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Assessment of outcomes of hearing and speech rehabilitation in children with cochlear implantation

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ABSTRACT

Objectives: This study aimed to assess the effect of hearing and speech rehabilitation in patients with Nurotron® cochlear implants.
Design: Ninety-eight paediatric patients with bilateral severe-to-profound sensorineural deafness who received cochlear implantation were divided into three groups according to age: group A (≤3 years), group B (4–7 years), and group C (8–16 years). All patients were followed up for one year for hearing and speech performance after the surgery. The comprehensive Auditory Perception Assessment, MAIS, CAP and SIR hearing and speech assessments and rating materials were used for assessment before the surgery and at 3, 6, and 12 months after implant activation.
Results: The scores of patients in the open-set speech assessment, Chinese Auditory Perception Assessment, MAIS, CAP and SIR significantly improved after cochlear implantation in all age groups. The younger the age at implantation, the better the results. Moreover, the hearing and speech performance of cochlear implant recipients gradually improved with the extension of rehabilitation time.
Conclusions: Nurotron® Venus™ cochlear implantation can improve the hearing and speech performance of patients with bilateral severe-to-profound sensorineural deafness.

1. Introduction

Sensorineural deafness is one of the key factors affecting the health and quality of life of human beings. A recent survey indicated that compared with people with normal hearing, the mortality risk of people with moderate and mild hearing loss was increased by 39% and 21%, respectively (Contrera et al., 2015). In addition, hearing loss negatively impacts patients' cognitive, psychological and physiological function to some extent (Contrera et al., 2015). A cochlear implant (CI) is a special electronic device that can convert acoustic energy into electric energy. The external acoustical signal is converted and processed into electrical stimulation signals, which can replace the function of the damaged hair cells of the inner ear to stimulate the auditory nerve and finally produce auditory signals. Cochlear implantation is considered as one of the best options to restore the hearing of patients with severe-to-profound deafness and to help them return to the world of sound (Chen and Oghalai, 2016; Hanvey et al., 2016; Russell et al., 2013).

Nurotron® Cochlear Implants were officially approved for clinical use in August 2011 and have been used in paediatric patients over 1 year of age since July 2012. Nurotron® is improved in Venus™ Cochlear Implant System based on the characteristics of Chinese pronunciation, which enables deaf children to understand the four-tone pronunciation of the Chinese language (Li et al., 2014, 2015; Gao et al., 2016). Because of the relatively short time since the initial clinical application of Nurotron® cochlear implants, reliable long-term follow-up data from a large sample of patients have not yet been obtained. To evaluate the effectiveness and safety of Nurotron® cochlear implantation, we carried out postoperative

Abbreviations: CI, Cochlear implant; APA, Auditory perception assessment; CAP, Categories of Auditory Performance; SIR, Speech Intelligibility Rate; MAIS, Meaningful auditory integration scale.

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auditory assessments and evaluated the rehabilitative effects after Nurotron® cochlear implantation, which provided a basis for further clinical applications of Nurotron® cochlear implants.

2. Materials and methods

2.1. Study subjects

Ninety-eight patients with bilateral severe-to-profound sensorineural deafness who received unilateral cochlear implantation at Yijisan Hospital of Wanan Medical College from July 2013 to October 2015 were included in this study. All patients were diagnosed with bilateral severe-to-profound sensorineural deafness through preoperative experimental examinations, middle ear mastoid process CT, head MRI and inner ear three-dimensional imaging, brainstem evoked potential, hearing tests and acoustic impedance examinations. Among them 51 were male and 47 were female. Seventeen of the patients had prelingual deafness, and 81 patients had postlingual deafness. Two of the patients received cochlear implantation on the left side and 96 cases received implantation on the right side; the youngest patient was 1 year old and the oldest was aged 16, with an average age at implantation of 8.86 ± 3.66 years. Group A included 10 patients under 3 years of age, group B included 26 patients aged between 4 and 7 years, and group C included 62 patients aged between 8 and 16 years. All subjects received hearing and speech rehabilitation training at various hearing rehabilitation centres in Anhui Province for 1 year after cochlear implantation. The study was reviewed and approved by the Ethical Committee of Yijishan Hospital.

