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Ten(HL)-test results and psychophysical tuning curves for subjects with auditory neuropathy

Resultados de la prueba TEN(HL) y de las curvas psicofísicas de entonación en sujetos con neuropatía auditiva

Abstract
Auditory neuropathy is a hearing disorder characterized by abnormal or absent auditory brainstem responses, and the presence of otoacoustic emissions and/or cochlear microphonics, indicating normal functioning of the outer hair cells. Here, subjects with auditory neuropathy, with near-normal hearing to moderate hearing loss, were tested using the TEN(HL) test for diagnosis of dead regions and also using psychophysical tuning curves (PTCs). Results for the majority of subjects met the TEN(HL)-test criteria at one or more frequencies (often at several or all frequencies). However, the PTCs did not show shifted tips. Hence, the positive results of the TEN(HL) test should not be interpreted as indicating the presence of dead regions. Rather, it appears that high thresholds in noise are caused by poor processing efficiency, perhaps associated with loss of neural synchrony.

Sumario
La neuropatía auditiva es un problema caracterizado por la ausencia de respuestas auditivas de tallo cerebral y la presencia de emisiones otoacústicas y/o microfónica coclear, que indican funcionamiento normal de las células ciliadas externas. Se estudiaron en este trabajo sujetos con neuropatía auditiva y con audición entre casi normal o con pérdida moderada, usando la prueba TEN(HL) para el diagnóstico de zonas muertas y usando también las curvas psicofísicas de entonación. (PTC). Los resultados en la mayoría de los sujetos alcanzaron los criterios de la prueba TEN(HL) en una o más frecuencias (frecuentemente en algunas o en todas ellas). No obstante, las PTC no mostraron variaciones en sus extremos. Por lo tanto, los resultados positivos con la prueba TEN(HL) no deben ser interpretados como indicativos de la presencia de áreas muertas. Más bien, parece que los altos umbrales en medio de ruido son causados por una eficiencia pobre en el procesamiento, quizás asociada a la pérdida de la sincronización neural.

Auditory neuropathy is a disorder characterized by abnormal or absent auditory brainstem responses (ABRs) and the presence of otoacoustic emissions (OAEs) and/or cochlear microphonics (CMs), indicating normal functioning of the outer hair cells (OHCs) (Starr et al, 1991, 1996; Berlin et al, 2003). Audiometric thresholds may vary over a wide range in people with auditory neuropathy, from normal to profound hearing loss. In subjects with auditory neuropathy, hearing can remain stable, show fluctuations (as in cases of temperature sensitivity or autoimmune disorders), or progressively worsen.

The underlying cause of auditory neuropathy remains unclear. Indeed, there may be multiple underlying causes (Rance, 2005). One possibility is that some abnormality in the synapse between primary neurons and inner hair cells (IHCs) leads to a large temporal 'jitter' in spike initiation, so that nerve spikes are no longer phase locked to the stimulating waveform (Berlin et al, 2003; Zeng et al, 2005). This could lead to the absence of ABRs, since these depend on neural responses being synchronized across neurons and phase locked to the stimulus. A second possibility is that there is loss of function of IHCs and/or auditory neurons, so that fewer, or no spikes are evoked in the auditory nerve. This could also lead to the absence of ABRs. Such a possibility is not inconsistent with the fact that some people with auditory neuropathy have near-normal audiometric thresholds, since only a few functioning IHCs and neurons are needed to allow near-normal thresholds for the detection of sounds (Schuknecht, 1993). It is possible that the IHCs and/or neurons are completely non-functional over one or more regions in the cochlea, giving what are called 'dead regions' (Moore et al, 2000; Moore, 2001, 2004). Auditory neuropathy might be associated with 'patchy' dead regions over a large part of the cochlea (Moore et al, 2003; Moore, 2004).

One way of diagnosing dead regions is by the use of psychophysical tuning curves (PTCs) (Chistovich, 1957; Small, 1959). These are measured using a sinusoidal signal which is fixed in frequency and in level, usually at a level just above the absolute threshold, say, 10 dB sensation level (SL). The masker can be either a sinusoid or a narrow band of noise, although a noise is preferable to reduce the influence of beat detection (Egan & Hake, 1950; Kluk & Moore, 2004, 2005). For each of several masker center frequencies, the level of the masker needed just to mask the signal is determined. For normally hearing subjects, or hearing-impaired subjects without dead regions, the tip of the PTC (i.e. the frequency at which the masker level is lowest) lies close to the signal frequency. In other words, the masker is most effective when its frequency is close to that of the signal. However, for subjects with dead regions, PTCs can have tips which are shifted away from the signal frequency (Thornton

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& Abbas, 1980; Florentine & Houtsma, 1983; Turner et al, 1983; Moore et al, 2000; Moore & Alcántara, 2001; Huss & Moore, 2003; Summers et al, 2003; Kluk & Moore, 2005, 2006). This happens when the signal frequency falls in a dead region. The masker frequency at the tip of the PTC is assumed to reflect the boundary of the dead region.

