loss is moderate or severe at the test frequency.

One hundred forty-eight patients were seen in the period of October 2005 to January 2006. They were being considered for digital hearing aids at the Audiology Department (clinic B), Ealing Hospital, London. Eighty-seven of these met the inclusion criteria for this study. Sixty-three patients (98 ears) were included (aged 63–101 years), being chosen on the basis of availability of time, equipment, and staff in the clinic. The incidence of medical abnormalities among the patients was as follows: 33 had tinnitus, 35 had hypertension, 7 had diabetes, 14 had noise-induced hearing loss, 7 had a history of heart disease, and 18 had other medical problems. This study was performed in accordance with

the Helsinki declaration on medical ethics issues.

### Procedures

A case history was obtained, and otoscopy was performed for all subjects. Pure-tone thresholds were measured in a sound-attenuating room following the British Society of Audiology recommended procedure for pure-tone air- and bone-conduction audiometry with and without masking (British Society of Audiology, 2004), using an Aurical audiometer with Madsen HB7 (TDH 39P) headphones and Radioear B71 bone vibrator. Air-conduction thresholds were measured at 0.25, 0.5, 1, 2, 4, and 8 kHz. Bone-conduction thresholds were measured at 0.5, 1, 2, and 4 kHz. The TEN(HL) test was performed almost following the protocol described by Moore et al (2004). The test signal and TEN from the TEN(HL) CD were replayed from a CD player (Technics SL-PG3) connected to a Grason-Stadler GSI 61 audiometer equipped with TDH 50P headphones. The Aurical and GSI 61 audiometers were calibrated in November 2005. Prior to administering the TEN(HL) test, absolute thresholds at 4 kHz were measured using the test tone on the CD, to check that these were the same as measured using the audiometer.

For administering the TEN(HL) test, the TEN was played continuously. The TEN level per  $ERB_N$  in dB HL was initially set to be equal to the absolute threshold at 4 kHz and was then progressively increased so as to be 10 dB higher than the absolute threshold at 4 kHz. The subjects were told that they would hear a steady noise like wind or rain, which they should ignore, and that they should press the button only when they heard a tone, just as they did earlier in the audiometry test. The duration of the presented tone was varied between 1 and 2 seconds. The right ear was tested first for all of the subjects except the ones who were tested using the left ear only. Subjects were told not to move the headphone during the test and to inform the tester if the noise was uncomfortably loud. The level of the TEN was never more than 95 dB HL/ $ERB_N$ . The maximum level of the pure-tone signal was never more than 104 dB HL. Once it was established that the TEN level was acceptable, the signal tone was

presented. The initial level was equal to the absolute threshold, and the level was increased in 5 dB steps until a response occurred. After a response occurred, the level was decreased by 10 dB, and another ascending series with 5 dB steps was used until the subject responded again. After that, the level was decreased by 10 dB, and ascending steps of 2 dB were used, until the subject responded at the same level on two successive tone presentations. This level was taken as the masked threshold. For cases where the absolute threshold at 4 kHz was 85 dB HL, and the TEN level was set to 95 dB HL/ERB<sub>N</sub>, if there was no response at the maximum signal output level of 104 dB HL, it was assumed that the level at masked threshold was 105 dB or greater (thus meeting the criteria for diagnosis of a DR). The procedure was then repeated for the other ear. Both ears were tested on the same day, and the duration of the TEN(HL) test was about five minutes on average for both ears, although the whole assessment session lasted about 60 minutes.

Since the TEN level/ERB<sub>N</sub> was chosen to be 10 dB above the absolute threshold, for all cases except one the masked threshold was 10 dB or more above the absolute threshold. If the masked threshold of the 4 kHz signal was 10 dB or more above the TEN level, this was taken as indicating a DR at 4 kHz. If the masked threshold was not 10 dB or more above the TEN level, this was taken as indicating the absence of a DR. For the one case where the masked threshold was less than 10 dB above the absolute threshold, the signal level at the masked threshold was below the TEN level/ERB<sub>N</sub>, and the ear was classified as not having a DR. There were some subjects for whom one ear had a DR and the other did not.

