Diagnosing Cochlear Dead Regions in Children

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Objective: A dead region (DR) is defined as a region in the cochlea where inner hair cells and/or neurons are functioning so poorly that a tone producing peak vibration in this region is detected by off-frequency listening, i.e., via a place on the basilar membrane with a characteristic frequency different from that of the tone. The presence of a DR can have a significant effect on the perception of speech. People with and without DRs may differ in the benefit obtained from amplification and require different hearing aid settings. The Threshold Equalizing Noise (TEN) test and psychophysical tuning curves (PTCs) are two procedures used to identify a DR in adults. Because diagnosing a DR involves measuring masked thresholds, and there are reports in the literature that young children perform poorly compared with adults in background noise, it may be possible that the criteria used with adults may not be appropriate when testing children. Therefore, the aim of this study was to evaluate the consistency of the fast-PTC and TEN tests in diagnosing a DR in hearing-impaired children. In addition, the masked thresholds for normal-hearing children were measured with different TEN levels to assess whether any age-related effect in children compared with adults may occur.

Design: Participants were divided into two groups: eight normal-hearing children (16 ears) and 12 hearing-impaired children (21 ears), aged 7 to 13 yr. TEN is based on measuring masked threshold in TEN. For normal-hearing participants, the masked thresholds were measured for five levels of noise (30, 40, 50, 60, and 70 dB per averaged equivalent rectangular bandwidth). For hearing-impaired participants, the level of the TEN was selected separately for each ear based on the highest acceptable level minus 5 dB. The TEN test results in hearing-impaired children were further validated by measuring fast-PTCs. The fast-PTC technique involves measuring the level of the narrowband noise masker needed to mask the signal. The center frequency of the masker sweeps across the required frequency range.

Results: The masked thresholds in TEN measured for normal-hearing children were usually below and never higher than 5 dB above TEN level per averaged equivalent rectangular bandwidth. This suggests that no age-related effect on masked threshold in children compared with adults was observed. All hearing-impaired children were able to perform the TEN test and fast-PTCs. The results of the two tests were consistent in 17 of 21 ears (81%): eight ears did not show evidence of a DR and nine ears did. In three ears, the criteria for a DR were met on the TEN test, but there was no evidence of a DR on the fast-PTC test. In one ear, the TEN test did not show evidence of DRs at two frequencies, whereas fast-PTCs did.

Conclusions: The results of this study suggest that DRs can be detected in children using the fast-PTC technique and the TEN test interpreted with the adult criteria, which are the most appropriate in terms of specificity and sensitivity. However, in cases in which the masked threshold is 10 to 15 dB above the TEN level, it is recommended to confirm DR diagnosis with fast-PTC measurement.

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INTRODUCTION

A dead region (DR) is defined as a region in the cochlea where inner hair cells and/or neurons are absent or functioning

so poorly that the tone producing maximum vibration is detected via a different place on the basilar membrane (Moore 2001, 2004). The presence of a DR can have several perceptual consequences: there is evidence of abnormal pitch perception (Huss & Moore 2005a; Moore & Carlyon 2005), rapid growth of loudness (McDermott et al. 1998), and distorted perception of pure tones (Florentine & Houtsma 1983; Huss & Moore 2005b). An important perceptual consequence, from a clinical perspective, is the effect that the presence of a DR may have on speech perception. Several researchers have investigated the effect of stimulus bandwidth on the ability of people with DRs to understand speech. Some of these studies suggest that providing amplification at frequencies well inside a DR may not provide additional benefit and, in some cases, have a deleterious effect on speech perception (Murray & Byrne 1986; Vickers et al. 2001; Baer et al. 2002; Vestergaard 2003; Preminger et al. 2005; Vinay & Moore 2007b; Vinay et al. 2008; Moore & Vinay 2009). In contrast, Mackersie et al. (2004) showed no difference in performance between participants with and without DRs when the speech material was presented in quiet and in low levels of noise. However, the participants in the study by Mackersie et al. had less severe hearing impairment and less extensive DRs compared with those in some of the previous studies. Therefore, the limited benefit from amplification may be restricted to subjects with extensive DRs. There is no evidence in the literature concerning the effect of a DR on speech perception in children. However, the importance of high-frequency amplification in children with moderate-to-severe hearing impairment has been highlighted in several studies (Stelmachowicz et al. 2001, 2002; Stelmachowicz et al. 2007).

Because the diagnosis and assessment of DRs may be of clinical significance in the fitting of hearing devices and management of hearing impairment (Moore 2004), it is important to evaluate the appropriateness of the adult criteria for diagnosing DRs to the diagnosis of DRs in children.