All patients had bilateral severe-to-profound sensorineural deafness and met the requirements set out in the guidelines for cochlear implantation (2013) (Editorial board of Chinese Journal of Otorhinolaryngology Head and Neck Surgery et al., 2014). The Hiskey-Nebraska Test of Learning Aptitude was used to test the patients over 3 years of age, and the Griffith Psychological Development and Behaviour Scale was used to test the patients under 3 years of age.

2.2. Assessment and evaluation methods

2.2.1. QuikSTAR auditory perception comprehensive assessment system

QuikSTAR Comprehensive Auditory Perception Assessment System was selected for the assessment (Li et al., 2015). This system includes the advanced Chinese auditory perception assessment (ACAPA) test and the comprehensive open Chinese speech and auditory perception assessment test. ACAPA includes four tests: word identification (including 24 questions on single character phrases, 24 questions on phrases with multiple characters and 10 questions on digital identification); basic assessment (16 questions on ambient sounds, 24 questions on recognition of simple or compound vowels of a Chinese syllable, 24 questions on recognition of the initial consonant of a Chinese syllable and 16 questions on recognition of tones); advanced assessment (64 questions on vowel recognition, 80 questions on consonant recognition test, 64 questions on tone recognition and 54 questions on musical notes test); and hearing threshold (25 questions on sequential numerical string threshold value, 25 questions on reverse numerical string threshold value, 25 questions on steady noise threshold value and 25 questions on dynamic noise threshold). There were 500 questions in the four tests, and with 2 scores for each question, the total possible score was 1000. The patients' final scores were given as percentages. The open-set Chinese speech and comprehensive auditory perception assessment mainly consists of recognition of Mandarin phrases, including house phrase recognition and recognition of 301 short sentences and 301 double-character phrases. The final score was also given as a percentage.

2.2.2. Meaningful auditory integration scale questionnaire (MAIS)

The MAIS was created in 1991. Each questionnaire includes 10 questions. Questions 1–2 reflect patients' confidence in hearing devices, questions 3–6 reflect auditory sensitiveness, and questions 7–10 reflect the ability to connect sounds with meaning (Robbins et al., 1991). The questionnaire includes information about the child's habits while wearing hearing devices, the distance at which the child can hear sound, and the child's ability to obtain more information from these sounds, e.g., the child's ability to distinguish between the voices of different people. The Questionnaire for Parents is completed by interview in which the testers read the questions to the parents and score or ideally record the parents' answers. If the parents have been interviewed twice, they may complete the questionnaire directly by themselves. Questions 1–2 are different for children with different conditions. Question 1 includes three levels (A, B, C) of questions: 1A is used for children under five years old, while 1B is used for children over 5 years old, and 1C is used for children who cannot answer either Q 1A or 1B. Question 2 includes two levels of questions (A, B): 2B is used if the parents cannot answer 2A. The tester reads the questions to the parents and score their answers. The criteria for the five-level (level 0–4) scoring are as follows: 0 = never, 1 = seldom, 2 = sometimes, 3 = frequently, 4 = always. Scores are also given according to the answers of the relatives or teachers of the patient.

2.2.3. Categories of auditory performance and speech intelligibility rating

Categories of Auditory Performance (CAP) and the Speech Intelligibility Rating (SIR) were developed by the University of Nottingham for the assessment of children's daily auditory and speech ability (Han et al., 2007), which have been widely used in the assessment of the effect of speech rehabilitation after cochlear implantation in young children (Li et al., 2014; Archbold et al., 1998; Nikolopoulos et al., 2005).

