Chinese Journal of Physiology 56(3): 129-137, 2013
DOI: 10.4077/CJP.2013.BAA065

Cochlear Dead Region and Word Recognition of Mandarin Chinese in Taiwan

Li-Min Tseng[1], Guo-She Lee[2, 3], Edward Yang[4], Neo Young[5], and Chien-Yeh Hsu[6]

[1]*Institute of Physiology, School of Medicine, National Yang-Ming University*
[2]*Faculty of Medicine and Institute of Brain Science, School of Medicine National Yang-Ming University*
[3]*Department of Otorhinolaryngology, Ren-Ai Branch, Taipei City Hospital*
[4]*Department of Speech and Hearing Disorders and Sciences, National Taipei University of Nursing and Health Sciences*
[5]*Assistive Technology Engineering Lab Inc.*
and
[6]*Graduate Institute of Medical Informatics, Taipei Medical University*
Taipei, Taiwan, Republic of China

Abstract

In a tonal language, the identity of a word depends largely on the tonal identification of the contour of vocal fundamental frequency energy of which usually centers in a low frequency of less than 600 Hz. However, cochlear dead region (DR) is present mostly in the frequency range of 2000 Hz to 4000 Hz, and the effect of DR on a tonal language is worth investigating. Thirty-two native Mandarin speakers with moderate-to-severe degree of sensorineural hearing loss were included in this study. The pure-tone audiometry, speech recognition threshold (SRT) and word recognition score (WRS) were used to evaluate the degree of hearing loss and word recognition. The threshold equalizing noise (TEN) tests were used to identify the presence of DR. The results showed that most DRs were present in high frequencies. The hearing thresholds of the ears with a DR were not significantly different from those without DR. However, the WRS was significantly worse for the DR ears, especially for those whose DR included three or more audiometric frequencies. A DR caused a significantly worse word recognition for the tonal language speakers of Mandarin in Taiwan, although the DR frequency occurred in the high frequency of 2000 Hz to 4000 Hz.

Key Words: cochlear dead region, Mandarin Chinese in Taiwan, sensorineural hearing loss, threshold equalizing noise, tonal language, word recognition

Introduction

Sensorineural hearing loss (SNHL) is common among the elderly and is a type of hearing loss associated with the pathologies in the cochlea, auditory nerve and/or central auditory nervous system. Measurement of hearing thresholds indicates the extent of SNHL, but cannot assess the distorted functions of cochlea. Therefore, subjects with similar pure tone thresholds may present with significantly different word recognition, and word recognition testing may provide a better quantification of the information carrying capacity of the cochlea (8). Damage to the cochlea gives rise to not only an abnormal hearing threshold but also a significant deterioration in word recognition.

Inner hair cells play a very important role in converting sound energy into neurological activities of the auditory system (20). Hearing impairment may sometimes be associated with loss of inner hair cells

Corresponding author: Dr. Guo-She Lee, Faculty of Medicine, School of Medicine, National Yang-Ming University, No. 155, Sec. 2, Li-Nong St., Bei-Tou District, Taipei 11221, Taiwan, R.O.C. Tel: +886-2-2826-7000 ext. 5100, Fax: +886-2-2820-2190, E-mail: guosheli@ms12.hinet.net; gslee@ym.edu.tw
Received: September 10, 2011; Revised (Final Version): June 13, 2012; Accepted: June 18, 2012.
 ISSN : 0304-4920. http://www.cps.org.tw

over a certain region of the basilar membrane, and the region is called as cochlear dead region (DR) (13, 14). The threshold equalizing noise (TEN) test is an alternative method other than psychoacoustic tuning measurements to identify the SNHL listeners with DR and is also used to detect the frequency of DR (16). Compared with the listeners without DR, previous studies reported that listeners with a DR showed worse understanding of vowel-consonant-vowel combination in the presence of noise (2) as well as a worse subjective hearing aid performance (11, 15, 17).

Most DRs are present in the high frequency from 2000 Hz to 4000 Hz (1, 18), and the tones falling within DR are perceived with an unclear pitch and/or a pitch different from "normal" whenever the tones fall more than 0.5 octave within a low- or high-frequency DR (9). In a tonal language, the identity of a word depends largely on tonal identification of the contour of vocal fundamental frequency (F_0) (5) in which the energy usually centers at a low frequency typically of less than 600 Hz. According to this characteristic of tonal language, the tonal language recognition might be less affected by a DR, especially when the DR is present in high frequency. The effect of DR on tonal language recognition is worth investigating.

In this work, the SNHL listeners with Mandarin as the native language were included. The TEN test was used to identify listeners with cochlear DR. The word recognition scores (WRS) were compared between participants with cochlear DR and those without cochlear DR. The degree of hearing loss, WRS and the number of audiometric frequencies within the DR were also obtained to explore the effects of DR on word recognition in the tonal language of Mandarin.

Materials and Methods

Subjects

Thirty-two subjects (18 males, 14 females) with moderate-to-severe SNHL and presenting to the audiologic clinic for fitting of hearing aids were recruited in the study. Subjects with a medical history of stroke, brain tumor, hypertension, diabetes mellitus, tuberculosis, chemotherapy, syphilis and treatment with streptomycin injection were excluded. All participants were native Mandarin speakers, and their ages ranged from 27 to 68 years old with a median of 59 years old (52.9 ± 12.2 years, mean ± SD). Informed consents were obtained from all participants.