## RESULTS

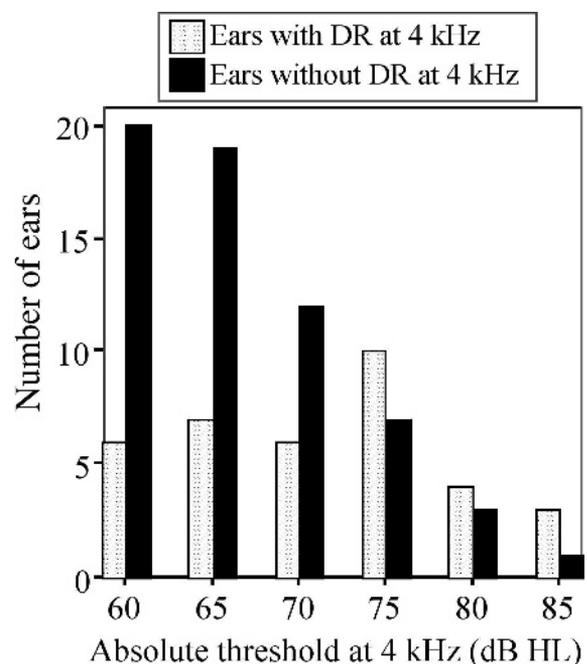
### Prevalence of DRs and Relationship to Age

Of 98 ears, 62 did not have a DR at 4 kHz, and 36 did have a DR. The mean age of the groups with and without DRs was 79.6 years (SD = 6.4) and 76.6 years (SD = 8.4), respectively. The difference in mean age was not statistically significant ( $t = 1.94$ ,  $df = 89.2$ ,  $p = 0.055$ ).

### Relationship of DRs to Absolute Thresholds

The mean absolute threshold at 4 kHz was 71.1 dB HL (SD = 7.7) for the ears with DRs and 66.5 dB HL (SD = 6.3) for the ears without DRs, and the difference in mean threshold was statistically significant ( $t = 3.19$ ,  $df = 96$ ,  $p < 0.002$ ). Thus, as expected from the studies described in the introduction, absolute thresholds at the test frequency of 4 kHz tend to be higher for ears with DRs at the test frequency than for ears without DRs.

Figure 1 shows the distribution of absolute thresholds at 4 kHz in ears with and without DRs at 4 kHz. Relative to the group without DRs, the group with DRs had a lower proportion of ears with absolute thresholds of 70 dB HL and below and a higher proportion of ears with absolute thresholds of 80 dB HL and above. However, it is noteworthy that 19 of the ears with DRs had absolute thresholds of 70 dB HL or lower, while 11 of the ears without DRs had absolute thresholds of 75 dB HL or higher. This indicates that the presence or absence of a DR cannot be determined precisely from the audiometric threshold at the test frequency.



**Figure 1.** The number of ears with each value of the absolute threshold at 4 kHz, for the 36 ears with DRs (white bars) and the 62 ears without DRs (black bars).

The presence/absence of a DR was not clearly related to the absolute threshold at frequencies below the test frequency of 4 kHz. The mean PTA (at 0.5, 1, and 2 kHz) for the group with DRs was 41.4 dB HL (SD = 12.6) and that for the group without DRs was 39.2 dB HL (SD = 14.6); this difference was not statistically significant ( $t = 0.75$ ,  $df = 96$ ,  $p = 0.45$ ).

**Relation of the Signal-to-Masker Ratio at Threshold with DRs**

The diagnosis of DRs using the TEN(HL) test is based on the signal-to-noise ratio at threshold (i.e., the signal level at threshold in dB HL minus the noise level/ERB<sub>N</sub> in dB HL), which is denoted here SNR(T). The value of SNR(T) was 12.7 dB (SD = 2.3) for the ears with DRs and 5.6 dB (SD = 2.5) for the ears without DRs. This difference was statistically significant, as expected ( $t = 14.07$ ,  $df = 96$ ,  $p < 0.001$ ), but is largely a consequence of the fact that the value of SNR(T) was used to decide whether or not a DR was present.