The extent of a DR may be defined in terms of its edge frequency (f_{edge}), which corresponds to the characteristic frequency of the inner hair cell and/or neurons immediately adjacent to the DR (Moore 2001). There are two masking techniques that have been used for diagnosing DRs and establishing f_{edge} : (1) psychophysical tuning curves (PTCs) and (2) the Threshold Equalizing Noise (TEN) test. A PTC shows the level of masker required to mask a signal fixed in level and frequency as a function of the masker center frequency (Chistovich 1957; Small 1959). The signal is usually a sinusoid, presented at a low sensation level, and the masker is typically a narrowband noise. In normal-hearing listeners, PTCs have a sharp tip at the signal frequency (f_{signal}). PTCs are usually broader than normal when cochlear hearing impairment is present; however, the tip still lies close to f_{signal} (Zwicker & Schorn 1978; Florentine et al. 1980; Moore 1998; Moore & Oxenham 1998). In listeners with a DR, the tip of the PTC is shifted away from f_{signal} . The frequency at the tip of the PTC

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indicates f_{edge} . The traditional PTC measurement procedure is time consuming and unsuitable for clinical use where time is restricted and listeners, such as children, may have limited spans of attention. Sek et al. (2005) developed a method previously used by Zwicker (1974) based on the use of a masker whose frequency sweeps across the required frequency range. However, Sek et al. used narrowband noise instead of a pure tone as a masker. Sek et al. systematically evaluated several parameters crucial for efficient measurement of PTCs such as the rate of change of the masker level, masker bandwidth, and the direction of the masker sweep. They showed that the fast-PTC method produced results that are similar to the traditional PTC measurements in adult listeners. Malicka et al. (2009) used a procedure similar to that of Sek et al. but with normal-hearing children and showed that the fast-PTC method is within the capability of most normal-hearing 7- to 10-yr old children. The results of Malicka et al. showed that all children were able to perform the task; however, the tip was defined only in 87% of the fast-PTCs. Although the variability in tip frequency was higher for children, the mean difference between children and adults was not statistically significant.

The TEN test is based on measuring the masked threshold of a sinusoid in TEN. TEN is based on similar principals as “uniform exciting noise” (developed by Zwicker and Stevens in the early 1950s), i.e., the masked threshold is independent of frequency. The uniform exciting noise produces equal intensity for each critical band, whereas TEN is designed to produce a fixed excitation level as a function of averaged equivalent rectangular bandwidth (ERB_N) of the auditory filter at moderate sound levels for young normal-hearing listeners. The original version of the TEN test was designed to measure masked thresholds in dB SPL (Moore et al. 2000), whereas the more recent version (TEN_{HL}) allows measurements to be made in dB HL (Moore et al. 2004). The criteria for diagnosing a DR using the TEN test were evaluated in adults by Moore et al. (2000). Initially, they assessed the masked threshold for various TEN levels with normal-hearing adult listeners. Moore et al. reported that mean masked thresholds were almost equal to TEN level/ ERB_N with an upper limit of 7 dB above the TEN level/ ERB_N . The broadened auditory filters in hearing-impaired listeners could increase the masked threshold by a further 2 to 3 dB. Therefore, this resulted in the following diagnostic rule: if the masked threshold in TEN is 10 dB or more above the TEN level/ ERB_N , and the TEN produces at least 10 dB of masking, this is indicative of a DR. Moore et al. then validated the TEN test criteria with hearing-impaired adults by comparing TEN test and PTC results (PTCs are assumed to be highly reliable indicators of a DR). They reported good agreement between shifted PTC tips and increase in masked threshold in 17 of 20 ears tested. In the three remaining ears, the TEN test showed false-positive results, i.e., the difference between masked threshold and TEN level/ ERB_N was >10 dB, but the tips of the PTCs were not shifted.

The appropriateness of the TEN criteria for diagnosing a DR in hearing-impaired adults has been confirmed in a number of studies (Huss & Moore 2003; Kluk & Moore 2006). In contrast, Summers et al. (2003) attempted to validate the TEN test results by measuring PTCs in hearing-impaired adults and argued that the TEN test does not provide an adequately sensitive and specific indication of a DR. They found only 56%

agreement between the results of the TEN test and the PTC procedure in hearing-impaired listeners when a 10-dB criterion was used (difference between masked threshold and TEN level/ ERB_N). However, altering the criterion to 14 dB changed the level of agreement to 89%. This suggests that, at some frequencies where a DR was not present, the TEN test produced higher masked thresholds than that predicted by Moore et al. (2000). There are additional reports in the literature in which the TEN test produced an abnormally high masking effect, e.g., when testing some hearing-impaired teenagers (Moore et al. 2003) or adults with auditory neuropathy (Vinay & Moore 2007c).