Pure-tone audiometry, speech recognition threshold (SRT), rollover test of performance versus intensity function for phonemically balanced words (PI-PB) and tone-decay test were performed for all participants. Ears with a pure-tone threshold of greater than 90 dB HL at any frequency or with an air-bone gap of greater than 10 dB from 500 Hz to 4000 Hz were also excluded. Ears with possible retro-cochlear pathologies evidenced by a positive PI-PB rollover test or tone decay test were also excluded. Finally, a total of 25 subjects and 45 ears were enrolled.

Measurement of Hearing Thresholds

The pure tone audiometry was performed by an audiologist using a clinical audiometer (Model AC 40, Interacoustic A/S, Assens, Denmark) coupled with a Telephonics TDH-39 headset in a sound-proof booth. The pure tone average was calculated by averaging the hearing threshold levels at 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz and 4000 Hz. The SRT was determined as the intensity level at which 50% of Mandarin spondee were responded correctly, and each spondee word included two mandarin syllables of equal stress. SRT is usually used to verify the test results of pure tone audiometry clinically, and it was used in this work also for validation of the pure-tone hearing threshold levels.

Word Recognition Test

In Taiwan, the speech material most commonly used for Mandarin speech recognition is the PI-PB word list published by Wang and Chang in 1981 (19). The speech material is monosyllabic, scored by phoneme identification, and consisted of two subsets (WSA and WSB) in which each set includes a list of 50 different Mandarin PB words. The test for word recognition is the WSA list that has been used previously to test speech performances in both the subjects with normal hearing and the hearing impaired subjects with cochlear and retro-cochlear pathology (19). The speech recognition curve of the WSA list in the normal hearing individuals averaged 20.3% at 15 dB HL, 83.1% at 30 dB HL, 94.7% at 45 dB HL and 98.3% at 60 dB HL, respectively. In this study, the WSA list was used to test the word recognition of the subjects. The most comfortable level (MCL) was measured using conversional speech material presenting firstly at the intensity of 10 dB above the SRT, and an up-intensity step of 5 dB was then used to determine the MCL of the participants. The WRS tests were performed at the intensity level of MCL, and the WRS at that intensity is more related to the amount of the dynamic range which is exceeds the hearing thresholds at important frequencies.

In our clinical practice, the WSA list was subdivided into two subsets (WSA-1 and WSA-2) in which each subset consisted of 25 different PB words (Table 1) (19). Each word repeated correctly was valued at 0.04. To achieve a data distribution of

Table 1. The Mandarin phonetic-balance word lists by Wang *et al*.

WSA-1												
tɕian	tɕyn	tʂ	liou	liŋ	ɕiau	ɕiɛ	xau	ʂaŋ	ɕiŋ	tou	pu	kuai
見	軍	之	六	領	小	寫	號	上	省	都	不	怪
t^{h}uŋ	tɕ^{h}yɛn	tʂ^{h}an	min	fɑ	p^{h}i	san	tsuei	k^{h}an	i	u	uan	
同	全	產	民	法	皮	三	最	看	意	五	灣	
WSA-2												
tɕiŋ	tɕiau	tʂaŋ	tʂŋ	liaŋ	ɕiɑ	xɤ	xai	ʂuei	tiɛn	pɑ	kau	t^{h}iɛn
經	教	長	種	兩	下	河	海	水	電	把	高	天
tɕ^{h}i	tʂ^{h}u	mei	fən	p^{h}ɔ	suo	ts^{h}	ni	ru	yuaŋ	uaŋ	uan	
氣	出	美	分	破	所	次	你	如	育	王	文	

binominal variance, the scores were ARCSIN transformed using the following equation:

$$\mathrm{tWRS} = \arcsin(\sqrt{\mathrm{WRS}})$$

where tWRS is the ARCSIN transformed WRS, and tWRS was also used for statistical comparisons between different groups.

To maintain the validity of the test material, the individual word items were not repeated during the test and the same subject was never tested using the same list more than once. In order to score the WRS consistently, a jury of three audiologists participated in the scoring and the speech recognition performance focusing on the pronunciation of phonemes to avoid the effects of accent. The response to the test word was scored as correct when this was agreed by at least two audiologists, and the scoring was made at the test occasion with all three audiologists simultaneously.

To exclude retrocochlear pathologies, the PI-PB rollover screening tests were performed after the WRS tests using the 50 words of the WSA word list. A positive test was assumed if the WRS score of the test intensity of 80 dB HL was less than the test intensity of 70 dB HL. The Olsen-Noffsinger tone decay tests were performed by presenting a 2000-Hz pure tone at the intensity of 20 dB SL with the supra-aural headphones, and the test results were marked as "≤ 20 dB tone decay" if the tone was audible after continuous presentation of the tone for one minute (7). A ear without the result of "≤ 20 dB tone decay" was, therefore, excluded from this research.

