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Evaluation of Mandarin Chinese Speech Recognition in Adults with Cochlear Implants Using the Spectral Ripple Discrimination Test

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Statistical Analysis C
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Background: The aim of this study was to explore the value of the spectral ripple discrimination test in speech recognition evaluation among a deaf (post-lingual) Mandarin-speaking population in China following cochlear implantation.

Material/Methods: The study included 23 Mandarin-speaking adult subjects with normal hearing (normal-hearing group) and 17 deaf adults who were former Mandarin-speakers, with cochlear implants (cochlear implantation group). The normal-hearing subjects were divided into men (n=10) and women (n=13). The spectral ripple discrimination thresholds between the groups were compared. The correlation between spectral ripple discrimination thresholds and Mandarin speech recognition rates in the cochlear implantation group were studied.

Results: Spectral ripple discrimination thresholds did not correlate with age (r=–0.19; p=0.22), and there was no significant difference in spectral ripple discrimination thresholds between the male and female groups (p=0.654). Spectral ripple discrimination thresholds of deaf adults with cochlear implants were significantly correlated with monosyllabic recognition rates (r=0.84; p=0.000).

Conclusions: In a Mandarin Chinese speaking population, spectral ripple discrimination thresholds of normal-hearing individuals were unaffected by both gender and age. Spectral ripple discrimination thresholds were correlated with Mandarin monosyllabic recognition rates of Mandarin-speaking in post-lingual deaf adults with cochlear implants. The spectral ripple discrimination test is a promising method for speech recognition evaluation in adults following cochlear implantation in China.

MeSH Keywords: Citrus • Cochlear Implants • Speech Recognition Software

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Background

For patients with severe and profound sensorineural deafness, cochlear implantation is the most effective method of hearing restoration, and the indications for cochlear implantation are expanding [1]. Since the first multi-channel cochlear implantation was performed in China in 1995, more than 10,000 patients have received multi-channel cochlear implantation at this time [2]. Cochlear implantation is the preferred treatment for adults with sensorineural deafness, including elderly patients [3].

The evaluation of speech recognition in patients with cochlear implants is important for postoperative rehabilitation training. In China, different sets of Mandarin speech test materials are now in use for the evaluation of postoperative speech recognition in adults with cochlear implants, including the monosyllabic Mandarin recognition test, the disyllabic Mandarin speech test, and the sentence perception test [4–9]. However, these tests require that the subjects must repeat the monosyllabic or disyllabic words or sentences that they hear during the test. If the subjects cannot speak Mandarin or cannot speak Mandarin fluently, these may not be used in these subjects.

China is a multi-ethnic country, and each minority group has its own language. There are hundreds of Chinese language dialects, which may be mutually unintelligible [10]. Mandarin Chinese is the first language in only 66.2% of the population, and a large proportion of the population cannot speak Mandarin [11]. For these individuals, conventional speech recognition tests are inappropriate, and it is important to develop a new speech recognition test for different minority languages. However, given the diversity of minority languages and the scarcity of audiologists specialized in minority languages, this approach to hearing testing may not be feasible in China.

The spectral ripple discrimination test is a new test for measuring spectral peak resolution in audiology research and has several advantageous properties, including the efficient use of time and the independence of language of the test. Spectral ripple discrimination may be used in postoperative speech recognition evaluation and can be used to improve sound coding strategies for cochlear implants [12–17]. In 2003, Henry and Turner first detected spectral peak resolution ability in adults with cochlear implants and showed that the spectral peak resolution ability was impaired in these patients when compared with healthy individuals and that there was a correlation with vowel recognition [12]. In 2005, Henry et al. further developed a three-interval force-choice adaptive procedure to compare the spectral peak resolution thresholds between cochlear implant users, deaf patients, and normal individuals [13]. Henry et al. found that the spectral ripple discrimination test thresholds were correlated with the recognition of vowels and consonants in adult cochlear implants users whose native language was American English [13]. Won et al. found that the spectral ripple discrimination test thresholds were significantly correlated with the consonant-nucleus-consonant monosyllabic word recognition under quiet conditions among adult cochlear implant users whose mother language was American English [15]. The above findings imply that it is possible to employ spectral ripple discrimination testing for speech recognition evaluation among cochlear implant users. Chinese and English are two distinct languages. Chinese is a tonal language, and standard Mandarin has four tones, which is unlike English. At present, there are no reports on the clinical use of spectral ripple discrimination testing in cochlear implant users who speak Mandarin Chinese.