PTCs are time-consuming to measure. Although a 'fast' procedure for measuring PTCs has been developed (Sek et al, 2005; Kluk & Moore, 2006), this is not yet available for use in clinical practice. A simpler and faster test, designed for use in clinical practice, involves the measurement of detection thresholds for sinusoidal tones in a special background noise, called threshold-equalizing noise (TEN) (Moore et al, 2000; Moore et al, 2004). In the original version of the test, called the TEN(SPL) test (Moore et al, 2000), the noise was designed to produce equal masked thresholds in dB SPL over a wide frequency range, for subjects with normal hearing. In the more recent version of the test, called the TEN(HL) test (Moore et al, 2004), the noise was designed to produce equal masked thresholds in dB HL over the frequency range from 500 to 4000 Hz, again for subjects with normal hearing. The TEN level is specified as the level in a one-ERB_N (132 Hz) wide band centered at 1000 Hz, where ERB_N stands for the equivalent rectangular bandwidth of the auditory filter as determined for young normally hearing listeners at moderate sound levels; see Glasberg and Moore (1990) and Moore (2003). For normally hearing listeners, the signal level at masked threshold is approximately equal to the noise level/ERB_N, specified in dB SPL for the TEN(SPL) test and in dB HL for the TEN(HL) test.

For a hearing-impaired listener, when there are well functioning IHCs and neurons corresponding to a frequency region with elevated absolute thresholds, a signal in that frequency region is detected via IHCs/neurons with characteristic frequencies (CFs) close to the frequency of the signal. In such a case, the threshold in the TEN is usually 2–5 dB higher than normal (Glasberg & Moore, 1986; Moore et al, 2000; Tyler, 1986). When a dead region is present, a signal falling in that region is detected via IHCs/neurons with CFs different from that of the signal frequency; in other words, off-place listening occurs. In such a case, the signal threshold in the TEN is expected to be markedly higher than normal. If the threshold in the TEN is 10 dB or more above the TEN level/ERB_N, and the TEN produces at least 10 dB of masking, this is taken as indicating a dead region at the signal frequency (Moore et al, 2000, 2004). These are referred to as the TEN-test criteria.

We are not aware of any study systematically applying the TEN test to people diagnosed as having auditory neuropathy. However, there have been several studies that have examined the thresholds of people with auditory neuropathy for detecting tones in noise (Rance, 2005; Zeng et al, 2001, 2005). The results have shown that thresholds are sometimes close to normal, but are often markedly higher than normal. Zeng et al (2005) found that subjects with auditory neuropathy could have thresholds that were 20–30 dB higher than 'normal'. They also reported that performance was not markedly impaired for tasks that probably did not depend on neural synchrony (phase locking), for example, intensity discrimination, frequency discrimination at high frequencies, and sound localization using interaural level differences. In contrast, they found markedly impaired performance for tasks that probably depend on neural synchrony, such as frequency discrimination at low frequencies, binaural beat detection, and sound localization using interaural time differences.

The abnormally high thresholds of people with neuropathy for detecting tones in noise might be indicative of dead regions. However, they might also indicate poor 'processing efficiency' (Patterson & Moore, 1986), perhaps associated with the loss of neural synchrony (Moore, 1975). Moore (2004) pointed out that caution should be used when the results of the TEN test reveal higher-than-normal masked thresholds for all or most test frequencies; the results in such cases might indicate poor processing efficiency or a central disorder (Langenbeck, 1965), rather than the presence of extensive dead regions.

In the present study we applied the TEN(HL) test to people diagnosed with auditory neuropathy and we measured PTCs in the same subjects. The PTCs were used as the 'gold standard' for deciding whether there was a dead region at any specific signal frequency. The results were intended to allow us to determine whether TEN-test results are abnormal in people with auditory neuropathy, and, if so, whether this indicates the presence of dead regions or is instead indicative of a problem with processing efficiency. We also assessed speech recognition in quiet.