Threshold-Equalizing Noise Test (TEN Test)

The audiometric and the TEN tests were performed using the AC-40 audiometer (Model AC-40, Interacoustics, Assens, Denmark) and the TEN used in this study was the version calibrated in dB HL (12). The TEN signals were generated by playing the TEN CD with the CD player (Model D-E707, SONY) and were then presented through a TDH-39 headphone of the audiometer. Calibrations were carried out before each subject was tested. The subjects were tested using the TEN at an intensity level of 10 dB/ERBN above the pure-tone hearing threshold of the test frequency (12). The test frequencies included 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz and 4000 Hz. The criteria of DR were a requirement of 10 dB or more for a signal to be perceived in a masked TEN. The 2-dB-up/5-dB-down step size was used to measure the thresholds, and a retest was done at the frequencies that met the criteria of DR. The AC-40 audiometer could output a pure-tone signal up to 120 dB HL from 400 Hz to 6300 Hz*, and for any audiometric frequency, the intensity level of TEN was less than 100 dB/ERBN.

Although there may be many different classification systems of DR, here we just wanted to make a simple definition system that might be used clinically in the future. The subjects with DR were grouped according to the number of DR frequencies for further

*Interacoustics A/S. Specifications of clinical audiometer AC40. 2011: 2007. http://www.widexhongkong.com.hk/pdf/ac40leaflet.pdf.

Table 2. The distribution of DR across the subjects†

Number of DR	0	1	2	3	4	5	6	
Number of Ears	22	6	8	6	2	0	1	
Percentage‡ (%)	48.9	13.3	17.7	13.3	4.4	0	2.2	
Frequency of DR	Nil	500	750	1000	1500	2000	3000	4000
Number of Ears	22	8	4	4	5	10	11	15
Percentage‡ (%)	48.9	17.7	8.9	8.9	11.1	22.2	24.4	33.3

†Total 25 subjects and 45 test ears. ‡The percentage in all test ears. DR, cochlear dead region.

analysis. The subgroups are [1] the group with one to two frequencies of DR (SDR); and [2] the group with three or more frequencies of DR (LDR).

Data Analysis

Comparisons of pure-tone average, MCL, WRS and ARCSIN transformed WRS between the group without any dead region (NDR) and the group with one or more dead regions were made using independent samples *t*-test. Correlations of mean hearing threshold levels with WRS were analyzed using Pearson's correlation analysis. Comparisons among NDR, SDR and LDR groups were made using one-way ANOVA and a *post-hoc* Student Newman-Keuls comparison. The software used for the statistical analysis was SigmaStat for Windows, Version 3.5 (Systat Software Inc., Chicago, IL, USA). A statistically significant difference was assumed to be present if $P < 0.05$.

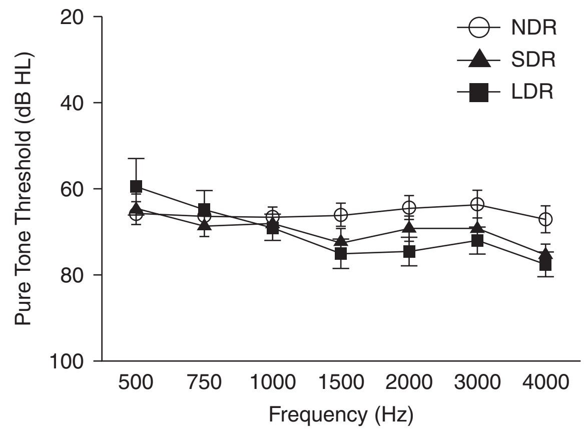

Fig. 1. The mean pure-tone hearing thresholds of the NDR, SDR and LDR groups. The number of observations for the NDR, SDR and LDR groups is 22, 13 and 10, respectively.

Results

The number of DR frequencies ranged from zero to six (Table 2), and twenty-three ears (51%) had a DR of at least one test frequency. In addition, the DR frequencies were found mainly in the range of 2000 Hz to 4000 Hz (Table 2). There were twenty-two ears that had no DR. Fourteen ears (31%) had a DR of one or two DR frequencies (SDR) and nine ears (20%) had a DR of 3 or more frequencies (LDR).

The pure-tone hearing threshold levels of NDR, SDR and LDR groups are illustrated in Fig. 1. The hearing thresholds of each test frequency were not significantly different among the three groups ($P > 0.05$, one-way ANOVA) except that the thresholds of the LDR group at 4000 Hz were worse than those of the NDR group ($P < 0.05$, power = 0.42, compared with NDR using one-way ANOVA, *post-hoc* Student Newman-Keuls comparison).

The results of the TEN test and pure-tone audiograms of the left ear of a participant without dead region (Fig. 2A) and of a participant with a DR (Fig. 2B) at three frequencies (1500 Hz, 2000 Hz and 3000 Hz) are demonstrated in Fig. 2. The pure-tone thresholds of the two participants are similar. However, the WRS of the participant with DR (24%) was much lower than that of the subject without DR (84%).