2.2.4. Data acquisition

Typically, patients with cochlear implants had their devices activated approximately 1 month after the surgery, and they were followed up at 3, 6, and 12 months after the device activation. QuikSTAR comprehensive hearing capacity assessment software, MAIS, CAP and SIR were used to assess and record the auditory and speech performance of patients prior to cochlear implantation and at 3, 6, and 12 months after the device activation. All cochlear implant recipients received postoperative rehabilitation and speech training at local hearing and speech rehabilitation centres.

2.2.5. Statistical analysis

SPSS 19.0 statistical software was used for the analysis. At each time point (before surgery, follow-up at 3, 6 and 12 months), MAIS scores, open-set speech assessment scores and scores of ACAPA all had a normal distribution. Repeated measures ANOVA was adopted. One-way ANOVA analysis of variance was adopted for comparing MAIS scores, open-set speech assessment scores and Chinese auditory perception assessment scores of the three age groups at each time point. The CAP and SIR levels rated for each time point were not normally distributed, and the rank-sum test was adopted. $P < 0.05$ was considered statistically significant.

3. Results

3.1. Hearing and speech ability of cochlear implant recipients in different age groups

3.1.1. Effect of cochlear implantation on MAIS scores in different age groups

Implantation of Nurotron® cochlear implants improved the MAIS score in all age groups of patients. As shown in Table 1, in each age group the score recorded after the implant activation were markedly higher than that before the surgery, indicating the improvement of the speech intelligibility conferred by Nurotron® cochlear implants. Moreover, MAIS score gradually increased as the time of rehabilitation extended.

3.1.2. Effect of cochlear implantation on scores of open-speech in different age groups

The scores of the open-set speech assessment for groups A, B and C before and after the surgery were recorded. The results of repeated measures ANOVA indicated that Nurotron® cochlear implantation significantly improved the open-set speech level of each group and the improvement was enhanced as the rehabilitation time increased (Table 2) (see Table 3).

3.1.3. Effect of cochlear implantation on scores of Chinese auditory perception in different age groups

In all age group of patients, the score of the Chinese Auditory Perception was significantly higher after the implantation of Nurotron® cochlear implants. Moreover, for each age group, the score increased as the time of rehabilitation extended.

3.2. CAP and SIR rating of each group at each time point after surgery

The Rank Sum Test was used to examine the CAP and SIR results of each group before and after the surgery. The differences among groups were not statistically significant before the surgery or at 3 months or 6 months after the device activation. Twelve months after activation, the CAP and SIR scores started to show significant differences among groups. These results were consistent with the results of the open-set speech assessment, auditory perception assessment, and MAIS questionnaire which all showed improvements in scores over time. Therefore, 12 months after the activation, QuickSTAR assessment software was used for hearing and speech assessment for each age group. The test of open-set speech assessment and Chinese auditory perception assessment further indicated the difference in the effects in different age groups. Results of CAP and SIR assessment are shown in Tables 4 and 5.

3.3. Comparison of hearing and speech ability of patients with different ages after cochlear implantation

3.3.1. Comparison of postoperative MAIS scores of patients from different age groups

The differences in MAIS scores of group A (23.60 ± 3.10), group B (26.31 ± 3.11) and group C (20.55 ± 3.66) at 3 months after implant activation were statistically significant ($F = 25.9$, $P < 0.01$). Comparisons between groups showed a p value of 0.039, 0.011, and 0.009 for group A vs. group B, group A vs. group C, and group B vs. group C respectively. Similarly, the differences in MAIS scores of patients of all age groups at 6 months ($F = 15.1$, $P < 0.01$) and 12 months ($F = 7.6$, $P < 0.01$) after the implantation were of statistical significance. Further comparisons between groups at 6 months showed that the MAIS score differed significantly between group A (27.70 ± 3.34) and group C (24.68 ± 3.23) ($p = 0.010$) and between group B (28.81 ± 3.69) and group C ($p < 0.01$) whereas the difference between group A and group B did not reach statistical significance ($p = 0.379$). The comparable MAIS scores in groups A (31.90 ± 5.02) and B (31.19 ± 3.81) ($p = 0.603$) and the significant differences between group A and group C (28.44 ± 3.33) ($P < 0.05$) and between group B and group C ($P < 0.05$) were also observed at 12 months after the implantation. These results indicated that the younger the age at cochlear implantation, the better the postoperative auditory and speech rehabilitation. See Table 1.