Method

Subjects

Eight subjects diagnosed with auditory neuropathy were tested. All diagnostic testing was conducted at the All India Institute of Speech and Hearing. None of the subjects had non-auditory neural conditions. Their ages ranged from 14 to 37 years; see Table 1 for details. All except S5 were female. Three subjects, S3, S4 and S7, were tested using one ear only. For the other subjects, each ear was tested separately. All subjects had normal middle ear transmission, as assessed using a GSI-33 immittance meter. Both ipsilateral and contralateral acoustic reflexes were absent in both ears for all subjects, consistent with previous work on subjects with auditory neuropathy (Berlin et al, 2003, 2005). The diagnosis of auditory neuropathy was based on the following tests:

1. Outer hair cell functioning was assessed, based on the presence of transient evoked otoacoustic emissions (TEOAEs), measured using an ILO 292 Otodynamics analyser. The emissions were recorded using 240 presentations of click stimuli at 70 dB SPL. TEOAEs were considered to be present when the emissions were 6 dB above the noise floor. TEOAEs were present for all of the subjects whose results are reported here.
2. Auditory brainstem responses (ABRs) were measured using the IaBASE II Version 4.08 EP 15 evoked potential instrument. The ABRs were measured at a stimulus level of 90 dB nHL using alternating polarity clicks with repetition rates of 11.1/s and 90.1/s. Subjects were tested several times at each rate. The presence of a detectable peak in the ABRs and replicability of the waveforms at one or both the repetition rates was considered as indicating the presence of ABRs. Failure to achieve a detectable peak or lack of replicability at both rates was considered as indicating absent ABRs. ABRs were absent for all of the subjects whose results are reported here.

Table 1. The left column shows the subject number, the ear, and the TEN level used. The second and third columns show the age and sex of each subject, respectively. The upper entry in columns 4–12 indicates the audiometric threshold in dB HL. The lower entry in columns 5–11 indicates threshold in the TEN, in dB HL. Asterisks indicate cases where the TEN(HL)-test criteria were met. NR means 'no response', i.e. the signal was not detected. SRS indicates speech recognition score.

			Frequency, kHz									
Subject/Ear TEN level	*Age*	*Sex*	*0.25*	*0.5*	*0.75*	*1*	*1.5*	*2*	*3*	*4*	*8*	*SRS (%)*
S1 RE	37	F	45	55	45	35	30	15	20	15	10	65
70 dB/ERB$_N$				76	74	70	72	70	70	70		
S1 LE			65	50	40	35	40	45	35	35	50	65
70 dB/ERB$_N$				78	80*	76	74	72	70	70		
S2 RE	28	F	60	20	30	40	25	20	25	30	15	70
70 dB/ERB$_N$				70	70	72	70	70	70	70		
S2 LE			70	60	50	45	45	25	40	40	30	25
70 dB/ERB$_N$				86*	74	78	74	70	72	74		
S3 RE	14	F	75	65	70	65	65	55	45	30	70	0
70 dB/ERB$_N$				90*	84*	78	80*	80*	76	70		
S4 RE	25	F	50	40	35	30	25	25	20	15	0	55
50 dB/ERB$_N$				90*	NR*	90*	90*	88*	76*	84*		
S5 RE	23	M	50	50	45	40	25	10	10	10	0	65
60 dB/ERB$_N$				NR*	NR*	NR*	NR*	88*	84*	82*		
S5 LE			35	30	30	30	20	15	15	15	5	55
50 dB/ERB$_N$				NR*	NR*	NR*	NR*	82*	68*	64*		
S6 RE	21	F	30	20	15	10	10	15	15	10	35	50
50 dB/ERB$_N$				66*	68*	64*	64*	62*	62*	66*		
S6 LE			20	15	10	10	10	10	15	20	15	70
50 dB/ERB$_N$				68*	68*	70*	68*	66*	64*	62*		
S7 LE	33	F	65	65	60	50	35	20	15	10	5	80
70 dB/ERB$_N$				84*	82*	76	70	72	70	70		
S8 RE	18	F	40	35	30	25	25	25	30	30	40	0
50 dB/ERB$_N$				NR*	NR*	NR*	NR*	90*	NR*	NR*		
S8 LE			40	45	40	30	35	40	35	35	50	0
50 dB/ERB$_N$				84*	86*	86*	86*	86*	76*	78*		

Procedure

Audiometric thresholds were measured using a Madsen OB922 clinical audiometer equipped with TDH39 headphones, for frequencies from 250 to 8000 Hz. The results are shown in Table 1. Most of the subjects had mild or moderate hearing loss. The TEN(HL) test was conducted using the same audiometer; signals from the TEN(HL)-test CD were replayed from a Sony CD player. For subjects with near-normal audiometric thresholds, the TEN(HL) level was chosen to be 50 dB/ERB$_N$. For subjects with mild or moderate hearing loss, the TEN(HL) level was selected to be 60 or 70 dB/ERB$_N$. Usually, the TEN(HL) level was selected to be at least 5 dB above the highest audiometric threshold at any frequency between 500 and 4000 Hz. However, in a few cases (S4 right ear and S8 left ear), subjects complained that the TEN(HL) level selected in this way was uncomfortably loud. In those cases, the TEN(HL) level was reduced until the subjects reported it to be comfortable. The TEN(HL) levels used are shown in Table 1. The TEN(HL) and signal levels were controlled by the attenuators within the audiometer. The signal level was varied in 2-dB steps to determine the thresholds, as recommended by Moore et al (2004). A 'no response' (NR) was recorded when the subject did not indicate hearing the signal at the maximum output level of the audiometer.