The aim of this study was to explore the value of the spectral ripple discrimination test in speech recognition evaluation among a deaf (post-lingual) Mandarin-speaking population in China following cochlear implantation. This study involved Mandarin monosyllabic recognition and the clinical value of the spectral ripple discrimination test in Chinese patients and also investigated whether age and gender and the long-term use of cochlear implants affected the spectral ripple discrimination in the Chinese population.

Material and Methods

Subjects studied

Twenty-three adults with normal hearing (normal-hearing group) and post-lingual deafness with unilateral cochlear implants (cochlear implantation group) were recruited into this study. The normal-hearing subjects were all native Chinese speakers who could speak Mandarin Chinese fluently, and who were aged between 23–50 years, with a median age of 30 years. The normal-hearing subjects were divided into men (n=10) and women (n=13), and the spectral ripple discrimination thresholds between the two groups were compared.

Normal hearing was defined as an average air conduction threshold ≤15 dB hearing level (HL), as shown by pure-tone audiometry, at test frequencies of 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, and 8,000 Hz. Inclusion criteria for the cochlear implantation group included age ≥18 years, post-lingual deafness, Chinese as the mother language, and the ability to speak Mandarin Chinese fluently before the occurrence of deafness, unilateral cochlear implantation, and bilateral severe or profound sensorineural deafness before cochlear implantation. Among the cochlear implant users, there were nine men and eight women, aged between 18–51 years (mean, 31.29±10.33 years). The mean cochlear implant-aided air conduction threshold ranged from 23–45 dB HL, tested in a

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Table 1. Baseline information of cochlear implant users.

Patient	Age	Sex	Duration of deafness (yr)	Etiology	Implantation side	Device	Duration of CI use (ms)
1	51	F	L 17, R 4	Meningitis (R), cholesteatoma (L)	R	Sonata	3
2	32	M	L7, R 7	Trauma	L	CS-10A	9
3	31	M	L2, R 2	Drug	R	Cochlear Nucleus CI512(N5)	0.5
4	44	M	L 1, R 1	Trauma	R	Sonata	3
5	44	F	L 13, R 13	Drug	L	Cochlear Freedom	6
6	20	M	L 16, R 16	Drug	R	Concerto	3
7	22	M	L 2, R 2	Unknown	R	CS-10A	3
8	39	F	L 2, R 2	Unknown	L	CS-10A	14
9	23	M	L17, R 17	Unknown	R	CS-10A	33
10	18	M	L12, R 12	Unknown	R	CS-10A	35
11	26	F	L4, R 4	Unknown	R	Sonata	25
12	27	F	L 17, R 17	Drug	R	AB HiRes90K	78
13	23	M	L 1.5, R 1.5	Unknown	R	Cochlear Freedom	31
14	21	F	L 3, R 3	Unknown	R	Concerto	19
15	47	F	L 5, R 5	Sudden deafness	R	Sonata	11
16	30	F	L 13, R 13	Sudden deafness	L	Cochlear Freedom	0
17	34	M	L 6, R 6	Unknown	R	Concerto	3

yr – years; CI – cochlear implant; ms – months; F – female; M – male; R – right; L – left.

free sound field with background noise below 20 dB, with the test frequencies of 125 Hz, 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, and 8,000 Hz. The baseline information of the cochlear implant users is shown in Table 1.

Mandarin Chinese monosyllabic recognition test and sentence recognition test

Under quiet conditions, and with any hearing aid removed on the other side, subjects with a cochlear implant were tested in a sound-free field with background noise <20 dB HL. The testing software was jointly developed by the Chinese Peoples' Liberation Army General Hospital and Tsinghua University. The Mandarin monosyllabic recognition and sentence recognition were detected in quiet conditions. For the Mandarin monosyllabic recognition test, a monosyllabic list developed by Ji et al. was used [18]. The test consisted of 22 pages, and 25 monosyllabic words were included in each sheet [18]. For the Mandarin sentence recognition test, Mandarin target sentences were taken from a revised Bamford-Kowal-Bench (BKB) standard sentence test list, which had ten sentences and 50 keywords [19]. The sound was delivered at 70 dB sound pressure levels (SPL). The loudspeaker was placed one meter in front of the subject at an angle of 45°, relative to the ears of the subject when in a sitting position. The subjects were required to repeat the words heard from the loudspeaker. The monosyllabic recognition and sentence recognition conducted in quiet were calculated automatically by software that was developed with the test [20].