The TEN test criteria were developed for adult listeners. It is known that psychoacoustic measurements with children are not only more variable than with adults but masked thresholds are also typically higher (Irwin et al. 1986; Hall & Grose 1990; Veloso et al. 1990; Hall & Grose 1991; Buss et al. 1999). Therefore, the criteria for the TEN test may not be appropriate for use in the pediatric population. Although the feasibility of using the fast-PTC method has been assessed with normal-hearing children, there are no studies reporting the use of fast-PTCs as a tool for diagnosing DRs in hearing-impaired children. Therefore, the aim of this study was to evaluate the consistency of the fast-PTC and TEN_{HL} tests in diagnosing DRs in hearing-impaired children. The TEN_{HL} test results and criteria were corroborated by measuring fast-PTCs. Previous research with adults suggests that the diagnostic criteria could be adjusted to optimize the validity of the TEN test (Summers et al. 2003); however, it is unknown whether this approach is applicable to school-age children. Therefore, one of the aims of this study was to investigate the sensitivity and specificity of the TEN_{HL} test for different diagnostic criteria. In addition, the masked thresholds for normal-hearing children were measured with various TEN levels to assess whether any age-related effect in children compared with adults may occur.

PARTICIPANTS AND METHODS

Participants

Eight normal-hearing participants with no history of hearing disorders and absolute thresholds better than 10 dB HL at 0.5 to 4 kHz were recruited. There were one girl and seven boys, aged between 7 and 12 yr. Both ears of each participant were tested. Hearing-impaired participants were selected from three sources: the clinical records from the Audiology Department at the Queens Medical Centre, Nottingham, Manchester Inclusion Service for Children with Hearing Needs, and Mary Hare Grammar School, Newbury. There were 12 experienced hearing aid users (five boys and seven girls, aged between 8 and 13 yr) with high-frequency sensorineural hearing impairment. Both ears of nine participants (18 ears) and one ear from three participants were tested. In two of the latter three cases (5-R and 8-R), the hearing impairment in the nontested ear was too severe to conduct the tests; in one case (12-R), the participant completed the tasks for one ear only because of time limitations. Absolute hearing threshold levels, age, and sex of the hearing-impaired participants are shown in Table 1. The study received ethical approval from the Nottingham Research Ethics Committee 1 (reference number 05/Q2403/146). Written consents were obtained from parents and participating children. Children with a history of developmental disability, based on

TABLE 1. Age, sex and absolute hearing threshold (dB HL) of the hearing-impaired listeners

Subject	Sex	Age (yr)	Ear	Absolute threshold (dB HL) at different frequencies (kHz)						
				0.5	0.75	1.0	1.5	2.0	3.0	4.0
1	M	10	L	35	45	50	60	60	65	65
			R	35	35	40	55	55	50	50
2	M	10	L	40	45	45	80*	80*	65	55
			R	35	45	60	80	70	60	55
3	F	8	L	50	55	60	60	55	60	65
			R	50	50	65	65	60	60	55
4	M	8	L	40	40	40	90*	95*	90*	115*
			R	20	35	45	85*	85*	85*	85*
5	M	11	L	70	75	80*	95*	105*	>110*	>110*
			R	45	45	60	75*	65*	60	60
6	F	9	L	50	50	50	65*	65*	60	55
			R	40	55	60	70	70	70	70
7	M	11	L	50	60	65	80	75	75	70
			R	80*	100*	105*	>110*	>110*	>110*	>110*
8	F	9	L	65	90*	100*	110*	110*	110*	>110*
			R	60	85*	100*	>110*	>110*	>110*	>110*
9	F	10	L	50	60	65	70	65	65	65
			R	55	60	65	65	70	70	70
10	F	12	L	15	70	75	105	100	95	90
			R	30	95*	95*	110*	110*	110*	110*
11	F	13	L	40	50	60	65	55	30	25
			R	40	50	60	65	55	30	25

* Frequencies at which a DR was present (diagnosed using TEN_{HL} test and fast-PTCs).
 DR, dead region; PTC, psychophysical tuning curve.

medical records and parental report, were excluded from the study.

Equipment and Procedure

TEN_{HL} Test • The TEN_{HL} compact disc comprises pure tones at 0.5, 0.75, 1, 1.5, 2, 3, and 4 kHz and the TEN. Testing at higher frequencies is not required because the presence of a DR at frequencies ≥ 5 kHz is not clinically significant with respect to amplification requirements. According to Vickers et al. (2001) and Baer et al. (2002), it is recommended to amplify up to one octave above f_{edge} . For f_{edge} of 5 kHz, amplification should be provided up to 10 kHz. This is consistent with high-frequency amplification recommended for hearing-impaired individuals without any DRs (Stelmachowicz et al. 2001; Vickers et al. 2001; Baer et al. 2002; Stelmachowicz et al. 2002; Stelmachowicz et al. 2007). The stimuli were controlled and amplified using a Kamplex KC35 (Interacoustic, Assens-Denmark) clinical audiometer fitted with 39 telephonics dynamic headphones. The pure tone was fed to one external input channel of the audiometer, and the noise was fed to the other. Calibration was performed before each test session in accordance with Moore et al. (2004). In the TEN_{HL} test, the masker level was held constant, and the signal level was adjusted to obtain the masked thresholds (in contrast to the fast-PTC procedure in which the converse was done). The absolute and the masked thresholds in TEN for each participant were measured following the British Society of Audiology recommended procedure (British Society of Audiology 2004), except that smaller audiometric step sizes were used. The initial descending step size was 10 dB. Once the participant stopped responding, thresholds were determined using a 2-dB ascending and 4-dB descending procedure as recommended by Cairns et al. (2007). For normal-hearing participants, the