PTCs were measured using a Maico 53 dual-channel clinical audiometer equipped with TDH39 headphones. The audiometer was set to dual-frequency mode. The signal tone was generated in one channel. It was presented at 10 dB SL and was pulsed on and off in a regular sequence (0.25 s on, 0.25 s off). A narrow band noise masker was selected in the other channel. The noise conformed to the specifications given in ANSI-S3.6 (2004), and had a bandwidth between 1/3 and 1/2 oct. The relatively large bandwidth is required to reduce the influence of beats on the PTCs (Kluk & Moore, 2005). The two channels were mixed in order to present the tone and noise to the same ear. The subjects were asked to respond when they could hear the tone in the presence of the noise. The minimum noise level required to mask the tone was determined by manual adjustment of the noise level. This was repeated for several masker frequencies placed at, below and above the signal frequency. The number of signal frequencies used varied across subjects, depending on the time for which they were available.

Speech recognition scores in quiet were measured using twenty monosyllables consisting of the vowel /a/ following one each of the following consonants: /k, g, tʃ, d_3, t., d., t, d, n, p, b, m, j, r, l, v, ʃ, s, h, l/. The speech level was 40 dB above the threshold of the individual subject for detecting the monosyllables (i.e. 40 dB SL). The stimuli were presented 'live' using the microphone and

headphones of the audiometer. The subjects were instructed to repeat each monosyllable after it was presented.

Results

The results of the TEN(HL) test are shown in Table 1. The TEN(HL)-test criteria were not met at any frequency for the right ears of S1 and S2, and were met at only one frequency for the left ears of S1 and S2. For the left ear of S7, the criteria were met for the two lowest frequencies only. For all the other subjects and ears, the criteria were met for most or all of the test frequencies. In several cases, the test tone was not reported as audible by the subject even at the highest level available from the audiometer. It seems implausible that subjects with near-normal audiometric thresholds, or only a mild hearing loss, such as S6 and S8, would have dead regions at all tested frequencies from 500 to 4000 Hz. The most likely explanation for the high masked thresholds of the tones in the TEN(HL) for these subjects is poor detection efficiency.

It is noteworthy that masked thresholds in the TEN, expressed relative to the TEN level, were often higher for low frequencies than for high frequencies. This was the case for S1 (both ears), S2 (left ear), S3 (both ears), S4 (right ear, the only ear tested), S5 (left ear, the only ear tested), S6 (left ear), S7 (left ear; the only ear tested), and S8 (left ear; the tone was undetectable at most frequencies in the right ear). To assess the significance of this effect, a repeated-measures analysis of variance (ANOVA) was conducted, based on the ratio of the signal level at masked threshold to the TEN(HL) level per ERB_N. When the threshold was not measurable, the threshold was arbitrarily assigned a value of 100 dB HL. The analysis was based on the data for all ears except the right ear of S8, since the signal was undetectable for all frequencies except one for that ear. The results showed a significant effect of signal frequency; $F(6, 66) = 10.77$, $p < 0.001$. The general trend for performance to be worse at low frequencies is consistent with the argument that auditory neuropathy involves loss of neural synchrony (Berlin et al, 2003; Zeng et al, 2005).

The PTCs are shown in Figures 1–8. The sharpness of the PTCs can be quantified using the measure Q_{10dB}, which is the centre frequency divided by the bandwidth at the point 10 dB above the minimum level of the PTC; this was estimated by interpolation and (in a very few cases) by extrapolation. For noise maskers with bandwidths comparable to those used here,