Although without significant differences ($P = 0.14$, independent samples *t*-test), the pure-tone averages of the 23 ears with DR (DR group, 71.6 dB HL ± 14.0 dB, mean ± 1 SD) were worse than the 22 ears without DR (NDR group, 65.9 dB HL ± 13.3 dB, mean ± 1 SD). The SRT of NDR group (68.2 dB HL ± 2.5 dB, mean ± 1 SD) was also not significantly different from the DR group (68.0 dB HL ± 2.2 dB, mean ± 1 SD) ($P = 0.97$, independent samples *t*-test). Moreover, the SRT of the NDR, SDR and LDR groups did not show significant between-group differences [$F(2, 18.87) = 0.15$, $P = 0.86$, one-way ANOVA]. The MCL of the NDR group was 82.3 dB HL ± 2.2 dB (mean ± 1 SD) and was not significantly different from the DR group (82.4 dB HL ± 1.8 dB, mean ± 1 SD) ($P = 0.97$, independent samples *t*-test). The MCLs of the three groups also showed no significant between-group differences [$F(2, 1.43) = 0.02$, $P = 0.99$, one-way ANOVA]. The homogeneity of variance using Levene Statistic was not significant for the

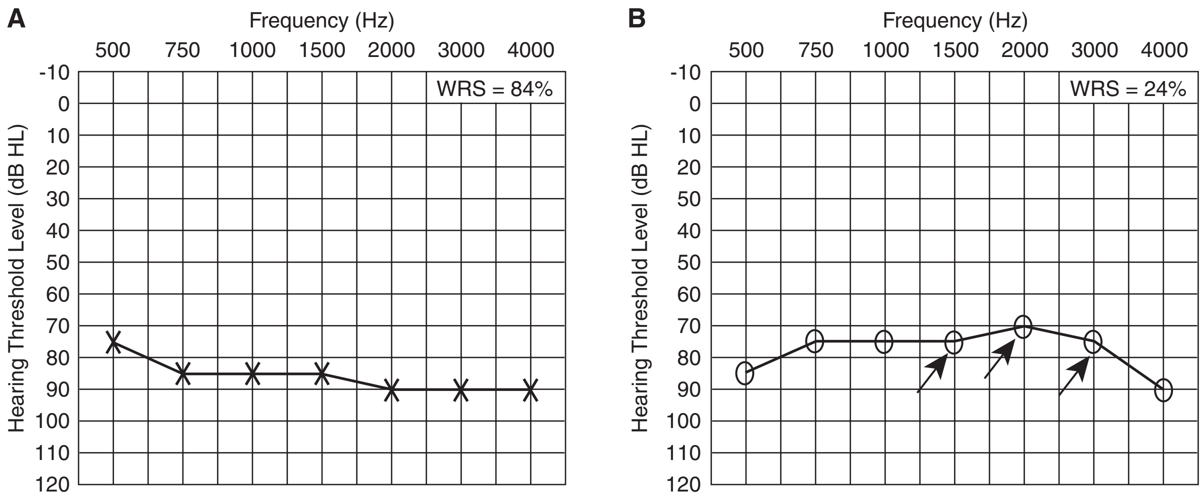

Fig. 2. The pure-tone audiograms and results of TEN test of the ears with sensorineural hearing loss (SNHL) but without a cochlear dead region (A), or with a cochlear dead region at the frequencies 1500 Hz, 2000 Hz and 3000 Hz (B). Crosses (✕), air-conduction hearing threshold level of the left ear; open circles (○), air-conduction hearing threshold level of the right ear; arrows (➚), presence of dead region at the test frequency.

above three tests ($P > 0.05$, ANOVA).

The tone-decay and PI-PB rollover tests were negative for all subjects. The WRS of the DR group (72.3% ± 3.3%, mean ± 1 SD) was significantly lower than the NDR group (82.7% ± 2.7%, mean ± 1 SD) ($P < 0.05$, power = 0.60, independent samples *t*-test). The ARCSIN-transformed WRS of the DR group (1.18 ± 0.19, mean ± 1 SD) was significantly lower than that of the NDR group (1.03 ± 0.16, mean ± 1 SD) ($P < 0.05$, power = 0.69, independent samples *t*-test). In addition, WRS also showed significant between-group differences across the NDR, SDR and LDR groups (Fig. 3A) [F (2, 14.07) = 8.32, $P < 0.001$, power = 0.93, one-way ANOVA]. The *post-hoc* pair-wise comparisons revealed significantly lower WRS for the LDR group than the NDR group ($P < 0.001$, one-way ANOVA, *post-hoc* Student Newman-Keuls comparison), and the WRS of the SDR group was also significantly better than the LDR group ($P < 0.05$, one-way ANOVA, *post-hoc* Student Newman-Keuls comparison). Moreover, after ARCSIN transformation, the transformed WRS also showed the same significant between-group differences across the NDR, SDR and LDR groups (Fig. 3B) [F (2, 7.7847) = 8.32, $P < 0.001$, power = 0.91, one-way ANOVA]. The *post-hoc* pair-wise comparisons revealed significantly lower ARCSIN-transformed WRS for the LDR group than the NDR group ($P < 0.001$, one-way ANOVA, *post-hoc* Student Newman-Keuls comparison), and the ARCSIN-transformed WRS of the SDR group was also significantly better than the LDR group ($P < 0.05$, one-way ANOVA, *post-hoc* Student Newman-Keuls comparison). These results suggested that word recognition was reduced in the ears with a DR of three or more audiometric frequencies.

The relationship between WRS and the mean hearing threshold level is shown in Fig. 4. For the ears without DR, the correlation of WRS with mean low-frequency hearing threshold levels (500, 1000, and 1500 Hz) was significant and was negative (Fig. 4A; $R = -.055$, $P = 0.01$, Pearson's correlation analysis). The correlation was also significant and negative for the high-frequency hearing (2000, 3000 and 4000 Hz) (Fig. 4C; $R = -0.53$, $P = 0.02$, Pearson's correlation analysis). However, for the ears with DR, the correlation between WRS and low-frequency hearing was lost (Fig. 4B; $R = -0.13$, $P = 0.47$, Pearson's correlation analysis). However, the correlation coefficient was also significant for the high-frequency hearing (Fig. 4D; $R = -0.47$, $P = 0.02$, Pearson's correlation analysis).