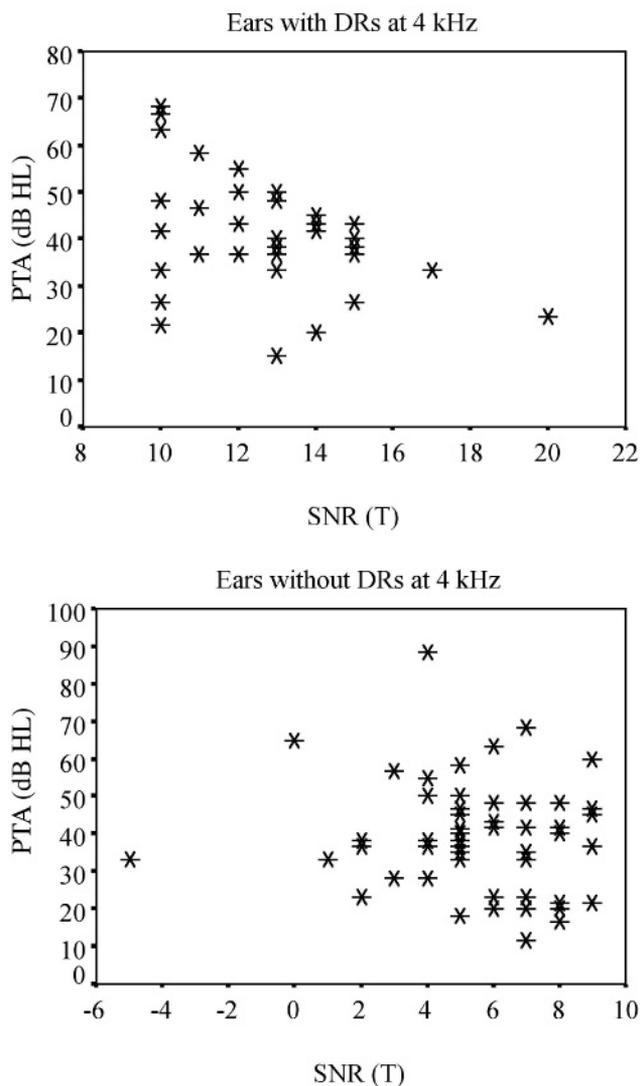
There was no statistically significant correlation between the value of SNR(T) and absolute threshold at 4 kHz either for the group with DRs ( $r = -0.22$ ,  $p = 0.20$ ), or for the group without DRs ( $r = -0.002$ ,  $p = 0.99$ ). However, as shown in Figure 2, there was a statistically significant (but relatively weak) negative correlation between SNR(T) and the PTA for ears with DRs ( $r = -0.43$ ,  $p = 0.009$ ). In other words, poor performance in the TEN test at 4 kHz was associated with better absolute thresholds at low frequencies. We discuss later why this might be the case. In contrast, there was no significant correlation between those quantities for ears without DRs ( $r = -0.17$ ,  $p = 0.19$ ).

**Relation of DRs to Audiometric Slope**

The slope of the audiogram over the frequency region below 4 kHz was estimated as the difference in audiometric threshold between 2 and 4 kHz. The mean difference was 17.5 dB (SD = 9.2) for the ears with DRs and 17.1 dB (SD = 12.3) for the ears without DRs. The difference was not statistically significant ( $t = 0.17$ ,  $df = 90.19$ ,  $p = 0.87$ ). The slope of the audiogram over the frequency

region above 4 kHz was estimated as the difference in audiometric threshold between 4 and 8 kHz. The mean difference was 13.2 dB (SD = 14.0) for the ears with DRs and 11.5 dB (SD = 12.7) for the ears without DRs. Again, the difference was not statistically significant ( $t = 0.62$ ,  $df = 96$ ,  $p = 0.53$ ).