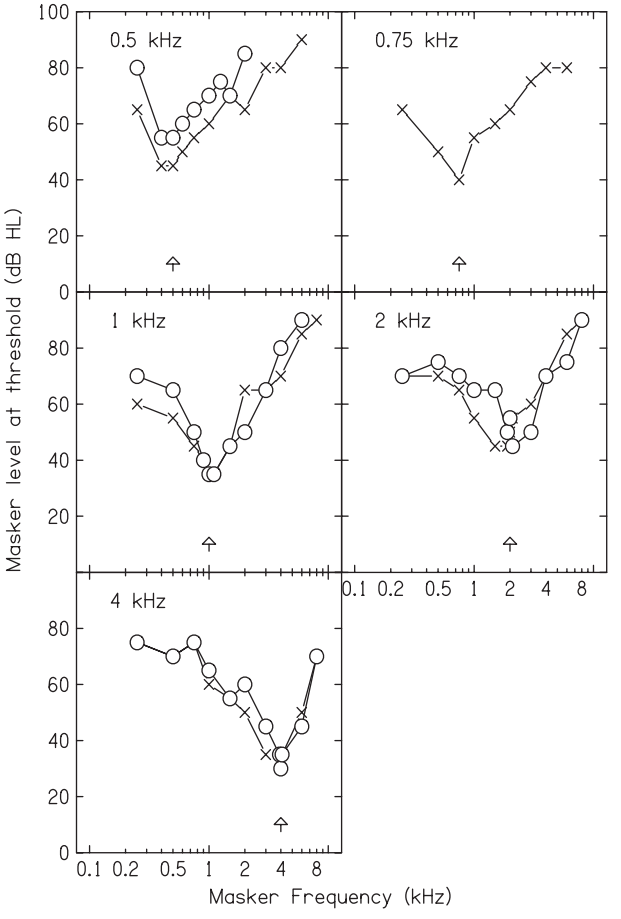

Figure 1. PTCs for the right ear (circles) and left ear (crosses) of S1. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

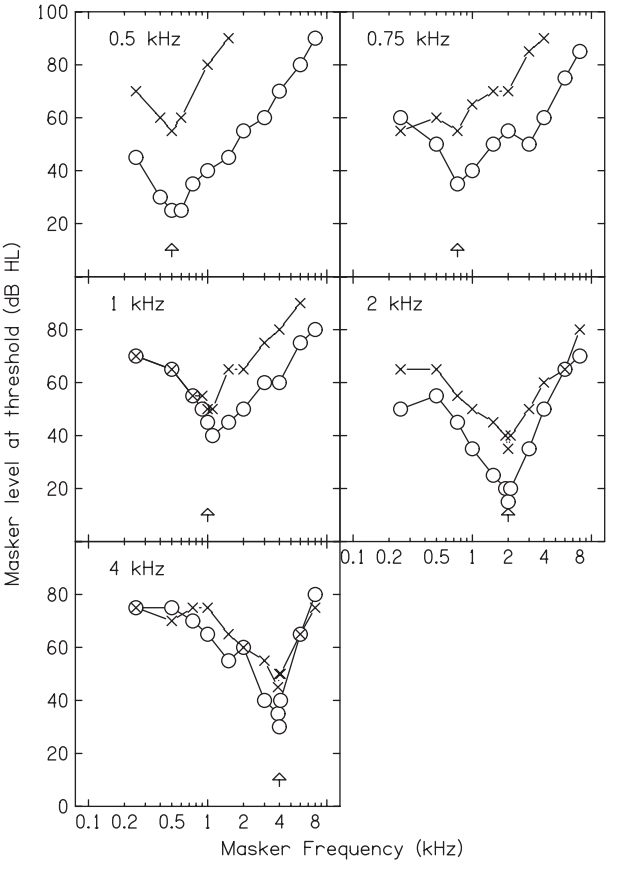

Figure 2. PTCs for the right ear (circles) and left ear (crosses) of S2. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

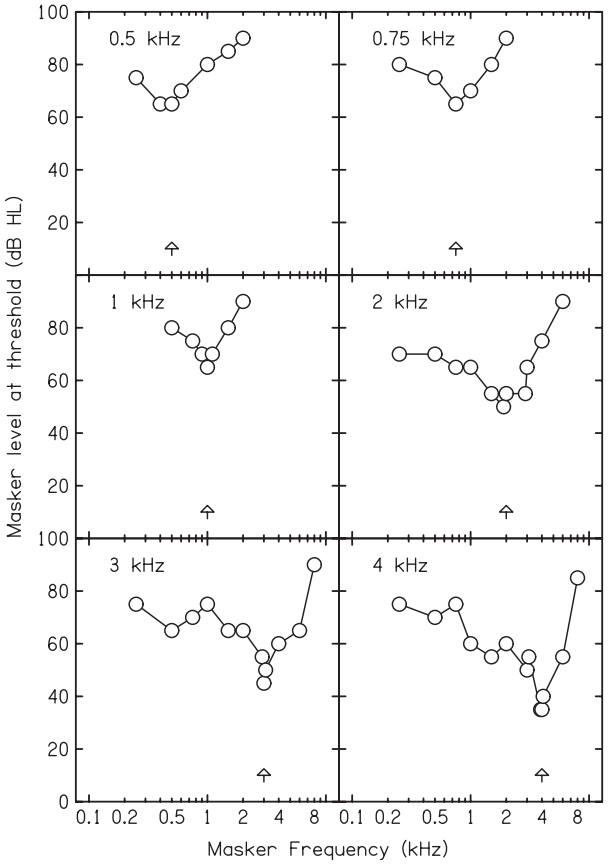

Figure 3. PTCs for the right ear only of S3. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