The power spectrum of the thirty-seven Mandarin Phonetic Symbols vocalized by a young female is illustrated in Fig. 5, and the symbols are expressed in international phonation alphabet (IPA)[#]. There are ten phonemes in which the energy concentrates at the frequency of 4000 Hz or higher.

Discussion

In this study, native Mandarin speakers with SNHL were evaluated using TEN tests to determine

[#]The International Phonetic Association. The International Phonetic Alphabet. 2005. http://www.langsci.ucl.ac.uk/ipa/IPA_chart_(C)2005.pdf.

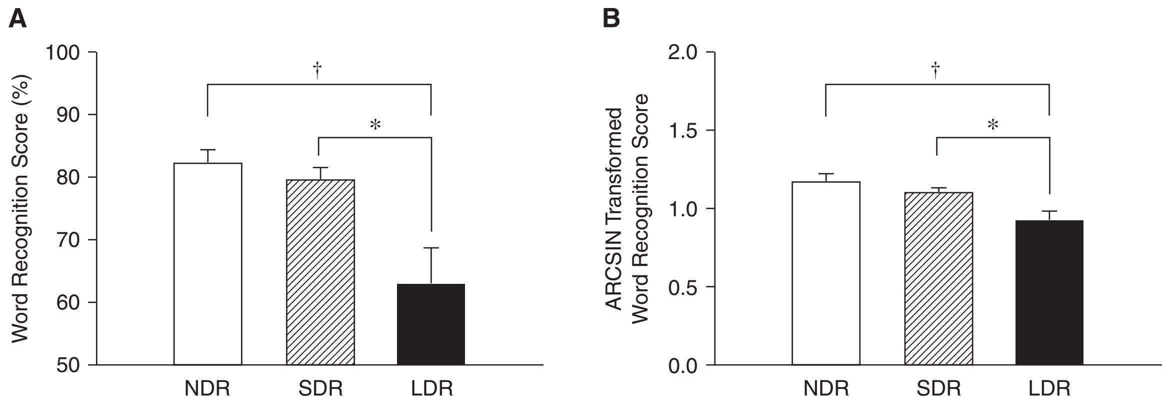

Fig. 3. Word recognition scores (A) and the scores after ARCSIN transformation (B) of the group without any cochlear dead region (NDR), the group a DR (DR), the group with a DR of one or two test audiometric frequencies (SDR), and the group with a DR of three or more test audiometric frequencies (LDR). $*P < 0.05$ and $^{\dagger}P < 0.01$, one-way ANOVA and *post-hoc* comparisons using Student Newman -Keuls comparison. Error bars indicate mean ± 1 SE. The number of observations of the NDR, DR, SDR and LDR groups is 22, 23, 13 and 10, respectively.