masked thresholds were measured for five levels of noise (30, 40, 50, 60, and 70 dB/ERB_N). For hearing-impaired participants, the level of the TEN was selected separately for each ear based on the highest acceptable level minus 5 dB (to avoid discomfort during testing) and ranged from 60 to 100 dB/ERB_N. The ears were initially classified into two groups, with or without DR, according to the adult criteria recommended by Moore et al. as follows: if for specified frequency the masked threshold is 10 dB or more above TEN level/ERB_N, and the difference between masked and absolute threshold is ≥ 10 dB, the result indicates presence of a DR at this frequency. In ears in which there was disagreement between the TEN_{HL} test and the fast-PTC, the TEN_{HL} test was repeated.

Fast-PTC • The software used to run the test was developed by one of the authors (R. J. B.) for use with a Kamplex KC 35 (Interacoustic, Assens-Denmark) clinical audiometer fitted with 39 telephonics dynamic headphones. The attenuation and mixing of the signals was performed using the audiometer under computer control. The PC was additionally equipped with an external 16-bit sound card (Edirol UA-5 Roland DG, Shizuoka-Japan). The masker was generated from low-pass white noise, which was multiplied by a pure tone to obtain a narrowband noise of the appropriate frequency as described by Malicka et al. (2009). The noise bandwidth was 20% of f_{signal} for $f_{signal} \leq 2$ kHz and 10% of f_{signal} for $f_{signal} > 2$ kHz. The rate of change of the masker was 0.005 and 0.01 kHz per presentation interval (linear frequency steps) for $f_{signal} < 1$ kHz and $f_{signal} \geq 1$ kHz, respectively. Fast-PTCs were measured for pulsed pure tones that were sinusoidally amplitude modulated at 8 Hz to minimize the effect of beat detection, which can affect the shape of the PTC (Kluk & Moore 2005). The signal duration was 500 msec, including 20 msec raised-cosine rise and fall times, and was centered in a 700-msec masker interval

with the same rise-fall times. There was a 200-msec silent interval between each masker presentation (400 msec between each signal presentation). The f_{signal} and masker frequency range were selected on the basis of whether the adult DR criteria were met on the TEN_{HL} test. For ears not meeting the criteria, PTCs were measured for two or three frequencies: usually, 1, 2, and 4 kHz and the center frequency of the masker swept from one octave below f_{signal} up to one octave above f_{signal} . For ears meeting the criteria for a DR on the TEN_{HL} test, PTCs at two f_{signals} were measured. The first PTC was measured with f_{signal} one octave below the closest frequency to f_{edge} for which the TEN_{HL} test met the criteria for a DR (border frequency [f_{border}]) and the masker sweep range as above. The second PTC was measured at f_{border} . In these cases, the masker swept from two octaves below f_{signal} up to one octave above f_{signal} . The fast-PTC commenced with the signal presented at 10 dB sensation level, and the initial masker level was selected according to the severity of the hearing impairment (usually 20 dB below the signal level). Participants were instructed to press the space bar on the keyboard when the target tone was audible and to release it when the target tone was inaudible. Pressing the space bar increased the masker level in 3-dB step sizes. To provide an objective measure of frequency at the tip (f_{tip}), the procedure used by Malicka et al. was used. This involved smoothing the raw data and using a two-point running average of successive reversal points. The frequency at which the minimum point of this line occurred was taken as f_{tip} . In the *Results* section, only the smoothed line is shown in the figures. Based on the results of Malicka et al. with normal-hearing children, the criteria for diagnosing DRs using fast-PTCs were as follows: for an ascending masker sweep direction, the difference between f_{signal} and f_{tip} of $>25\%$ of f_{signal} toward higher frequencies or 20% toward lower frequencies was taken as an indication of a DR.