Rippled noise stimuli

Rippled noise stimuli were identical to those previously described by Henry et al. [13]. The stimulus bandwidth was between 100–5,000 Hz with a modulation depth of 30 dB, which was obtained by algebraic summation of 200 pure-tone components. The amplitude of pure-tone components was determined from the sinusoidal envelope with ripples spaced on a logarithmic frequency scale. The beginning of each component was randomized to avoid regular pitch clues. There were 14 ripple frequencies that included 0.125, 0.176, 0.250, 0.354, 0.500, 0.707, 1.000, 1.414, 2.000, 2.828, 4.000, 5.657, 8.000 and 11.314

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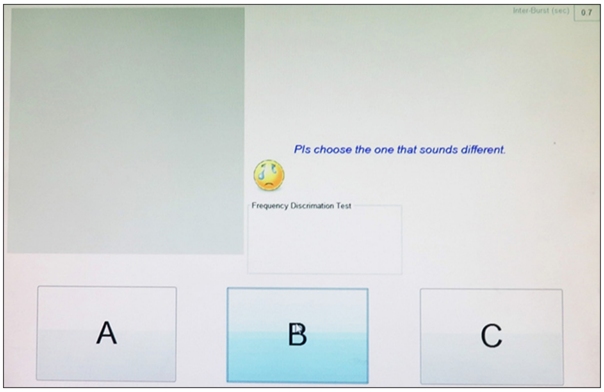

Figure 1. Operating screen of the spectral ripple discrimination test. If the answer is incorrect, a 'crying' face appears

ripples per octave. The frequency ratio was 1.414. For standard rippled stimuli, the spectral envelope phase of the stimuli was adjusted to zero phase at the low-frequency end. For inverted stimuli, the inverted phase was set. The duration of stimuli was 500 ms, with the rise and fall time of 150 ms, and the interval between stimuli was 500 ms. The stimuli were shaped with a filter, which approximated the long-term speech spectrum [21].

Spectral ripple discrimination test

The spectral ripple discrimination test was carried out in a sound field, as described above. Three stimuli (two stimuli were identical, and the third was the inverted stimulus) were delivered to the subjects at 70 dB SPL, and participants were required to pick out the different stimuli. If the subject perceived that the first stimulus was different from the other two, the letter 'A' would be selected on the computer screen; if the second stimulus was perceived to be different, the letter 'B' would be selected on the computer screen; if the third stimulus was perceived to be different, the letter 'C' would be selected on the computer screen; if the subject could not discriminate between the stimuli, they were required to select the 'best guess.' During the test, there was feedback on the computer screen, as shown in Figure 1.

The initial ripple frequency of each test was 0.176 ripples per octave. If the answer was wrong, the ripple frequency was reduced by a frequency ratio of 1.414; if the answer was right in two consecutive responses, the ripple frequency was increased by a frequency ratio of 1.414. The average number of ripples per octave for the final eight of 13 reversals was calculated as the 'spectral ripple discrimination thresholds. There were 60 groups of stimuli for each test, and it took about three minutes to complete each test. Before the test, 5–10 groups of stimuli were practiced so that the subjects were familiar with the test procedures. Each subject was tested three times, with a rest for one minute between two test runs. The final spectral ripple discrimination thresholds were determined as the mean of the three test runs.

