

Original Article

Residual Hearing Improves Early Auditory Perception and Speech Intelligibility in Mandarin-Speaking Children with Cochlear Implants

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BACKGROUND: To investigate the relationship between residual hearing and early auditory speech performance in Mandarin-speaking children with cochlear implants.

METHODS: Twenty-four prelingually deaf children implanted with a cochlear implants participated in the study. Auditory performance and speech intelligibility were longitudinally evaluated by categories of auditory performance, infant-toddler meaningful auditory integration scale/meaningful auditory integration scale, speech intelligibility rating, and meaningful use of speech scale. According to the postoperative pure tone average threshold, children were grouped as "better" and "worse" residual hearing.

RESULTS: Better hearing preservation was observed in 7 children (29.2%) and worse preservation in 17 children (70.8%). The scores of categories of auditory performance, infant-toddler meaningful auditory integration scale/meaningful auditory integration scale, speech intelligibility rating, and meaningful use of speech scale were higher in children with better residual hearing. The residual hearing level was significantly associated with the performance of meaningful use of speech scale ($P = .004$), as well as the performance of speech intelligibility rating ($P = .049$).

CONCLUSION: The present study showed that children with better residual hearing exhibited advantages in the early auditory and speech outcomes. The study highlighted the effects of residual hearing on early auditory performance and speech intelligibility development in Mandarin-speaking children with cochlear implants.

KEYWORDS: Residual hearing, children, cochlear implants, auditory performance, speech intelligibility

INTRODUCTION

Cochlear implant (CI) technology, surgery, and rehabilitation have been tremendously developed in recent years to provide considerable benefits in speech understanding for children and adults with hearing impairment. Initially, CIs were only provided to candidates with profound hearing loss.¹ Meanwhile, the existence of residual hearing was deemed as a contraindication. More recently, inclusion criteria has expanded, and the presence of residual hearing are presently deemed as candidates with evolving device technology and clinical algorithms. Current CIs can provide satisfactory speech perception in quiet. However, compared with normal hearing peers, they provide neither optimal performance for lexical and musical pitch perception and speech perception in noise nor timbre discrimination tasks.² Literature supported that the preservation of functional low-frequency hearing and fine structure processing promoted speech perception in noise, sound localization, and music appreciation.³ Eisenberg et al reported that children with moderate-to-severe hearing loss using hearing aids (HAs) exhibited a better understanding of sentences than children with CIs in noise.⁴ Therefore, the impaired perception of the suprasegmental features of speech in children with CIs could be due to the functional low-frequency acoustic hearing deterioration.

Since conservation of postoperative residual hearing became possible, many researchers have focused on the possibility and benefit of combined electrical and acoustic stimulation (EAS). The principle of EAS is that the nonfunctioning high-frequency areas of the basal cochlea are amplified with electrical stimulation, yet the low-frequency areas of the apical cochlea are amplified with acoustic stimulation. Thus, EAS candidacy not only includes patients with normal-to-moderate low-frequency hearing loss but also includes those with severe-to-profound high-frequency hearing loss.¹ Gifford has verified that recipients achieved greater EAS benefits than a conventional CI, provided that adequate low-frequency hearing was preserved postoperatively.⁵ The speech perception in noisy conditions, pitch recognition, spectral discrimination, and music appreciation has improved in most patients receiving EAS.⁶ Gantz et al⁷ showed there was a significant correlation between post-operation residual hearing and speech perception in noise. In fact, a large number of adults have benefited from EAS, whose correct percentages of sentence recognition in noise were above 50%.⁸ They suggested that the enhanced abilities of speech perception compared with conventional CIs relied on the retention of residual hearing. Once residual hearing thresholds decreased to a profound level, the benefits might disappear.

To date, several researchers have reported the benefits of residual hearing in adults with CI,⁹ but there is currently limited information about the effects of residual hearing on pediatric patients. Furthermore, Mandarin is distinctive from Western languages because it is a tonal language, which contains four phonological tones and is featured by fundamental frequencies (F0) contour patterns and amplitude, which tonal changes within the same phonemic segment often cause changes in the meaning of words. Listeners with normal hearing generally depended on the most efficient prosodic cue, that is, F0 variations. In contrast, the poor recognition of musical and emotional speech prosody observed in individuals with CI is usually attributed to a defect in F0 representation. So, it is necessary to investigate the effects of the residual hearing on the postoperative performance in Mandarin-speaking children with CIs. The specific focus of this study was to explore the relationship between residual hearing and early auditory performance and speech intelligibility in children with CI who came from Mandarin-speaking families. Based on the adult work, it was hypothesized that better residual hearing would closely correlate with auditory and speech performance.