RESULTS

Normal-Hearing Children

The results of the TEN_{HL} test for the normal-hearing children are presented in Figure 1. The mean masked thresholds measured with TEN at 30, 40, and 50 dB/ERB_N were almost invariant across all frequencies and below the TEN level/ERB_N, regardless of f_{signal} . For TEN levels of 60 and 70 dB/ERB_N, the relative increase in masked threshold was greater at high frequencies. However, individual masked thresholds measured in normal-hearing children were never increased > 5 dB above the TEN level/ERB_N, regardless of noise level and test frequency. The difference between masked threshold and TEN level/ERB_N is crucial because it defines the criterion for diagnosing a DR. The results of this study with normal-hearing children are comparable with those reported previously with normal-hearing adults (Moore et al. 2000) and teenagers (Moore et al. 2003). Therefore, it is suggestive that the adult 10-dB criterion may be appropriate for diagnosing DRs in hearing-impaired children. On the other hand, because of limited listening experience, hearing-impaired children may be more prone to masking, and the criteria developed for normal-hearing participants may need to be altered for hearing-impaired individuals.

Fig. 1. TEN_{HL} results for 16 ears of normal-hearing children. The symbols represent the mean masked thresholds measured for different TEN levels/ERB_N, and the error bars show ± 2 SD. TEN, Threshold Equalizing Noise; ERB_N, averaged equivalent rectangular bandwidth.

Hearing-Impaired Children

All children were able to perform the TEN_{HL} test and the fast-PTC test. Both procedures were used to establish the presence or absence of DRs in 21 ears. Figure 2 shows the results for the eight ears that did not show evidence of a DR on the TEN_{HL} test and the fast-PTC test. Each column represents findings for one ear. The top row shows TEN_{HL} test results obtained with the TEN level specified in the bottom left corner of each panel. The absolute and masked thresholds are represented by filled and open squares, respectively. The masked thresholds for all tested frequencies were within 10 dB (mean 3.6 dB, range 0 to 9 dB) of the TEN level/ERB_N. The bottom row shows fast-PTCs (smoothed lines). The fast-PTCs presented in Figure 2 were measured at 1, 2, and 4 kHz in all ears, except 2-R in which the PTCs were measured at 0.5 and 1 kHz and 11-L in which the PTCs were measured at 2 and 3 kHz only. The open symbols represent f_{tip} of the PTC. The filled symbols (with respective shape) represent the f_{signal} for which the PTC was measured. Ideally, for participants without any DR, the open and the filled symbols should indicate the same frequency. However, in practice, the f_{tip} is often shifted away from f_{signal} , and the magnitude of this shift is considered as a criterion for diagnosing a DR. The mean shift in the tip of PTCs presented in Figure 2 was 8.7% of f_{signal} (range 0.3 to 18%), which is consistent with the TEN_{HL} test results and the absence of a DR in these ears.

Figure 3 shows results for nine ears that met the criteria for a DR both on the TEN_{HL} test and on the fast-PTC test. Each column shows findings for one ear. The TEN_{HL} test results are

Fig. 2. Results for the eight ears without any evidence of a DR on the TEN_{HL} test and the fast-PTC test. Each column contains results for one ear. The TEN_{HL} test (top row) was measured with the TEN level specified in the bottom left corner of each panel. Absolute threshold and masked threshold are represented by filled and open squares, respectively. The PTC results are shown in the bottom row. The smoothed line represents two-point running average of successive reversal points. The open symbols correspond to f_{tip} of the PTCs measured for f_{signal} represented by filled symbol with respective shape. The value of f_{tip} for each PTC is given in the left bottom corner of each panel containing PTCs. DR, dead region; PTC, psychophysical tuning curve; TEN, Threshold Equalizing Noise; f_{tip} , tip frequency; f_{signal} , signal frequency.

shown in the first row, followed by fast-PTCs measured at f_{signal} outside the DR (middle row) and finally PTCs measured at f_{border} (bottom row). The TEN_{HL} results are presented in the same format as Figure 1. The frequencies for which the criteria for a DR were met on the TEN_{HL} test are represented by single hashed area on the figures.

The mean masked threshold measured for frequencies outside the DR was 5.5 dB (range 0 to 9 dB) above TEN level/ERB_N. For frequencies falling within a DR, the masked threshold was increased ≥ 15 dB for all ears, except 9-L and 9-R, at 0.75 and 1 kHz, in which the masked threshold was 10 dB above the TEN level/ERB_N. The mean shift in the tip of the

PTCs obtained with f_{signal} outside the DR was 7.5% of f_{signal} (range 0.7 to 20%). The bottom row shows PTCs measured with f_{signal} equal to f_{border} . For these PTCs, the shift varied between 33.1 and 65% of f_{signal} . Six ears with severe to profound degrees of hearing impairment showed extensive DRs limited only from the low-frequency side. In all these ears, the fast-PTC measured at f_{border} displayed shifted tips consistent with the presence of a DR. The audiometer output level was not high enough to establish the masked thresholds at some frequencies (4-L at 2 and 4 kHz; 8-L at 1 kHz; 9-L at 1.5, 2, and 3 kHz; and 11-R above 0.75 kHz), but the masked threshold was at least 20 dB above TEN level/ERB_N and produced at