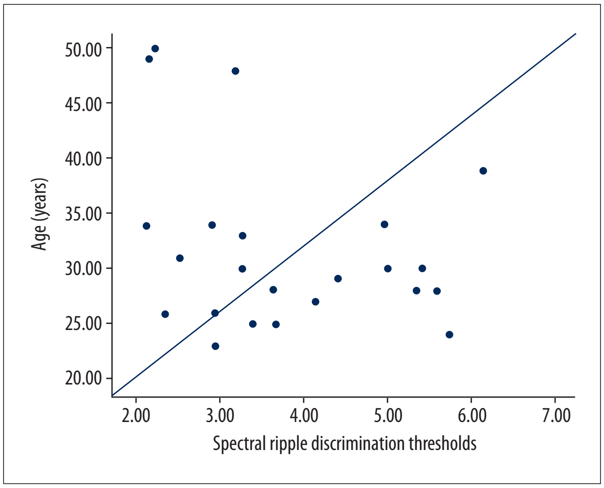

Figure 2. Correlation between the spectral ripple discrimination thresholds and age among normal-hearing adults. The spectral ripple discrimination thresholds are not significantly correlated with age among normal-hearing adults (r=–0.19) (p=0.22).

Statistical analysis

Statistical analysis was performed using SPSS version 16.0 software. Kendall's tau non-parametric rank correlation analysis was used to determine the correlation between spectral ripple discrimination thresholds and age between normal-hearing subjects. Spectral ripple discrimination thresholds among the male group and the female group were compared using a t-test. Any correlation between spectral ripple discrimination thresholds, Mandarin monosyllabic recognition, and sentence recognition in quiet conditions between the cochlear implant group were analyzed by using Kendall's tau correlation analysis. Differences in spectral ripple discrimination thresholds and Mandarin monosyllabic recognition among long-term users of cochlear implants (≥6 months) and short-term users of cochlear implants (<6 months) were analyzed using a t-test.

Results

Spectral ripple discrimination thresholds among normal-hearing subjects ranged from 2.14–6.13 ripples per octave, with a mean of 3.80±1.30 ripples per octave. Spectral ripple discrimination thresholds were not correlated with age (r=–0.19; p=0.22) (Figure 2). There was no significant difference in spectral ripple discrimination thresholds between the male group and female group (p=0.654). These findings indicated that spectral ripple discrimination thresholds were not related to gender or age.

The Mandarin monosyllabic recognition rate among cochlear implant users was between 12–96% with the mean of 38.35±21.77% (95% CI: 27.16–49.55%). The Mandarin sentence

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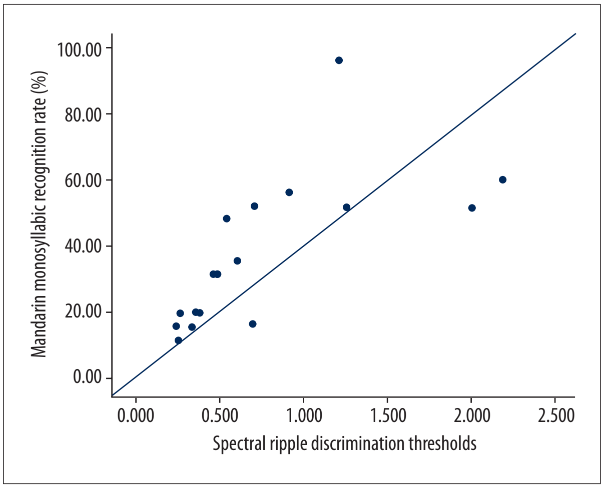

Figure 3. Correlation between the spectral ripple discrimination thresholds and Mandarin monosyllabic recognition rates among adult cochlear implant users. The spectral ripple discrimination thresholds show a significantly positive correlation with Mandarin monosyllabic recognition rates (r=0.84) (p=0.000).

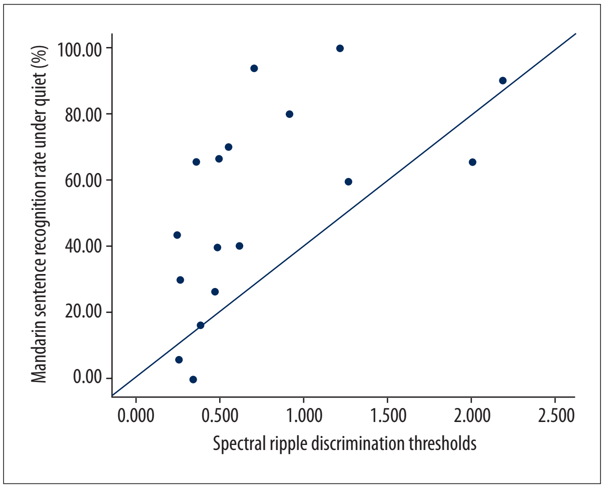

Figure 4. Correlation between spectral ripple discrimination thresholds and Mandarin sentence recognition rates among adult cochlear implant users. The spectral ripple discrimination thresholds showed a moderately significant positive correlation with Mandarin sentence recognition rates (r=0.537) (p=0.003).