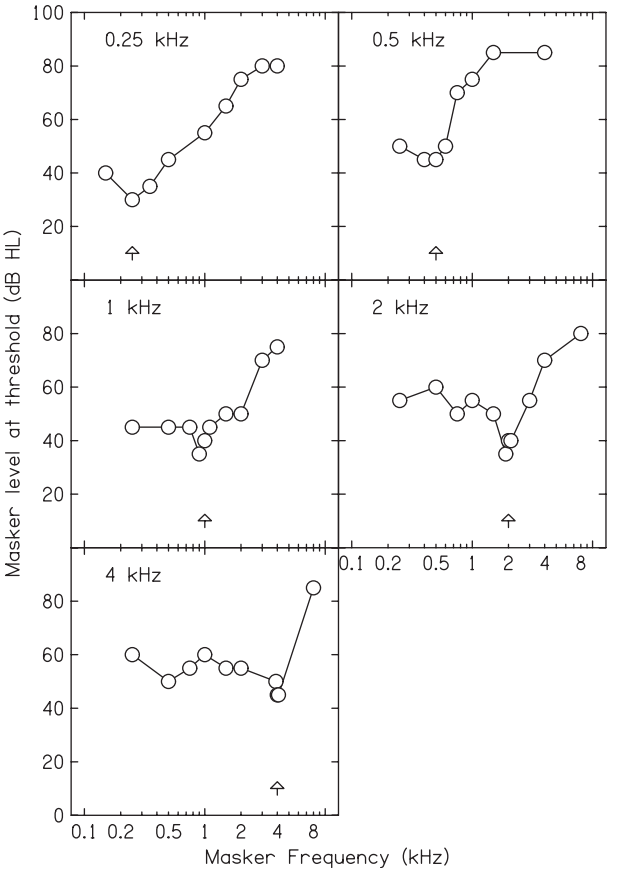

Figure 4. PTCs for the right ear only of S4. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

Kluk and Moore (2004) reported that PTCs for normally hearing subjects had Q_{10dB} values of 2.6 and 4.9 at 1000 and 4000 Hz, respectively. The mean Q_{10dB} values of the PTCs reported here are 1.4 and 3.1 at 1000 and 4000 Hz, respectively. These values indicate somewhat less sharp tuning than reported by Kluk and Moore (2004), which can be attributed to the higher signal and masker levels used here; higher levels lead to less sharp PTCs (Moore et al, 1984). The Q_{10dB} values of the PTCs for our subjects are generally greater than those found for subjects with cochlear hearing loss (Kluk & Moore, 2006). Overall, the Q_{10dB} values for the PTCs in Figures 1–8 are consistent with good OHC function.

For subject 1 (Figure 1), the PTCs all had tips at or close to the signal frequency, indicating the absence of dead regions. This was true even for the left ear at 750 Hz, a frequency at which the TEN(HL)-test criteria were met. For subject 2 (Figure 2), the PTCs for both the left and right ears again all had tips at or close to the signal frequency, except for the left ear and a signal frequency of 750 Hz, where the low-frequency side of the PTC was rather flat. The PTC for the left ear of S2 at 500 Hz had a tip at 500 Hz, a frequency at which the TEN(HL)-test criteria were met. For the right ear of S3 (Figure 3), the PTCs all had tips at the signal frequency, despite the TEN(HL)-test criteria being met for frequencies of 500, 750, 1500 and 2000 Hz. For the right ear of S4 (Figure 4), the PTCs sometimes had shallow low-frequency sides, especially for the signal frequency of 4000 Hz, but all the PTCs had tips at the signal frequency, despite the TEN(HL)-test criteria being met at all frequencies.

The PTCs for the left and right ears of S5 (Figure 5) all had tips at the signal frequency, despite the TEN(HL)-test criteria being met at all frequencies. For S6 (Figure 6), the PTCs were somewhat irregular, especially for the left ear, and the PTC for the 2000 Hz signal frequency in the left ear showed a tip at 1000 Hz, with a second tip at 2000 Hz. Apart from that one case, the PTCs all had tips at the signal frequency, despite the TEN(HL)-test criteria being met at all frequencies in both ears. For the left ear of S7 (Figure 7), the PTCs all had tips at the signal frequency, including 500 and 750 Hz, frequencies at which the TEN(HL)-test criteria were met. Finally, the PTCs for both ears of S8 (Figure 8) all showed tips at the signal frequency, despite the TEN(HL)-test criteria being met at all frequencies.