MATERIALS AND METHODS

Participants

The participants were 24 children, including 9 females and 15 males. The mean age at implantation was 37.21 ± 19.93 months, ranging from 12 to 67 months. All children were raised in a Mandarin-speaking family and recruited from our tertiary referral hospital. Children with coexisting disabilities that may affect auditory performance and speech intelligibility, such as mental retardation or speech motor problems, were excluded from the study. Nine children received CI in the right ear (37.5%) and 15 in the left ear (62.5%). Eighteen children received Med-EL CIs, 5 received Advanced Bionics (AB) CIs, and 1 received a Cochlear® CI. Cochlear implant was implanted in the ear with worse hearing in all subjects. "Round window" technique was used in the surgery to help preserve residual hearing. Table 1 listed the demographic and audiometric characteristics of the children included in the study.

The study was approved by the Institutional Research Ethics of Beijing Children's Hospital, Capital Medical University (Ethics committee approval number: 2015-37). Written informed consent was obtained from the patients' parents.

Residual Hearing Thresholds Assessment

Residual hearing thresholds were achieved by play audiometry at frequencies from 125 to 8000 Hz. Play audiometry was carried out at pre-operation and 6 months post-operation, respectively. Following the previous study, we defined pure tone average (PTA) for low frequencies of 125, 250, and 500 Hz. If the maximum output of the audiometer did not respond at a given frequency (fmax), fmax plus 5 dB was entered.¹⁰ Postoperative PTA thresholds were classified as better hearing conservation (PTA thresholds ≤ 90 dB) or worse hearing conservation (PTA thresholds > 90 dB).

Auditory Performance and Speech Intelligibility Evaluation

Our current study evaluated the auditory performance and speech intelligibility of 24 children from the switch on to 12 months, which is a longitudinal study. The assessment was separately performed at 0, 1, 2, 3, 6, 9, and 12 months after switching on. The auditory performance evaluation tools were categories of auditory performance (CAP) and infant-toddler meaningful auditory integration scale/meaningful auditory integration scale (IT-MAIS/MAIS). The CAP scale is an indicator of daily auditory performance, which is an outcome measurement of the abilities of the auditory receptivity. It is a hierarchical scale of perceptive auditory ability consisting of 8 performance categories, ranging from 0 "no awareness to environmental sound" to 7 "can use the telephone with a familiar talker." Infant-toddler meaningful auditory integration scale/meaningful auditory integration scale is a widely used parent questionnaire, aiming to assess early auditory development. Each score of the 10 questions is ranging from 0 (lowest) to 4 (highest): 0 = never (0%), 1 = rarely (25%), 2 = occasionally (50%), 3 = frequently (75%), and 4 = always (100%). The maximum score for MAIS/IT-MAIS is 40. Speech intelligibility can be defined as the accuracy, that is, a speaker can make a speech that others can understand, the evaluation tools were speech intelligibility rating (SIR) and meaningful use of speech scale (MUSS). The SIR is applied to evaluate the speech intelligibility of the children with CIs by quantifying daily spontaneous speech in children, and it is a scoring scale comprising 5 performance categories ranging from "pre-recognizable words in spoken language" to "connected speech is intelligible to all listeners." The MUSS is used to evaluate communicative interactions, vocalization efforts, and the use of spoken language. The grading standard of MUSS is consistent with MAIS/IT-MAIS, and the maximum score for MUSS is 40.

All the evaluation items were administered in a structured interview between the parent(s) and the audiologist. Parents were asked about their children's spontaneous auditory behaviors in daily situations. The audiologist recorded the parents' responses during the interview, and a higher score reflected better auditory performance and speech intelligibility skills.