3.3.2. Comparison of postoperative open-set speech scores of patients from different age groups

Comparisons of open-set speech scores among three age groups indicated that the differences in scores at 3 months after device activation were statistically significant ($F = 46.07$, $P < 0.01$). The score of group B (27.38 ± 5.33) was higher than that of group A (24.30 ± 2.36) and group C (19.42 ± 2.85) ($P = 0.025$, B *vs.* A; $P < 0.01$, B *vs.* C), and group A performed better than group C ($P < 0.01$). The score differences among age groups were also observed at 6 ($F = 72.71$, $P < 0.01$) and 12 months ($F = 41.02$, $P < 0.01$) after the surgery. Both group A and group B scored higher than group C (**A vs. C:** 32.81 ± 2.74 vs. 24.89 ± 3.21 at 6 months, $P < 0.01$, and 49.50 ± 5.68 vs. 36.83 ± 3.48 at 12 months, $P < 0.01$; **B vs. C:** 36.81 ± 6.69 vs. 24.89 ± 3.21 at 6 months, $P < 0.01$, and 47.31 ± 9.48 vs. 36.83 ± 3.48 at 12 months, $P < 0.01$). These results indicate that the younger the age at cochlear implantation, the better the postoperative speech rehabilitation. See Table 2.

3.3.3. Comparison of postoperative chinese auditory perception scores of from different age groups

Comparisons of the Chinese auditory perception scores among three age groups indicated that the differences in scores at 3 months after device activation were statistically significant ($F = 8.2$, $P = 0.001$). The score of group B (48.65 ± 5.36) was higher than that of group A (39.90 ± 7.39) and group C (44.34 ± 6.37) ($P < 0.01$, B vs. A; $P = 0.004$, B vs. C), and group A performed better than group C ($P = 0.039$). The score differences among age groups were also observed at 6 ($F = 1.9$, $P = 0.145$) and 12 months ($F = 3.5$, $P = 0.033$) after the surgery. Further comparisons between groups at 12

Table 1
MAIS scores of each patient group before and after cochlear implantation.

Group	Before Implantation	After activation			P Value
		3 Months	6 Months	12 Months	
Group A (10)	8.90 ± 2.51	23.60 ± 3.10	27.70 ± 3.34	31.90 ± 5.02	<0.01
Group B (26)	13.42 ± 3.35	26.31 ± 3.11	28.81 ± 3.69	31.19 ± 3.81	<0.01
Group C (62)	13.94 ± 4.40	20.55 ± 3.66	24.68 ± 3.23	28.44 ± 3.33	<0.01
F Value	6.85	25.90	15.10	7.6	
P Value	0.002	0.000	0.000	0.001	

Table 2
Scores of open speech assessment for each group before and after cochlear implantation (%).

Group	Before Implantation	After activation			P Value
		3 Months	6 Months	12 Months	
Group A (10)	9.70 ± 2.41	24.30 ± 2.36	32.81 ± 2.74	49.50 ± 5.68	<0.01
Group B (26)	13.89 ± 3.27	27.38 ± 5.33	36.81 ± 6.69	47.31 ± 9.48	<0.01
Group C (62)	13.69 ± 3.90	19.42 ± 2.85	24.89 ± 3.21	36.83 ± 3.48	<0.01
F Value	5.66	46.07	72.71	41.02	
P Value	0.005	0.000	0.000	0.000	

Table 3
Results of Chinese auditory perception assessment for each group before and after the cochlear implantation (%).