The value of SNR(T) was not significantly correlated with the audiogram slope between 2 and 4 kHz, for either group (for ears with DRs,  $r = 0.065$ ,  $p = 0.71$ ; for ears without DRs,  $r = 0.154$ ,  $p = 0.23$ ). Similarly, the value of SNR(T) was not significantly correlated with the audiogram slope between 4 and 8 kHz, for either group (for ears with DRs,  $r = 0.006$ ,  $p = 0.97$ ; for ears without DRs,  $r = -0.103$ ,  $p = 0.43$ ).



**Figure 2.** Scatterplots of the PTA (0.5, 1, and 2 kHz) as a function of SNR(T) for the 36 ears with DRs (top panel) and the 62 ears without DRs (bottom panel).

### PREDICTING THE PRESENCE/ ABSENCE OF DRs FROM THE AUDIOMETRIC THRESHOLD

In this section, we consider the extent to which the presence/absence of a DR can be predicted from the absolute threshold at the test frequency. For instance, if we choose an absolute threshold of 65 dB HL or higher as indicating a DR, without performing the TEN test, what proportion of cases will be correctly classified? This was determined by assessing the sensitivity and specificity obtained using several different criterion values of the absolute threshold, with the results of the TEN(HL) test as the “gold standard” for diagnosis. Sensitivity refers to the proportion of ears with DRs that are diagnosed correctly based on the absolute threshold (having an absolute threshold above the criterion value). Specificity refers to the proportion of ears without DRs that are diagnosed correctly based on the absolute threshold (having an absolute threshold below the criterion value). Given the significant correlation found between SNR(T) and PTA for the group with DRs, we also considered whether the optimum criterion would depend on the PTA.

#### Classification Based on Absolute Threshold at 4 kHz

Absolute threshold criteria of 60, 65, 70, 75, 80, and 85 dB HL were used. The

sensitivity, specificity, and overall percent correct values are given in Table 1. As expected, the sensitivity decreases progressively as the criterion hearing loss increases, while the specificity increases progressively. The criterion leading to the highest overall percent correct is 75 dB HL. However, with this criterion, only 47% of ears with DRs would correctly be diagnosed as having DRs, while 18% of ears without DRs would be incorrectly diagnosed as having DRs. Thus, accurate diagnosis of DRs cannot be achieved using only the audiometric threshold at the test frequency. However, if the TEN(HL) test were conducted for all ears with an absolute threshold of 60 dB HL or higher, then no ears with DRs would be missed.

#### Classification Based on the Absolute Threshold Combined with the PTA

To assess whether the optimum criterion hearing loss for predicting the presence/absence of a DR depended on the PTA, subjects were divided into four groups, based on four ranges of the PTA. These are denoted C0 (PTA = 15–25 dB HL), C1 (PTA = 26–40 dB HL), C2 (PTA = 41–55 dB HL), and C3 (PTA > 56 dB HL). For each group, we carried out an analysis similar to that described above. The results are shown in Table 2. The number of subjects in each group with absolute thresholds exceeding 75 dB

**Table 1. Sensitivity and Specificity of the Diagnosis of the Presence/Absence of a DR at 4 kHz, Based on Different Criterion Values of the Absolute Threshold at 4 kHz**

Absolute threshold criterion, dB HL	60	65	70	75	80	85
Sensitivity (%)	100	83	63	47	19	8
Specificity (%)	0	32	62	82	93	98
Overall % correct	50	51	63	69	66	65

**Table 2. As Table 1, but with Subjects Divided into Groups according to the PTA at 0.5, 1, and 2 kHz**

PTA group	Absolute threshold criterion, dB HL	60	65	70	75
C0 (19)	Sensitivity (%)	100	75	50	*
	Specificity (%)	0	46	66	*
	Overall % correct	21	53	63	*
C1 (33)	Sensitivity (%)	100	92	64	42
	Specificity (%)	0	42	73	94
	Overall % correct	42	63	70	72
C2 (33)	Sensitivity (%)	100	69	61	46
	Specificity (%)	0	25	70	80
	Overall % correct	39	42	70	67

Note: Asterisks indicate that there were too few subjects for meaningful values to be calculated.

HL at 4 kHz was too small to allow meaningful calculations, so results are presented only for criterion values up to 75 dB HL. Similarly, the number of subjects in group C3 was small, so results for this group are not shown.