recognition rate in quiet conditions ranged from 0–100%, with a mean of 52.59±30.51%. Spectral ripple discrimination thresholds among cochlear implant users ranged between 0.25–2.18 with a median of 0.49 ripples per octave. Spectral ripple discrimination thresholds showed a significant positive correlation with Mandarin monosyllabic recognition rates (r=0.84; p=0.000) (Figure 3). Spectral ripple discrimination thresholds showed a moderately significant correlation with sentence recognition rates in quiet conditions (r=0.537; p=0.003) (Figure 4). The long-term and short-term users of cochlear implants differed significantly in spectral ripple discrimination thresholds (mean, 1.01±0.65 *vs.* 0.38±0.17 ripples per octave) (p=0.026). The two groups also showed a significant difference in Mandarin monosyllabic recognition rates (mean, 49.50±20.60% *vs.* 24.00±1 3.86%) (p=0.012).

Discussion

Speech recognition evaluation of cochlear implant users is important for the rehabilitation training and tuning of cochlear implants. The most common method of patient evaluation following cochlear implant is to measure the monosyllabic recognition rate, disyllabic recognition rate, and sentence recognition rate under quiet conditions or noise, by requiring the subjects to repeat the words they hear [4–9]. However, in China, more than 250 different dialects and languages are in use, and many Chinese people cannot speak Mandarin Chinese [22]. For cochlear implant users who cannot speak Mandarin or who speak Mandarin fluently, the traditional speech recognition evaluation methods are inappropriate. Speech recognition test materials in some dialects have now been developed [23], but there remain unmet needs for the variety of dialects required. Therefore, a new speech recognition test that is not dependent on language is required.

The spectral ripple discrimination test can satisfy the requirement of speech recognition testing, which is independent on language or dialect, by measuring spectral peak resolution [24]. The spectral ripple discrimination test was first used to evaluate normal-hearing subjects [24]. Henry et al. applied spectral ripple discrimination to hearing-impaired subjects or cochlear implant users and found that normal-hearing subjects achieved the highest spectral ripple discrimination thresholds, followed by hearing-impaired subjects, and cochlear implant users performed the worst on testing [12,13]. Furthermore, spectral ripple discrimination thresholds showed a moderately positive correlation with vowel and consonant recognition under quiet conditions among cochlear implant users whose mother tongue was American English [12,13]. Won et al. found that spectral ripple discrimination thresholds had a moderately significant negative correlation with speech recognition thresholds under noise conditions among cochlear implant users whose mother tongue was American English (r=–0.55 in babble noise; r=–0.62 in steady-state noise), and they had a moderately positive correlation with the consonant-nucleus-consonant monosyllabic word recognition test under quiet conditions (r=0.50) [14]. Another previously published study indicated that the coefficient of correlation between spectral ripple discrimination thresholds and consonant-nucleus-consonant monosyllabic word recognition among cochlear implant users whose mother tongue was American English was as high as 0.66 [25]. This finding indicated the close relationship between spectral ripple discrimination thresholds and speech recognition among cochlear implant users whose mother tongue was American English [25].

The present study focused on the correlation between spectral ripple discrimination thresholds and Mandarin speech recognition among Chinese cochlear implant users and found a highly significant positive correlation between spectral ripple discrimination thresholds and Mandarin monosyllabic recognition rates (r=0.84; p<0.01). The correlation coefficient was much greater than that reported by Won and Drennan et al. [14,25], probably due to language difference, as discussed above. Furthermore, the duration of cochlear implant use was also different when compared to other previously published studies. The median duration of cochlear implant use was nine months; 41.18% (7/17) of the patients wore cochlear implants less than six months. In the studies by Won et al., and also by Drennan et al., the proportion of patients wearing cochlear implants for less than 6 months was 3.85% (1/26) and 0% (0/28), respectively [14,25].