Statistical Analysis

Comparisons of auditory perception and speech intelligibility between better and worse residual hearing groups were performed by independent-samples *t*-test. In addition, the effects of residual

Table 1. Patient Characteristics and Pre- and Post-Operation Pure-Tone Average, Change in Pure-Tone Average, and Hearing Conservation Category

Patient No.	Gender	Duration of CI Use (Month)	Age at Implantation (month)	Implant ear	Etiology	Type of Implant	Preoperative PTA Threshold _a (dB HL)	Postoperative PTA Threshold _a (dB HL)	Contralateral PTA Threshold _a (dB HL)	Hearing Conservation Category _b
1	F	13	39	L	Unknown	Pulsar standard	110	115.0	82.5	Worse
2	M	18	24	L	Unknown	Pulsar standard	77.5	110.0	62.5	Worse
3	M	3	32	R	LVAS	Sonata standard	70	112.5	80	Worse
4	M	19	16	L	Unknown	AB 90K 1J	87.5	100.0	77.5	Worse
5	M	19	42	L	LVAS	Pulsar standard	72.5	105.0	67.5	Worse
6	M	3	67	L	Unknown	Sonata standard	81.6	72.5	74.5	Better
7	M	7	12	L	Unknown	Sonata standard	97.5	93.3	91	Worse
8	M	7	12	L	Unknown	Sonata standard	105	91.6	106	Worse
9	M	18	37	L	ANSD	Pulsar standard	95	105.0	80	Worse
10	F	10	46	R	LVAS	Sonata standard	77.5	96.6	96.67	Worse
11	M	13	43	L	Unknown	AB 90K 1J	95	97.5	82.5	Worse
12	M	2	51	R	LVAS	Sonata standard	61.7	65.0	70.83	Better
13	F	7	25	L	GJB2 mutation	Pulsar standard	78.3	96.6	73.33	Worse
14	M	7	60	L	LVAS	Sonata standard	101.7	101.6	91.67	Worse
15	M	2	18	L	Unknown	Concerto FLEX	97.5	105.0	84	Worse
16	M	3	37	R	Unknown	Concerto FLEX	80	105.0	90	Worse
17	M	10	37	L	LVAS	AB 90K HiFocusHelix	110	87.5	86.25	Better
18	F	13	33	L	LVAS	AB 90K HiFocus 1J	102.5	96.6	105	Worse
19	F	10	16	L	Unknown	AB 90K HiFocusHelix	105	90.0	105	Better
20	F	13	66	R	Unknown	Sonata standard	90	86.6	100	Better
21	F	10	54	R	LVAS	Pulsar standard	65	92.5	62.5	Worse
22	F	1	40	R	Unknown	Concerto FLEX ^{coft}	87.5	96.6	82.5	Worse
23	F	1	45	R	Unknown	CI512	46.7	51.7	65	Better
24	M	1	41	R	LVAS	Concerto FLEX ^{coft}	68.3	65.0	55	Better

^aPTA threshold was calculated as average at 125, 250, and 500 Hz (maximum audiometer output +5 dB used at frequencies with no response).^b"Better" refers to postoperative PTA threshold ≤90 dB, "Worse" refers to postoperative threshold PTA >90 dB.

hearing and other potential factors on auditory performance and speech intelligibility were analyzed by a multiple linear regression model, and the level of significance was established for P -values $<.05$. Statistical analyses were performed with the SPSS 19.0 package (IBM SPSS Corp.; Armonk, NY, USA).

RESULTS

Residual Hearing Assessments

The mean threshold of pre- and post-operation at each frequency were shown in Figure 1. Some preservation of low-frequency hearing was achieved in all 24 children. Better hearing preservation (post-operation PTA threshold ≤ 90 dB) was observed in 7 children (29.2%) and worse preservation (post-operation PTA threshold >90 dB) in 17 patients (70.8%). All children experienced some threshold loss post-operatively. The results of multiple linear regression analysis showed that electrode length and age at implantation had no significant effect on hearing threshold preservation, however, better preservation was seen in children with Large Vestibular Aqueduct Syndrome (LVAS) than with other causes (Table 2).

Auditory Performance and Speech Intelligibility Evaluation

The relationship between residual hearing threshold and early auditory preverbal skills at each assessment point was shown in Table 3. In general, the performance of CAP, IT-MAIS/MAIS, SIR, and MUSS was

higher in children with better residual hearing. The children's MUSS performance exhibited a significant difference between the better and the worse residual hearing group at 12 months after switching on (t -test, $P = .012$). Multiple regression analysis showed that the residual hearing level was significantly associated with the performance of MUSS and SIR ($P = .004$ and $.049$, respectively), and age of implantation was significantly associated with the performance of CAP, SIR, and IT-MAIS/MAIS ($P < .001$, $P = .002$, $P < .001$, respectively).