Group	Before Implantation	After activation			P Value
		3 Months	6 Months	12 Months	
Group A (10)	17.2 ± 5.57	39.90 ± 7.39	55.40 ± 10.46	68.70 ± 10.07	<0.01
Group B (26)	20.77 ± 5.16	48.65 ± 5.36	59.65 ± 8.77	72.54 ± 9.79	<0.01
Group C (62)	24.78 ± 8.06	44.34 ± 6.37	56.16 ± 7.21	67.27 ± 7.57	<0.01
F Value	6.4	8.2	1.9	3.5	
P Value	0.002	0.001	0.145	0.033	

Table 4
Comparison of CAP assessment results for all groups before and after cochlear implantation.

Group	Before Implantation (mean rank value)	After activation		
		3 Months (mean rank value)	6 Months (mean rank value)	12 Months (mean rank value)
Group A (N = 10)	48.10	42.50	36.40	32.45
Group B (N = 26)	54.88	46.27	53.77	63.65
Group C (N = 62)	47.47	51.98	49.82	46.31
t Value	1.73	3.85	3.79	12.79
P Value	0.420	0.146	0.151	0.002

Table 5
Comparison on SIR scores of all groups before and after cochlear implantation.

Group	Before Implantation (mean rank value)	After activation		
		3 Months (mean rank value)	6 Months (mean rank value)	12 Months (mean rank value)
Group A (N = 10)	46.00	49.50	34.75	69.80
Group B (N = 26)	46.00	49.50	52.67	56.81
Group C (N = 62)	51.53	49.50	50.55	43.16
t Value	4.33	0.00	4.23	12.61
P Value	0.115	1	0.121	0.002

months showed that the scores differed significantly between group B (72.54 ± 9.79) and group C (67.27 ± 7.57) ($P = 0.009$) whereas the difference between group A (68.70 ± 10.07) and group B (72.54 ± 9.79) did not reach statistical significance ($P = 0.226$), group A and group C also were not statistically significant ($P = 0.622$).

4. Discussion

4.1. Selection of speech assessment materials after cochlear implantation

This study utilized the QuikSTAR Auditory Perception Comprehensive Assessment System, which includes the ACAPA test, the comprehensive assessment and test of open-set Chinese speech and auditory perception. The ACAPA includes four tests, i.e., word identification (single-character, multiple-character phrases and digital identification), basic assessment (ambient sound, recognition of simple or compound vowels, recognition of the initial consonant and recognition of tones), advanced assessment (vowel recognition test, consonant recognition test, tone recognition test and musical notes test) and hearing threshold (threshold of sequential numeric string, threshold of reverse numeric string, threshold of steady noise and threshold of dynamic noise). The QuikSTAR comprehensive auditory perception assessment system was specifically created for the assessment of auditory performance after implantation. The software is installed on a laptop, making the test more convenient. The system includes basic auditory perception and open-set speech tests. The contents of the assessment are well illustrated and are appealing for paediatric patients. Children can usually patiently complete the tests. However, some contents included in the system may be too difficult for young children and children who are lack of social contact, the final result may have some errors. If we encountered a few of children who had some difficult to answer those questions, we usually would allow children parents could give appropriate help. In this study, we also used CAP and SIR assessments, and we found that in all age groups the scores at 3 and 6 months following implantation did not differ significantly from that before the surgery. Significant differences began to appear at 12 months after the implantation. Different age groups showed different auditory performance. Therefore, combined use of these methods helps more accurately and reliably evaluate the postoperative auditory and speech performance for paediatric cochlear implant recipients.

4.2. Effect of rehabilitation time on hearing and speech outcomes

In this study, 98 patients with cochlear implants received hearing and speech assessments before the surgery and at 3, 6 and 12 months after the device activation. The results of MAIS and QuikSTAR Comprehensive Assessment System indicated that both the hearing and speech abilities improved over time after implantation, and the differences were statistically significant. CAP and SIR scores showed no obvious improvement at 3 or 6 months following the implant activation. While at 12 months, the scores became significantly improved. Within one year of follow-up, the auditory and speech performance improved over time. Due to children's growth and development, long-term follow-up is absolutely essential. With gradual improvements in hearing and speech, attention should be paid to children's abilities to get along with their classmates in school and their adaptability to social life in long-term follow-up after cochlear implantation.