The speech recognition scores (SRS) are shown as percentages in the rightmost column of Table 1. The scores vary over a wide range, from 0% up to 80%. One might expect that poor results in the TEN(HL) test (i.e. high signal-to-noise ratios at threshold) would be associated with poor SRS. To assess whether this was

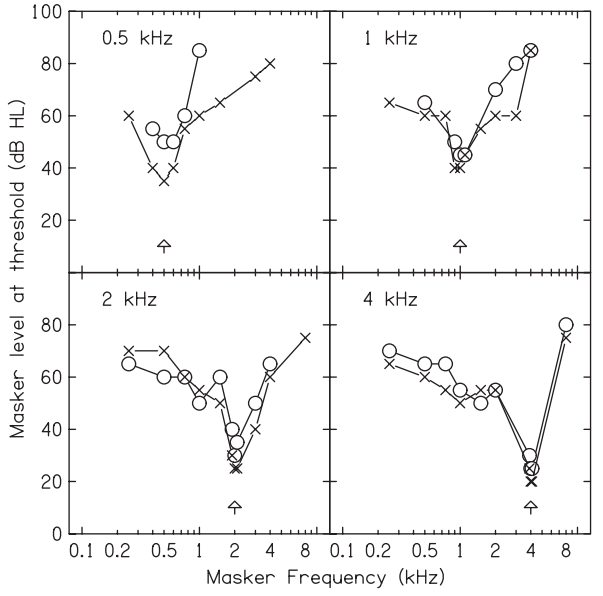

Figure 5. PTCs for the right ear (circles) and left ear (crosses) of S5. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

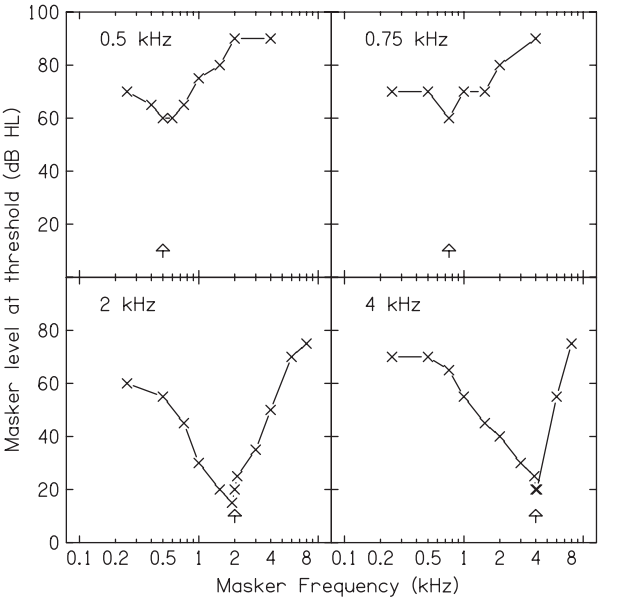

Figure 7. PTCs for the left ear only of S7. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

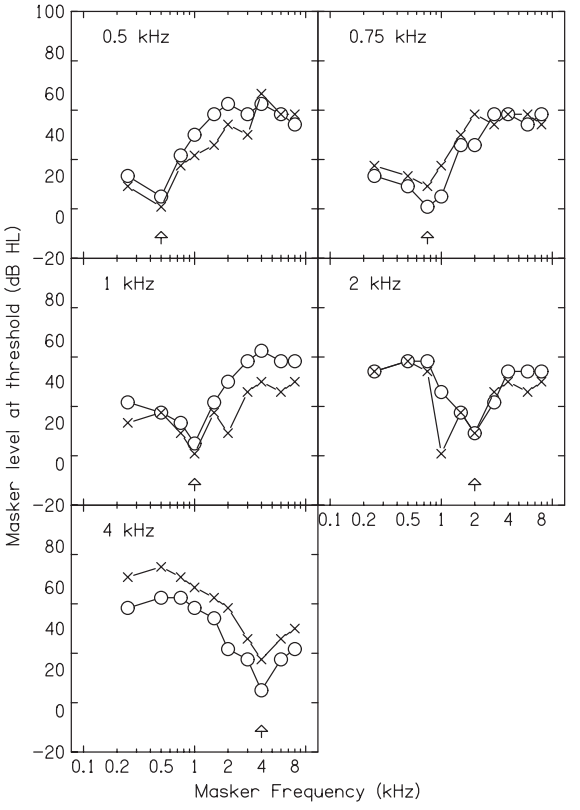

Figure 6. PTCs for the right ear (circles) and left ear (crosses) of S6. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

the case, the ratio of the signal level at masked threshold to the TEN(HL) level per ERB_N was averaged across frequency for each ear of each subject, giving a value SNR_{ave}, and the correlation was calculated between the values of SNR_{ave} and the SRS. As before, when the threshold was too high to be measured it was assigned a value of 100 dB HL. The correlation was −0.393. This is in the expected direction, but is not significant at a level of 0.05.