DISCUSSION

Preservation of Residual Hearing

Residual hearing preservation and speech perception is the most critical issue for pediatric CI candidates. In our study, thresholds after cochlear implantation showed a minimal rise in low-frequency compared with hearing thresholds at pre-operation. We achieved better preservation in 29.2% of all cases, defined as a post-operation PTA threshold ≤ 90 dB. Our results suggested that it was possible to preserve residual hearing during cochlear implantation even if the residual hearing level before the operation was limited. Furthermore, in the present study, 18 children received a 31.5 mm electrode, 5 children received a 24.5–25 mm electrode, and 1 child received a 19 mm electrode. Analysis showed that residual hearing preservation was not associated with electrode length. A previous study also reported that no electrode design achieved better hearing preservation,

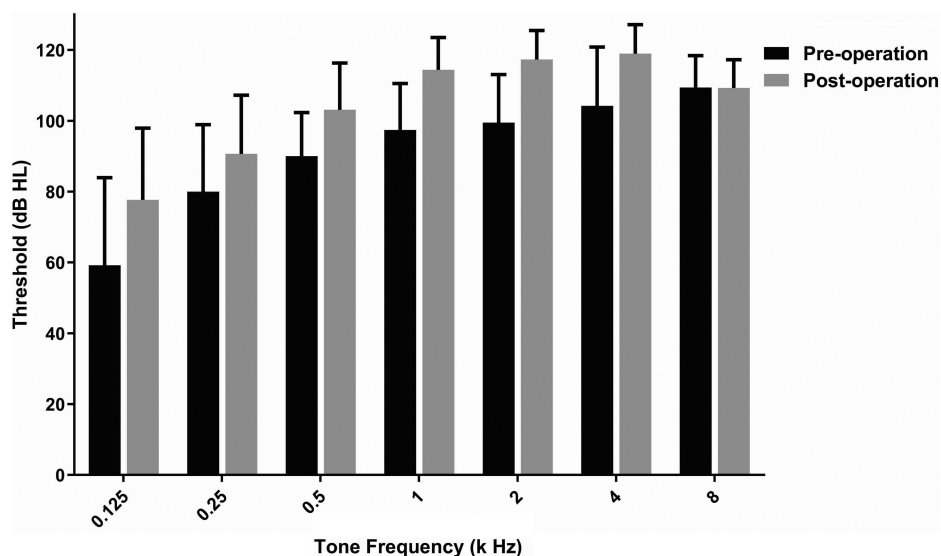


Figure 1. Pre- and postoperative median thresholds across frequency. The X-axis represents the tone frequency (k Hz), the Y-axis represents the behavior thresholds (Play Audiometry, dB HL) pre- and post-operation.

Table 2. Residual Hearing Post-operation as a Factor of Electrode Length, Age at Implantation, and Etiology. "Others" Etiology Included "Unknown," ANSD, GJB2 Mutation

Factor	N	Group	Postoperative PTA Threshold ^a (dB HL)	P
Electrode length	18	31.5 mm	95.30	.286
	6	19.0–25.0 mm	87.22	
Age at implantation	8	≤ 30 months	93.03	.66
	16	> 30 months	93.43	
Etiology	14	Others	99.51	.037
	10	LVAS	89.54	

^aPTA threshold was calculated as an average threshold at 125, 250, and 500 Hz.

Table 3. Auditory Performance and Speech Intelligibility Between Better and Worse Residual Hearing Groups

Assessment Materials	Residual Hearing Group	Time after Switch on (Month)						
		0	1	2	3	6	9	12
CAP	Better residual hearing	2.86	2.8	3.20	4.00	4.82	4.96	5.14
	Worse residual hearing	1.47	2.21	2.98	3.43	3.33	4.88	4.53
	<i>P</i>	.176	.349	.729	.564	.450	.535	.289
ITMAIS/MAIS	Better residual hearing	13.83	19.33	16.67	21.5	28.00	33.4	31.86
	Worse residual hearing	7.5	15.00	19.82	21	18	24.4	28.33
	<i>P</i>	.017*	.036*	.648	.310	.636	.164	.322
SIR	Better residual hearing	1.05	1.25	1.40	1.40	2.00	2.00	2.5
	Worse residual hearing	1.07	1.07	1.36	1.50	1.55	1.63	1.62
	<i>P</i>	.535	.132	.887	.769	.440	.332	.407
MUSS	Better residual hearing	10.33	10.67	11.00	13.33	16.25	13.00	21.67
	Worse residual hearing	2.53	2.64	5.14	4.56	7.18	11.71	8.89
	<i>P</i>	.008*	.011*	.088	.078	.076	.891	.012*