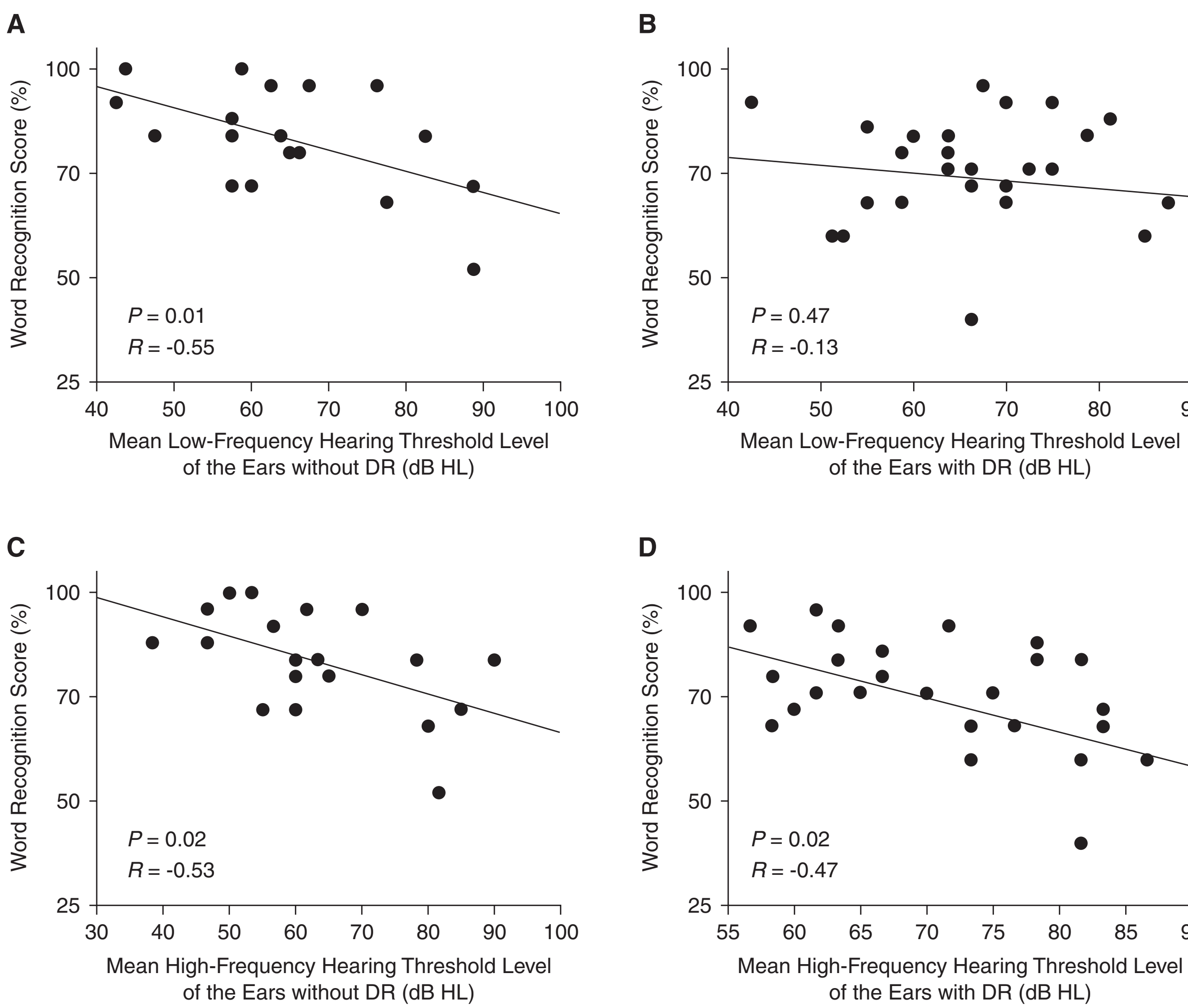

Fig. 4. Correlations of the mean low-frequency hearing threshold levels (500, 1000 and 1500 Hz) and mean high-tone hearing threshold levels (2000, 3000 and 4000 Hz) with word recognition scores for the ears without cochlear dead region (A and C), or with cochlear dead region (B and D). The relationships were analyzed using Pearson's correlation analysis. Significant correlation was assumed if $P < 0.05$. DR, cochlear dead region; R, correlation coefficient.

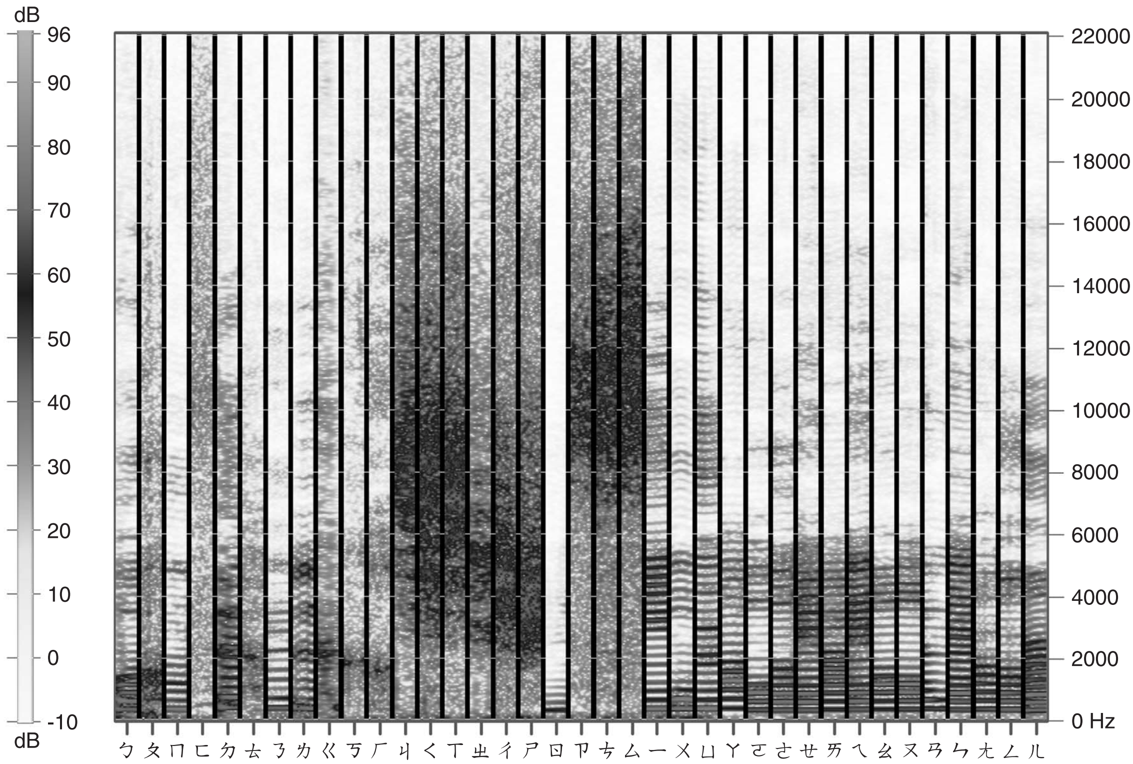

Fig. 5. The power spectrum of the thirty-seven Mandarin Phonetic Symbols vocalized by a female. The ten alphabets that are expressed as the international phonation alphabets (IPAs) (ㄈ, IPA [f]; ㄐ, IPA [tɕ]; ㄑ, IPA [tɕ^{h}i]; ㄒ, IPA [ɕ]; ㄓ, IPA [tʂ]; ㄔ, IPA [tʂ^{h}]; ㄕ, IPA [ʂ]; ㄗ, IPA [ts]; ㄘ, IPA [ts^{h}]; ㄙ, IPA [s]) concentrate their energy at the frequency of 4000 Hz or higher.

the frequencies of cochlear DR. The word recognition scores were obtained to represent the acuity of word recognition. The results revealed that the WRS of subjects with a DR was significantly worse than subjects without DR. However, the pure-tone average, SRT and MCL were not significantly different between the two groups. In addition, for the 20% ears (n = 9) with a DR of three or more audiometric frequencies, the WRS was even more profoundly affected.