The overall percent correct of classifications is never higher than 70% for any PTA group. There is no combination of PTA group and threshold criterion at 4 kHz that leads to both high sensitivity and high specificity. The “optimum” criterion does not vary markedly with PTA group. These results show that the presence or absence of a DR cannot be diagnosed reliably from the audiogram. No matter what audiometric threshold criterion is chosen, it is impossible to get both high sensitivity and high specificity. This means that an additional test, like the TEN test, needs to be conducted to assess whether or not a DR is present. This conclusion is consistent with the findings of Halpin et al (1994); they showed that patients with and without DRs could have very similar audiograms.

If a clinician is attempting to decide whether a DR is present based on the audiogram alone, then, for the 4 kHz signal frequency used here, a threshold criterion of 70 dB HL might be the best choice. For all subjects combined, this criterion led to sensitivity and specificity that were both over 60%. The same was true for the groups C1 and C2, selected according to the PTA. However, for group C0, the group with the lowest (best) PTA, this criterion would lead to a sensitivity of only about 50%.

## DISCUSSION

### Comparison to Earlier Studies

The prevalence of DRs at 4 kHz in elderly adults with absolute thresholds of 60–85 dB HL was relatively high (37% of 98 ears), and the mean age did not differ significantly for subjects with and without DRs. Preminger et al (2005) studied a similar population and found that 29% of 49 individuals had DRs in the cochlea at one of the frequencies tested. They found no association between gender/age and the presence/absence of DRs. The slightly lower prevalence found by Preminger et al may be related to the fact that, when interpreting the results of the TEN test, they used a stricter criterion than

the one used here; for them, a positive diagnosis of a DR required that SNR(T) was 15 dB and that the masked threshold was at least 15 dB above the absolute threshold.

Markessis et al (2006) tested adults with absolute thresholds between 65 and 90 dB HL at 4 kHz, and an audiogram slope of more than 20 dB/octave. They found that 52% of 69 ears had DRs. The higher prevalence found by them may be associated with the greater hearing losses of some of their subjects, and/or with the steeper audiograms of their subjects; the mean audiogram slope of our subjects was less than 20 dB/octave. See below for further discussion of the effect of audiogram slope.

### Dead Regions and Audiogram Configuration

It has been suggested that hearing losses at high frequencies less than 50–60 dB might result from loss of OHC function alone, whereas losses greater than 50–60 dB will usually involve some loss of function of IHCs (Moore and Glasberg, 1997, 2004; Huss and Moore, 2003). It appears that damage to IHCs needs to be rather severe before it produces an appreciable elevation in absolute thresholds (Schuknecht, 1993; Schuknecht and Gacek, 1993). Therefore, one might expect that the prevalence of DRs would increase as the hearing loss increases above about 60 dB. Our results are consistent with this expectation. The percentage of ears with DRs was 23, 27, 33, 59, 57, and 75 for hearing losses of 60, 65, 70, 75, 80, and 85 dB, respectively.

Moore (2004) suggested that a steeply sloping hearing loss (slope of 50 dB/octave or more) may be indicative of a high-frequency DR. Preminger et al (2005) suggested that an audiogram slope steeper than 19 dB/octave is associated with an increased probability of a DR, and Markessis et al (2006) showed that 87% of subjects with an audiogram slope of more than 20 dB/octave met the criteria for a DR. In the present study no subjects had an audiogram slope of more than 50 dB/octave; the mean slope of the audiograms was about 17 dB/octave between 2 and 4 kHz and about 12 dB/octave between 4 and 8 kHz. There was no statistically significant difference in the slope of the audiogram below or above 4 kHz between ears with and without DRs at 4 kHz. Our results suggest

that the presence/absence of a DR cannot be predicted reliably from the slope of the audiogram when the audiogram slope is less than 20 dB/octave, although previous work suggests that a slope greater than 20 dB/octave may be indicative of a DR.