Fig. 3. Results for the nine ears with evidence of DRs on the TEN_{HL} test and the fast-PTC test. Each column contains results for one ear. Top row shows results of the TEN_{HL} test as shown in Fig. 2. The symbols with upward-pointing arrows indicate cases in which the threshold was too high to be measured. Single hashed area indicates frequencies where DR criteria are met on the TEN_{HL} test, i.e., the difference between masked threshold and TEN level/ERB is ≥ 10 dB, and the difference between masked and absolute threshold is ≥ 10 dB. The double hashed area indicates frequencies where the output level of the audiometer was not sufficient to measure absolute and/or masked threshold, but the presence of DR at these frequencies is likely. The middle row shows PTCs measured with f_{signal} outside a DR. Bottom row shows PTCs measured with f_{signal} from inside the DR. The f_{tip} (open star) and f_{signal} (filled star) values are given in the left corner of each panel containing PTC. DR, dead region; PTC, psychophysical tuning curve; TEN, Threshold Equalizing Noise; ERB, equivalent rectangular bandwidth; f_{signal} , signal frequency; f_{tip} , tip frequency.

Fig. 4. The findings for four ears showing disagreement between the TEN_{HL} test and fast-PTCs. Same format as Fig. 3. PTC, psychophysical tuning curve.

least 10 dB of masking. Therefore, despite the limitations of the audiometer, the presence of a DR was established by the TEN_{HL} test at these frequencies.

The interpretation of the TEN_{HL} test becomes more complicated at frequencies where it was not possible to establish a relationship between masked and absolute threshold because of severity of hearing impairment (8-L above 1 kHz; 9-L at 4 kHz; and 9-R above 1 kHz). In these cases, the results of TEN_{HL} test are inconclusive, although it is likely that a DR is present based on the severity of hearing impairment (double hashed area on the graph). For one ear (8-L), it was not possible to determine f_{edge} based on the TEN test results. However, the PTC measured with an f_{signal} of 0.5 kHz showed evidence of a DR because the tip was shifted toward low frequencies at 0.237 kHz (52.6% of f_{signal}). The shift in the tip of the PTC measured with an f_{signal} of 0.25 kHz was within 14% of f_{signal} , and this is consistent with no DR at this frequency.

There were three examples of “island DRs,” i.e., limited from low- and high-frequency side. According to the TEN_{HL} test for ears 2-L, 6-L, and 6-R, the low-frequency f_{edge} was located between 1 and 1.5 kHz, and the high-frequency f_{edge} was located between 2 and 3 kHz. For these ears, f_{tip} of the PTCs, measured with an f_{signal} of 1 kHz (outside DR) was within 20% of f_{signal} . The PTCs measured at f_{border} : for ear 2-L and 6-L at 1.5 kHz (low-frequency f_{border}) and for 6-R at 2 kHz (high-frequency f_{border}) displayed tips shifted toward 1 kHz irrespective of f_{signal} . The magnitude of the shift varied between 38.3 and 47.5% of f_{signal} . Therefore, it may be assumed that these signals are detected via a filter with characteristic frequency close to 1 kHz. Interestingly, for 6-R, the other tip is visible between 2 and 3 kHz, which may suggest that both places are responsible for detection of 2-kHz signal.

Four of the 21 ears showed a disagreement between the outcome of the TEN_{HL} test and the fast-PTC test (3-L, 3-R, 5-L, and 12-L). The results for these ears are presented in Figure 4. In these ears, the TEN_{HL} test was conducted on two occasions. The mean test-retest difference was 1.6 dB (SD =

1.7), and there was no change in diagnostic category; therefore, only data from the first attempt were analyzed and shown on the graphs. For 3-L, the mean masked threshold was 8 dB above the TEN level (range 4 to 14 dB) showing abnormally high masking for 1.5, 3, and 4 kHz. The f_{tip} of the PTC measured with an f_{signal} of 1 kHz (no DR on the TEN_{HL} test) was within 19.2% of f_{signal} , although shifted toward lower frequencies (opposite to masker sweep direction) but still in line with no DR at this frequency. The f_{tip} of the PTC measured with an f_{signal} of 4 kHz (the criteria for a DR met on the TEN_{HL} test) was within 8.3% of f_{signal} . Therefore, the results of TEN_{HL} and fast-PTCs are in agreement at 1 kHz but not at 4 kHz. A similar pattern is present for ear 3-R. The mean masked threshold was 9.3 dB (range 5 to 14 dB) above the TEN level, and the criteria for a DR were met at 1.5, 2, and 3 kHz. The PTCs measured for 1 and 2 kHz did not show evidence of DR (shift in the tip, 24.5 and 9.3% of f_{signal} , respectively). Consequently, the results of both tests at 1 kHz are consistent with no DR, whereas at 2 kHz, the TEN_{HL} test results remain in disagreement because there is no evidence of off-frequency listening on the fast-PTC test. For ear 12-L, the mean masked threshold was 6.9 dB (range 4 to 12 dB) above the TEN level. The criteria for DR were met on TEN_{HL} at 0.75 and 1 kHz (masked threshold 12 dB above the TEN level). The fast-PTCs measured at 0.5 kHz (outside the DR according to the TEN_{HL} test) displayed a tip shifted toward higher frequencies. The magnitude of the shift was 25% of f_{signal} , which is borderline abnormal using the criteria specified above. At 1 kHz, the fast-PTC showed a tip within 8% of f_{signal} , which suggests no DR, and this remains in contrast to the TEN_{HL} test results.