There were 16 subjects (53%) who had at least a DR in one ear. This finding is in agreement with a previous study that reported 57.4% of adult SNHL subjects having at least one DR in one ear (18). The frequencies of DR were distributed mainly between 2000 Hz and 4000 Hz. However, there were also several ears showing a DR with a frequency as low as 500 Hz. In the middle frequency range of 750 Hz to 2000 Hz, the incidence of DR was relatively lower. The above results are in agreement with the research of Vinay and Moore in 2007 (18). Subjects with similar pure tone thresholds may have different word recognition performances (6), and the presence of cochlear DR that might not be strictly revealed by a TEN test may be the factor causing this significant difference. The inclusion of a test that is able to identify cochlear DR as a part of routine audiometric testing might be beneficial. In this work, we showed that the TEN tests were effective to detect a cochlear DR in the Mandarin speakers with SNHL in Taiwan and the TEN tests might be helpful in a clinical setting for hearing assessment and/or amplification.

A DR may cause more hearing loss at the frequency within the DR, and there was only a trend of worse pure-tone average of the DR group than the NDR group. The averaging process might explain this result. The DR was mainly present in the high frequency range from 2000 Hz to 4000 Hz. However, averaging the thresholds of all audiometric frequencies might have reduced the threshold difference between individual frequencies. In Fig. 1, both the NDR and DR subjects exhibited a similar degree of hearing loss in the low frequency range from 500 Hz to 1000 Hz, which is an important range for identification of the F_0 contour in Mandarin. The test material used for SRT is spondee words, which include two-syllable words having equal stress on each syllable. The transitions and contour of F_0 may provide a clue for recognition of the spondee in Mandarin. Therefore, the SRTs might not reveal a significant difference between the two groups. However, the test words of WRS, which are consonant-vowel syllables, may have a shorter duration of F_0 contour and fewer information of formant transition. This may not provide enough information for word recognition. The recognition has to depend more on phonetic identification of the word itself. Therefore, the WRS differed significantly between the two groups. In a study using a low-pass filtering technique and vowel-consonant-vowel nonsense syllables, the speech performance revealed a significant increase in the subjects without DR as the cut-off frequency used for low-pass filtering was increased. Besides, it was the amplifications up to 1.7 times of the edge frequency of a DR could be helpful for speech performance (17). Our results also supported that research on DR and revealed that the SNHL subjects with a DR of three or more frequencies had significantly impaired word recognition, even though the pure-tone average and SRT might be similar to that of the subjects without DR as that is revealed in Fig. 1.

The interaction of subject groups and the frequency on hearing threshold may have confounded the results of WRS. However the LDR group showed a significantly worsening of WRS ($P < 0.001$). Our results suggest another point of view that a high-frequency DR may affect word recognition more than the hearing threshold itself, at least for the tonal language of Mandarin. Therefore, a pure-tone audiometry and SRT may not predict the performance of word recognition well for Mandarin. A TEN test may provide additional information of the cochlear function related to the speech perception, and may be more sensitive in detecting a SNHL subject with impaired word recognition, especially for the tonal language speakers of Mandarin. However, to determine the exact effects of a DR on phoneme and tonal identification, there should be more explicit measurements such as inclusion of information transmission analysis. We here propose paying attention to the importance of determination of a DR in a tonal language listener with hearing impairment and the TEN test may be extrapolated into the domain of work recognition.

A full-list testing of 50 words has previously been recommended to determine the word recognition score (4), and the variability of the 25-word lists might be larger than a 50-word list. However, the significant worsening of WRS for the LDR group ($P < 0.001$) may still imply that a DR caused more impairment on speech discrimination than the hearing thresholds alone. A speech intelligibility index for Mandarin should be developed in the future to make more precise measurements of word recognition for Mandarin.

The high-frequency hearing thresholds were reported to be the major predictor for WRS in noise (3). However, our results showed a significant correlation of low- and high-frequency hearing threshold with the WRS only in NDR group. For the DR group, the correlation was only significant for the high-frequency hearing thresholds. The loss of linear correlation between WRS and the low-frequency hearing for the ears with DR suggests that the information loss in cochlear is not only in terms of the expected effects of amplification, especially for the ears with DR.