The significances of asterisk and bold text are $P < .05$. That is, * $P < .05$.

neither a shorter length nor a contoured electrode array was used.¹⁰ In the study by Brown et al.¹¹ completed hearing preservation was achieved in 45% of all children ($N = 31$) with standard length electrodes. Manjaly et al.¹² reported that hearing preservation was achievable in 55.5% of children with standard length electrodes, furthermore, 33% of the children achieved complete retention of residual hearing. Bruce et al.¹³ reported that 93% of children (13 out of 14) achieved measurable hearing retention, with two-thirds receiving a 31.5 mm MED-EL Flex-soft array. To date, there was no agreement on the optimum insertion depth and the length of electrodes for residual hearing preservation.

Relationship between Residual Hearing and Early Preverbal Skills

Literature about the effects of residual hearing on auditory performance and speech intelligibility of children, particularly in infants, is still limited. Our study indicated that the auditory performance and speech intelligibility of children with better residual hearing was superior to the worse residual hearing peers. The mechanism of how residual hearing promotes speech perception remains controversial. Chiossi et al.³ put forward one possibility, which was that the presence of residual hearing might promote the development of the auditory cortex and help maintain the integrity of the auditory pathway. During the first 2 years after cochlear implantation, the auditory preverbal skills developed rapidly.^{14,15} Certainly, not all of this progress could be attributed to CI, the accumulation of auditory experience and the development of the auditory cortex might also play an important role.¹⁴ More satisfactory results were obtained in Bakhshaei et al.¹⁶ and Wu et al.¹⁷'s study, both using the SIR as the evaluation tool: about 80% of the children became fully intelligible within 5 years of CI use. A large number of studies have shown that the linguistic skills of children with CI exhibited significant individual variabilities. These variabilities could potentially result from a number of reasons, such as the age of hearing loss and cochlear implantation and general intellectual skills.¹⁸ Perhaps, the residual hearing level may also be an influencing factor.

The present result indicated that only a small part of residual hearing still showed a positive effect on the early auditory and speech skills

of children with CIs. Our results further supported that the residual hearing should be attempted to preserve in all CI recipients, regardless of the degree of residual hearing before operation. Apart from that, the reason might be related to the fact that all the subjects in this study were children with Mandarin Chinese. We presumed that CI users with residual hearing might have access to the F0 cues. As increasing numbers of children with residual hearing became CI candidates, especially those who speak Mandarin, it was important to know how residual hearing affected outcomes. Our results highlighted that residual hearing might improve early auditory performance and speech intelligibility in Mandarin-speaking children with CIs. The present study is limited by the small sample size. Future research will expand the number of subjects and follow up the influence of residual hearing on children's hearing and speech development for a long time based on the findings of this study.

CONCLUSION

Successful outcomes and hearing preservation should be expected after CI operation in Mandarin-speaking children with residual hearing. Preliminary research demonstrated that children with better residual hearing exhibited advantages in auditory performance and speech intelligibility, although the amount of residual hearing was limited. The study highlighted the effects of residual hearing on early auditory and speech skills development in Mandarin-speaking children with CIs.

Ethics Committee Approval: The study was approved by the Institutional Research Ethics of Beijing Children's Hospital, Capital Medical University (Ethics committee approval number: 2015-37).

Informed Consent: Written informed consent was obtained from the patients' parents.

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Author Contributions: Concept – H.L.; Design – H.L.; Supervision – X.J.; Data Collection and/or Processing – J.Z., X.Z.; Analysis and/or Interpretation – Y.L.; Literature Review – X.Z.; Writing Manuscript – Y.L.; Critical Review – J.Z.

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Declaration of Interests: The authors have no conflict of interest to declare.

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