The findings of the present study found that as the monosyllabic recognition rate increased significantly among long-term users of cochlear implants (>6 months) compared with short-term users of cochlear implants (<six months) (P<0.05), spectral ripple discrimination thresholds also increased significantly (P<0.05). These findings indicated a synchronized improvement of spectral ripple discrimination ability and speech recognition over time among cochlear implant users. However, according to Drennan et al., only monosyllabic recognition improved among patients using cochlear implants for 12 months compared with those using cochlear implants for one month, while spectral ripple discrimination thresholds did not increase significantly [25]. Such an inconsistent finding may be due to smaller change of speech recognition rates between the two groups. In the study by Drennan et al., the difference in consonant-nucleus-consonant monosyllabic word recognition rates was only 8.3% on average between the two groups [25]. In contrast, the difference in monosyllabic word recognition rates reached as high as 24.5% between patients using cochlear implants for more than six months and those using cochlear implants for less than six months in our study.

Also, in this study, spectral ripple discrimination thresholds were significantly correlated with sentence recognition rates under quiet condition (r=0.537; p<0.01), indicating a close relationship between spectral ripple discrimination and speech recognition among cochlear implant users. No significant correlation was found between spectral ripple discrimination thresholds and age among normal-hearing subjects, which agreed with the previous findings by Henry et al. [13]. Comparison of spectral ripple discrimination thresholds between normal-hearing women and men indicated no gender difference (P>0.05). The spectral ripple discrimination test was time-efficient, as it took only about 15 min to complete the test. Previously published studies have consistently confirmed the test-retest reliability of spectral ripple discrimination, which does not show a significant learning period or effect [14,25,26]. Therefore, spectral ripple discrimination is a candidate method for postoperative speech recognition evaluation among Chinese cochlear implant users, especially those who cannot speak Mandarin Chinese. Therefore, it is possible that the spectral ripple discrimination test might be suitable to replace the monosyllabic word recognition test.

However, before recommendations can be made regarding the implementation of the spectral ripple discrimination test for clinical application, further controlled, multi-center studies are required that include a larger study sample size to confirm the findings of the present study, including the significant correlation between spectral ripple discrimination thresholds and Mandarin monosyllabic recognition rates among cochlear implant users. Whether or not both the spectral ripple discrimination test and the monosyllabic recognition test will be improved over time remains to be determined. Also, the correlation between spectral ripple discrimination thresholds and Mandarin monosyllabic recognition rates among pre-lingual deaf adult cochlear implant users remains to be investigated. Finally, whether spectral ripple discrimination thresholds are highly correlated with monosyllable recognition rates in main Chinese dialects also remains to be investigated.

Also, the spectral ripple discrimination test not only has the potential to be applied to adult cochlear implant users but also to children and teenager users. Jung et al. reported that there was no significant difference in spectral ripple discrimination thresholds between pre-lingual deaf children with cochlear implants and post-lingual deaf adult cochlear implant users whose mother tongue was English [27]. In the same previous study, spectral ripple discrimination thresholds among pre-lingual deaf children with cochlear implants were significantly correlated with consonant-nucleus-consonant monosyllabic word recognition rates under quiet conditions and speech recognition rates under noise conditions [27]. This finding was similar to that of post-lingual deaf adult cochlear implant users [14]. However, the correlation between spectral ripple discrimination thresholds and Mandarin monosyllabic recognition rates among children and teenage cochlear implant users remains to be investigated.

Conclusions

In a Mandarin Chinese speaking population, spectral ripple discrimination thresholds of normal-hearing individuals were

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unaffected by both gender and age. Spectral ripple discrimination thresholds were correlated with Mandarin monosyllabic recognition rates of Mandarin-speaking in post-lingual deaf adults with cochlear implants. The spectral ripple discrimination test is a promising method of speech recognition evaluation in adults following cochlear implantation in China.

Spectral ripple discrimination thresholds showed a highly significant correlation with Mandarin monosyllabic recognition rates among post-lingual deaf adult cochlear implant users and showed a moderately positive correlation with Mandarin sentence recognition rates under quiet. Moreover, spectral ripple discrimination thresholds were not correlated with age or gender. Spectral ripple discrimination thresholds and monosyllabic recognition rates increased synchronously as the continued use of cochlear implants. Given that the spectral ripple discrimination test is rapid, reliable and independent from languages, it is a promising method for speech recognition evaluation in Chinese adult cochlear implant users.

Conflict of interest

None.

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