A different pattern of results was observed for ear 5-L. The TEN_{HL} test indicated f_{border} at 1 kHz because the masked threshold was 10 dB above TEN level and 20 dB above the absolute threshold. It would be expected that if the TEN level was high enough to produce masking at f_{border} , the difference between masked and absolute threshold should be carried forward toward higher frequencies (where the hearing impair-

ment is more severe). However, it was not the case at 1.5 and 2 kHz, where the masked thresholds were 10 and 16 dB above TEN level, respectively, but <10 dB above the absolute threshold. The f_{tip} of the fast-PTCs measured with an f_{signal} of 0.75 and 1.5 kHz was 0.8 kHz (within 6.7% of f_{signal}) and 0.695 kHz (within 53.7% of f_{signal}), respectively, and this confirms f_{edge} around 0.75 kHz and presence of a DR at 1.5 kHz.

DISCUSSION

The TEN_{HL} test and the fast-PTC procedure were examined for use with school-age children using equipment commonly available in the clinic. Both techniques are within the capability of children of this age because all children were able to complete the tasks. Thus, it should be expected that the results of both tests will give the same classification for the presence or absence of a DR. In this study, the TEN_{HL} test results interpreted using the adult 10-dB criteria were verified by measuring fast-PTCs as the standard reference. In 17 ears (81%), results obtained using both techniques were in agreement: nine ears did not meet the criteria for a DR and eight met the criteria. In four ears (19%), the results were in disagreement. This agreement rate is consistent with previous studies using adult listeners (Moore et al. 2000; Kluk & Moore 2006) but in contrast with the findings of Summers et al. (2003). The discrepancy in the outcome of the TEN tests and the fast-PTC tests reported previously was thought to be due to false-positive results on the TEN test. The 56% agreement rate reported by Summers et al. increased to 89% after changing the TEN_{HL} test criterion referring to a difference between the masked threshold and the TEN level/ERB_N to 14 dB.

On the basis of the findings of this study, the results of the TEN_{HL} test and the PTC procedure were in agreement when the masked threshold in TEN was <10 dB (no DR) or ≥15 dB (DR) of the TEN level/ERB_N. When the masked threshold was increased 11 to 14 dB above the TEN level/ERB_N, the disagreement in the outcomes of both tests was apparent (3-L, 3-R, and 12-L). The fast-PTCs have been successfully used as a technique for identifying off-frequency listening in adults (Summers et al. 2003; Sek et al. 2005; Kluk & Moore 2006) and can be reliably used with school-age children (Malicka et al. 2009). Therefore, it was assumed that the cases of disagreement are most likely due to false results on the TEN_{HL} test. False positives on the TEN_{HL} test have also been reported in previous studies with adults (Moore et al. 2000; Summers et al. 2003). One of the approaches to overcome the disagreement is to alter the TEN_{HL} test diagnostic criterion as done by Summers et al. (2003). However, adjusting the difference between masked threshold and TEN level/ERB_N indicating the presence of a DR from 10 to 14 dB did not increase the agreement rate because it reduced the false positives but increased false-negative results. Table 2 shows how a change in TEN_{HL} test criterion affects sensitivity and specificity of the test. Sensitivity and specificity (combined) shows the highest value when the TEN_{HL} test results were interpreted using the 10-dB criterion. Therefore, on the basis of the results of this study, the adult criteria proposed by Moore et al. (2000) seem to be the most appropriate when diagnosing a DR in children. However, in one case (5-L), the findings cannot be explained according to the theory of off-frequency listening because of the presence of a DR. The masked thresholds at two frequen-

TABLE 2. Sensitivity and specificity for different TEN_{HL} diagnostic criteria (difference between masked threshold and TEN level/ERB_N)

TEN _{HL} criterion (dB)	Sensitivity	Specificity
≥10	10/10 (100%)	34/37 (92%)
≥11	7/10 (70%)	34/37 (92%)
≥13	7/10 (70%)	37/37 (100%)

Sensitivity is defined as number of frequencies with evidence of a DR on the TEN_{HL} test divided by number of frequencies with evidence of a DR on PTCs. Specificity is defined as number of frequencies without evidence of a DR on the TEN_{HL} test divided by number of frequencies with no evidence of a DR on PTCs.