### Values of SNR(T)

For listeners with cochlear impairment, but without any DR at the signal frequency, masked thresholds in broadband noise are typically only 2–3 dB higher than for normally hearing listeners (Glasberg and Moore, 1986). However, in our study, the values of SNR(T) for ears without DRs ranged from -5 up to +9 dB. The high values found for some of the subjects may reflect relatively poor “detection efficiency” (Patterson and Moore, 1986), since detection efficiency tends to worsen with increasing age (Patterson et al, 1982; Peters and Moore, 1992).

For ears with DRs, the value of SNR(T) depends on several factors, including

(1) How far inside the DR the signal frequency is; the further inside, the greater the threshold elevation.

(2) The residual frequency selectivity of BM vibration. If the tuning is very broad (large spread), then the threshold elevation will be relatively small.

(3) The functional status of the IHCs at the place in the cochlea where the signal is detected (Moore, 2004). The worse this status, the greater the threshold elevation.

As shown in Figure 2, there was a statistically significant negative correlation between SNR(T) and PTA for ears with DRs at 4 kHz. Although the correlation between PTA and SNR(T) was relatively weak, it remained significant if the right-most two data points in the top panel of Figure 2 were excluded from the computation ( $r = -0.345$ ,  $p < 0.05$ ), indicating that the correlation is not the result of a few outliers. The direction of the correlation means that high values of SNR(T) at 4 kHz are associated with low (good) mean absolute thresholds at 0.5, 1, and 2 kHz. This might be explained in terms of factor 2 above. Low PTA values might be associated with sharp tuning on the BM, and this could lead to high values of SNR(T). On the other hand, the correlation might have happened because, for people with more severe hearing loss, the masked threshold

was sometimes too high to be measured. For example, if a person had a hearing loss at 4 kHz of 80 dB, the TEN level/ERB<sub>N</sub> would be 90 dB HL. If the masked threshold was above 104 dB, this would give a positive diagnosis of a DR, and SNR(T) would be recorded as 14 or 15 dB. This value of SNR(T) would be an underestimate of the true value of SNR(T). This could account for why there were not many high values of SNR(T) when the PTA was large.

The data in Figure 2 illustrate a problem with the TEN test. Of the 36 ears diagnosed as having DRs, eleven (31%) only just met the criteria, having values of SNR(T) of 10 or 11 dB. Of the 62 subjects diagnosed as not having DRs, 11 (18%) just failed to meet the criteria, having values of SNR(T) of 8 or 9 dB. Given the errors associated with the measurement of the masked thresholds, and the fact that “detection efficiency” (Patterson and Moore, 1986) is likely to vary across subjects, a considerable number of ears have SNR(T) values falling in a range where the diagnosis must be considered somewhat uncertain. In such cases, it would be desirable to repeat the TEN test, or, preferably, to administer a test that does not depend on detection efficiency. For example, the measurement of PTCs could be used; as noted earlier, shifted tips of the PTCs are taken as an indication of a DR at the signal frequency (Thornton and Abbas, 1980; Florentine and Houtsma, 1983; Turner et al, 1983; Moore and Alcántara, 2001; Kluk and Moore, 2005; Kluk and Moore, 2006). Although PTCs can be time-consuming to measure, a “fast” method for measuring PTCs has been described (Sek et al, 2005; Kluk and Moore, 2006), and this method could be used in clinical situations.

## CONCLUSIONS

Of 98 elderly subjects with absolute thresholds between 60 and 85 dB at 4 kHz, 36 (37%) met the criteria for a DR at 4 kHz using the TEN(HL) test. The prevalence of DRs at 4 kHz increased with increasing hearing loss at 4 kHz and exceeded 50% for hearing losses greater than 70 dB. The presence/absence of a DR was not associated with the slope of the audiogram in the frequency region below or above 4 kHz, and was also not associated with the PTA for frequencies of 0.5, 1, and 2 kHz. It is not

possible to predict the presence/absence of a DR reliably from the audiometric threshold at the signal frequency. However, the assumption that a DR is present when the absolute threshold at 4 kHz exceeds 70 dB leads to a sensitivity of 62% and a specificity of 63%.

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