Compared with the results of the open-set speech test, the score of the auditory perception assessment was higher, indicating that cochlear implantation can effectively enhance the hearing ability of the patient, while speech training is required to improve postoperative speech ability. Although hearing and speech abilities of the patient gradually improved over time, we observed differences among age groups and variation among individuals. This may be because the patients were from different regions and they received rehabilitation training after the surgery in local rehabilitation schools close to their homes instead of in the same rehabilitation centre. Different rehabilitation centres had different hearing and speech training modes, faculty and teaching equipment, which may affect the results to some extent. In addition, the family environment and the educational backgrounds of the patients may also affect the results, especially in the open-set speech assessment.

4.3. Effect of age at cochlear implantation on postoperative hearing and speech outcomes

Sharma and colleagues (Sharma et al., 2002, 2009) believed that the best time to restore hearing is under 6 years of age. With increasing age, the ability to restore hearing gradually decreases, especially after age 7. Currently, the age for implantation recommended for prelinguistic deaf patients is generally 1–6 years in the Guideline for Cochlear Implants in many countries (Editorial Board of Chines, 2013; Bradham and Jones, 2008). The younger the age at implantation, the better the effect. Earlier implantation helps patients restore hearing and receive speech training earlier (Leigh et al., 2016; Mikic et al., 2014). However, children of different ages have different characteristics in speech development. In general, age 2–12 years is the period for voice finalizing. Children over 6 years of age can still acquire verbal ability through speech rehabilitation training. In clinical practice, for children over age 6 with severe to profound sensorineural deafness who could not acquire hearing with hearing aids, cochlear implantation remains their best choice. It was reported that in older prelingual children the quality of life and speech recognition significantly improved their auditory performance after cochlear implantation (Clinkard et al., 2015; Straatman et al., 2014; Watson et al., 2016). Further studies are warranted to determine the effect of Nurotron® cochlear implants on auditory outcomes in older children.

By taking into account of speech development, paediatric growth, and the best period for hearing restoration, this study divided the patients into three groups based on age: i.e., $\leq$3 years, 4 $\leq$ age$\leq$7, and 8 $\leq$ age$\leq$16. Our results showed that hearing and speech abilities of groups A and B were better than that of Group C, indicating that the younger the age at implantation, the better the outcomes. Compared with group A, the better performance of group B may be the result of poorer cooperation of younger children. Children in group C achieved significantly higher scores in the Chinese auditory perception assessment, open speech assessment, and MAIS assessment after the surgery, suggesting cochlear implantation can substantially improve older children's hearing and speech ability. Moreover, because of plasticity of the auditory cortex, older deaf children with cochlear implantation can maintain or even improve their speech perception and cognitive abilities, social activities, and therefore have a better quality of life. The impact of age at implantation on auditory and speech outcomes may diminish over time (Dunn et al., 2014; Fallon et al., 2008; Glick and Sharma, 2017; Ryugo, 2015). It is therefore worthwhile to consider cochlear implantation in older deaf children.

Speech processing strategy of imported cochlear implants may help patients who are native English speakers enhance speech intelligibility and improve recognition. However, for patients using Chinese as their native language, the speech recognition improvement after implantation of imported cochlear implants is not as evident as that achieved in English-speakers. Chinese is a language with tones and semantic recognition of Chinese largely depends on tones. Previous studies demonstrated that Chinese deaf patients generally have tone perception disorder and pronounce without tones after implantation of imported cochlea (Han et al., 2007; Chang et al., 2016). In order to strengthen tone perception, Nurotron Company has been continuously improving "Morning Star" Cochlear Implant System to make them more ideal for deaf patients who are Chinese speakers (Jiao et al., 2015; Liu et al., 2014).

Data availability statement

See supplemental file for the research data.

Disclosure statement

The authors have no conflicts of interest to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.joto.2019.01.006.

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