TEN, Threshold Equalizing Noise; ERB_N, averaged equivalent rectangular bandwidth; DR, dead region; PTC, psychophysical tuning curve.

cies inside the DR were not increased above absolute threshold as expected because the masker was sufficient enough to produce masking at f_{border} . One of the explanations for this phenomenon could be that the listener is attending to distortion products instead of components at the target tone frequency, which could potentially occur due to high stimulus presentation levels. However, further analysis of the stimulus spectrum for this measurement condition using an artificial ear (B&K type 4152) and spectrum analyzer (B&K type 2250) did not show the presence of any additional spectral components available for detection to the listener. Therefore, the TEN_{HL} results for 5-L at 1.5 and 2 kHz remain unexplained.

It has been suggested that the fast-PTC procedure provides more precise estimation of f_{edge} of DR than the TEN_{HL} test in adult listeners (Moore 2004; Sek et al. 2005; Kluk & Moore 2006). However, the large and variable shift in f_{tip} observed in normal-hearing (Malicka et al. 2009) and hearing-impaired children (this study) suggests that the estimation of f_{edge} is not more precise than that identified by the TEN_{HL} test. Furthermore, the time required to complete the TEN_{HL} test (about 15 min per ear) is shorter than the time required to complete the fast-PTCs (seven frequencies × approximately 5 min each fast-PTC measurement per ear). However, the fast-PTCs are considered a more reliable tool for diagnosing DRs. Therefore, in clinical practice, it would be recommended to use the fast-PTC procedure to confirm the TEN_{HL} test results (especially at frequencies where the masked threshold is 10 to 14 dB above the TEN level/ERB_N) rather than a separate tool for more precise estimation of f_{edge} .

Interestingly, participants who produced conflicting results on the TEN_{HL} test also experienced more difficulties when completing the fast-PTC test. This resulted in relatively large shifts in the tips of PTCs measured with f_{signal} outside DR (as indicated by TEN_{HL} test). Furthermore, the mean masked threshold in TEN across all tested frequencies for those ears (8.1 dB) was considerably higher than that for ears without a DR (3.6 dB) and for ears with DRs at frequencies outside a DR (5.5 dB). One of the explanations for these findings may be that problems in central auditory processing are responsible, at least in part, for the difficulties in attending to and extracting signals from the background noise. The mean test-retest repeatability on TEN_{HL} test in these participants was good, and no change of diagnostic category was observed on retest. However, without test-retest data for both measures in hearing-impaired children, the reason for this finding remains unclear.

Generally, the mean masked thresholds measured in the hearing-impaired children were higher than those previously

reported with hearing-impaired adults (Moore et al. 2000; Moore et al. 2004; Kluk & Moore 2006; Vinay & Moore 2007a) and hearing-impaired teenagers (Moore et al. 2003). There are also reports in the literature that young children perform poorly in background noise compared with adults (Irwin et al. 1986; Allen et al. 1989; Allen & Wightman 1992, 1994, 1995) but usually reach adult-like performance by the age of 10 to 12 yr (Schneider et al. 1989; Werner & Marean 1996). To assess whether or not the age of children affects the ability to detect a signal in TEN, a group of normal-hearing children was tested. The masked thresholds measured for TEN of low intensity (30, 40, and 50 dB/ERB_N) were below the TEN level/ERB_N irrespective of tested frequency. For noise levels of 60 and 70 dB/ERB_N, the masked thresholds increase relative to the TEN level/ERB_N, especially at high frequencies; however, they were never >5 dB above TEN level/ERB_N. The greater masking effect for higher levels at high frequencies may be explained in terms of the broader tuning at high levels related to an effect of spread of excitation along the basilar membrane (Glasberg & Moore 1990; Rosen & Baker 1994; Ruggero et al. 1997; Baker & Rosen 2006). The results of this study are in line with the results for normal-hearing adults (Moore et al. 2000) and normal-hearing teenagers (Moore et al. 2003). This suggests that there is not an age-related effect on masked thresholds in children compared with adults. However, there is a difference between normal-hearing and hearing-impaired children. This may be due to the history of reduced access to the sounds and the limited listening experience in hearing-impaired individuals.

CONCLUSIONS

The TEN_{HL} test and the fast-PTC technique can be successfully used with children as young as 8 yr. There is good agreement between outcomes of TEN_{HL} test and fast-PTCs, suggesting that the adult criteria for the TEN_{HL} test are appropriate in this age group. However, TEN_{HL} test results should be interpreted with caution when masked thresholds are 10 to 14 dB above the TEN level/ERB_N. Measuring fast-PTCs to reduce false-positive results in these cases is recommended.

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