In tonal language, the identification of a word depends much on the tonal identity of the F_0 contour, which has the range 77 Hz to 261 Hz in adult Mandarin speakers (5). In this study, most DRs were present mainly between 2000 Hz and 4000 Hz, which is an important frequency range for phonemic identification. Nonetheless, the results still showed a significant worsening of word recognition when a high-frequency DR was present. It has been shown in the literature that secondary cues are used in Mandarin for word recognition when the primary cue of the tonal pattern is unavailable (10). The identity of a Mandarin word also depends a lot on its phonemic structure. In addition, 27% (10/37) of Mandarin Phonetic Symbols reveal an energy concentration at the frequency of 4000 Hz or higher (Fig. 4). Therefore, a preservation of high-frequency hearing is also important for word recognition in the tonal language of Mandarin, especially when the degree of SNHL is moderate to severe.

In conclusion, there is a significant worsening of word recognition in the Mandarin SNHL speakers with DR, even though the hearing thresholds were similar to the subjects without DR and the DR was present mostly in the high frequencies from 2000 Hz and 4000 Hz. Besides, for participants with a DR of three or more audiometric frequencies, the word recognition was affected more severely. The TEN test was useful in identification of this cochlear pathology and might help to predict the performance of word recognition for the tonal language speakers with SNHL.

References

1. Aazh, H. and Moore, B.C.J. Dead regions in the cochlea at 4 kHz in elderly adults: relation to absolute threshold, steepness of audiogram, and pure-tone average. *J. Am. Acad. Audiol*. 18: 97-106, 2007.
2. Baer, T., Moore, B.C.J. and Kluk, K. Effects of low pass filtering on the intelligibility of speech in noise for people with and without dead regions at high frequencies. *J. Acoust. Soc. Am*. 112: 1133-1144, 2002.
3. Barrenas, M.L. and Wikstrom, I. The influence of hearing and age on speech recognition scores in noise in audiological patients and in the general population. *Ear Hear*. 21: 569-577, 2000.
4. Beattie, R.C., Svihovec, D.A. and Edgerton, B.J. Comparison of speech detection and spondee thresholds and half- versus full-list intelligibility scores with MLV and taped presentations of NU-6. *J. Am. Audiol. Soc*. 3: 267-272, 1978.
5. Chen, S.H. The effects of tones on speaking frequency and intensity

ranges in Mandarin and Min dialects. *J. Acoust. Soc. Am*. 117: 3225-3230, 2005.

6. Ching, T.Y.C., Dillon, H. and Byrne, D. Speech recognition of hearing-impaired listeners: predictions from audibility and the limited role of high-frequency amplification. *J. Acoust. Soc. Am*. 103: 1128-1140, 1998.
7. Gelfand, S.A. Behavior Tests for Audiological Diagnosis. In: edited by New York: Thieme Medical Publishers, Inc., 2009, p. 304.
8. Halpin, C. and Rauch, S.D. Clinical implications of a damaged cochlea: pure tone thresholds *vs*. information-carrying capacity. *Otolaryngol. Head Neck Surg*. 140: 473-476, 2009.
9. Huss, M. and Moore, B.C.J. Dead regions and pitch perception. *J. Acoust. Soc. Am*. 117: 3841-3852, 2005.
10. Liu, S. and Samuel, A.G. Perception of Mandarin lexical tones when F0 information is neutralized. *Lang. Speech* 47: 109-138, 2004.
11. Mackersie, C.L., Crocker, T.L. and Davis, R.A. Limiting high-frequency hearing aid gain in listeners with and without suspected cochlear dead regions. *J. Am. Acad. Audiol*. 15: 498-507, 2004.
12. Moore, B.C.J., Glasberg, B.R. and Stone, M.A. New version of the TEN test with calibrations in dB HL. *Ear Hear*. 25: 478-487, 2004.
13. Moore, B.C.J., Huss, M., Vickers, D.A., Glasberg, B.R. and Alcantara, J.I. A test for the diagnosis of dead regions in the cochlea. *Brit. J. Audiol*. 34: 205-224, 2000.
14. Moore, B.C.J., Vickers, D.A., Glasberg, B.R. and Baer, T. Comparison of real and simulated hearing impairment in subjects with unilateral and bilateral cochlear hearing loss. *Brit. J. Audiol*. 31: 227-245, 1997.
15. Preminger, J.E., Carpenter, R. and Ziegler, C.H. A clinical perspective on cochlear dead regions: intelligibility of speech and subjective hearing aid benefit. *J. Am. Acad. Audiol*. 16: 600-613, 2005.
16. Vestergaard, M.D. Dead regions in the cochlea: implications for speech recognition and applicability of articulation index theory: Regiones cocleares muertas: implicaciones en el reconocimiento del lenguaje y su aplicabilidad en la teoría del índice de articulación. *Int. J. Audiol*. 42: 249-261, 2003.
17. Vickers, D.A., Moore, B.C.J. and Baer, T. Effects of low-pass filtering on the intelligibility of speech in quiet for people with and without dead regions at high frequencies. *J. Acoust. Soc. Am*. 110: 1164-1175, 2001.
18. Vinay, Moore, B.C. Prevalence of dead regions in subjects with sensorineural hearing loss. *Ear Hear*. 28: 231-241, 2007.
19. Wang, L.-T. and Chang, B.-L. A study on clinical application of the PB-word list in Mandarin speech sound. *J. Taiwan Otolaryngol. Head Neck Surg*. 16: 9-20, 1981.
20. Yates, G.K. Basilar membrane nonlinearity and its influence on auditory nerve rate-intensity functions. *Hear. Res*. 50: 145-162, 1990.