Discussion and conclusions

The results clearly show that the tips of the PTCs were not shifted in the great majority of cases, even when the TEN(HL)-test criteria were met. This means that the high thresholds for detecting the test tones in the TEN(HL) were not the result of dead regions (off-place or off-frequency listening), but resulted instead from relatively poor detection efficiency; in other words, subjects with auditory neuropathy require a higher than normal signal-to-noise ratio at the output of the auditory filter in order to detect the signal. A possible reason for this is that thresholds for detecting a tone in noise may be partly determined by neural synchrony (phase locking) to the tone (Moore, 1975, 2003; Zeng et al, 2005); auditory neuropathy is associated with disruption of neural synchrony. Consistent with this interpretation, the signal-to-noise ratios at masked threshold were greater at low frequencies than at high frequencies. Another possibility is that IHCs are functioning poorly, or are reduced substantially in number, but are not completely non-functioning over any substantial region along the cochlea.

Whatever the reason for the high thresholds of subjects with auditory neuropathy for detecting tones in noise, it is clear that the high thresholds do not indicate dead regions. Thus the

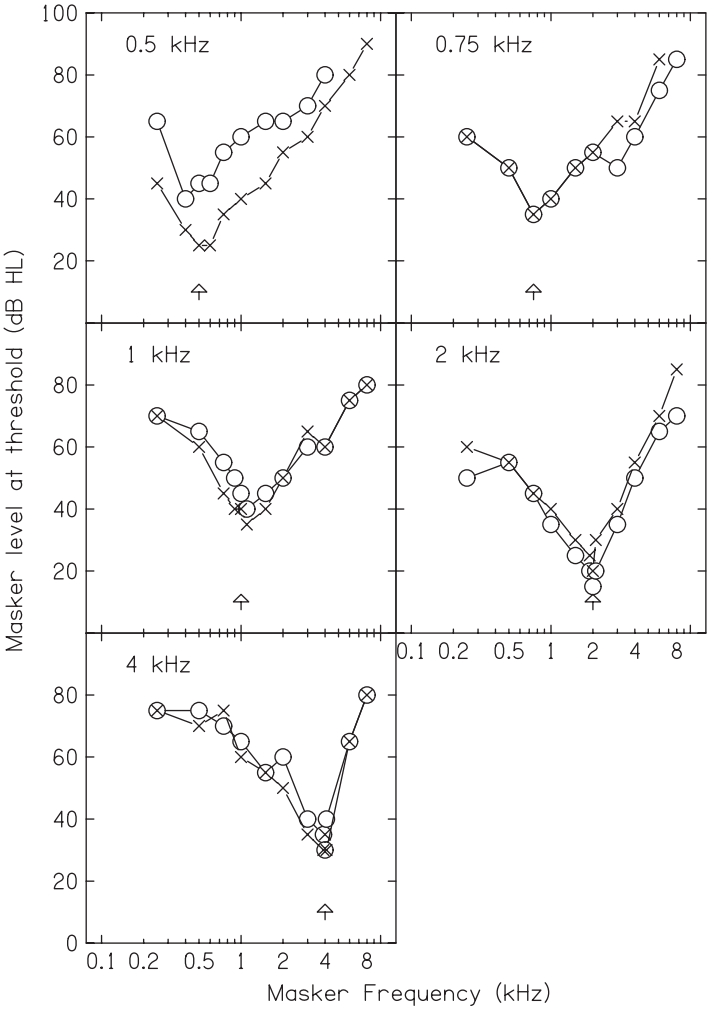

Figure 8. PTCs for the right ear (circles) and left ear (crosses) of S8. Each panel shows results for one signal frequency. The masker level required for threshold is plotted as a function of the masker center frequency. Up-pointing arrows indicate the signal frequency.

results of the TEN(HL) test need to be interpreted differently from 'normal' in cases when auditory neuropathy is present. High thresholds in the TEN(HL) test were found to be only weakly associated with speech recognition, although the speech test used here involved live voice and only 20 items, and was therefore not very precise. Further research on the relationship between the results of the TEN(HL) test and speech recognition appears justified.

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