



Tone production of Mandarin Chinese speaking children with cochlear implants

Demin Han^a, Ning Zhou^b, Yongxin Li^a, Xiuwu Chen^a,
Xiaoyan Zhao^a, Li Xu^{b,*}

^a Department of Otolaryngology – Head & Neck Surgery, Beijing Tongren Hospital,
Beijing Institute of Otorhinolaryngology, Beijing, PR China

^b School of Hearing, Speech and Language Sciences, Ohio University, Athens, OH, USA

Received 25 November 2006; received in revised form 3 February 2007; accepted 17 February 2007

KEYWORDS

Cochlear implant;
Tone production;
Pediatric;
Tone language;
Mandarin Chinese

Summary

Objective: The purpose of the present study was to investigate tone production performance of native Mandarin Chinese speaking children with cochlear implants and to evaluate the effects of age at implantation and duration of implant use on tone production in those children.

Methods: Fourteen prelingually deaf children who had received cochlear implantation and 14 age-matched normal-hearing children participated in the study. Both groups were of native Mandarin Chinese speaking children. One hundred and sixty tone tokens were recorded from each of the children. The total of 4480 tokens (160 × 28) were then used in the tone perception tests in which seven normal-hearing native Mandarin Chinese speaking adults participated.

Results: The tone production of the cochlear implant children showed tremendous individual variability. The group mean performance was 48.4% correct, statistically significantly lower than the group mean performance of 78.0% correct in the normal-hearing controls. The tone confusion matrix analysis revealed that the production of Mandarin tone 2 (the rising tone) was most severely impaired in the cochlear implant children, followed by tone 3 (the low and dipping tone) and tone 4 (the falling tone). The most frequently perceived tone irrespective of the target tone was tone 1 (the high level tone). The tone production performance was negatively correlated with the age at implantation and positively correlated with the duration of implant use.

Conclusions: There is a remarkable deficit in tone production in a majority of native tone language speaking, prelingually deaf children who have received cochlear implants. While an increased duration of implant use might facilitate tone production,

* Corresponding author. Tel.: +1 740 593 0310; fax: +1 740 593 0287.
E-mail address: XuL@ohio.edu (L. Xu).

the age at implantation appears to have a negative effect on tone production in cochlear implant children. Therefore, early implantation might be beneficial to tone production in prelingually deaf children whose native language is a tone language.
© 2007 Elsevier Ireland Ltd. All rights reserved.

1. Introduction

The number of children who have received cochlear implants in China has increased dramatically in recent years. The total number of multichannel cochlear implantees in China is estimated to be around 4000 today. As of February 2007, we have implanted 600 patients among whom 500 are children (i.e., ≤ 18 years old) since the first establishment of the Cochlear Implant Center at Beijing Tongren Hospital in 1996. The number of cochlear implantations in China is expected to continue to increase at an even more rapid rate due to the economic growth and philanthropic efforts.

There is no doubt that cochlear implants have helped prelingually deafened children to gain hearing and to learn communication skills. Mandarin Chinese, as well as many other tone languages, has its unique characteristic, that is, tone or pitch of each monosyllable conveys lexical meaning. The tone patterns of Chinese monosyllabic words are the variations of fundamental frequency (F0) over time of the vowel part of the syllables. In Mandarin Chinese, the patterns vary in one of four ways, thus four tones: (1) flat and high, (2) rising, (3) low and dipping, and (4) falling. For example, tones 1 through 4 of the same syllable, *ma*, produce four words of unrelated lexical meanings: (1) 'mother', (2) 'hemp', (3) 'horse', and (4) 'scold'. However, pitch information essential for tonal languages is not explicitly represented in the electrical stimulation

of current cochlear implant systems. A few studies have demonstrated a significant deficit in tone perception in cochlear implant children whose native language is a tone language [1–3].

In a preliminary report, we showed that prelingually deafened native Mandarin speaking children who had received cochlear implants demonstrated various degrees of deficits in tone production [4]. Peng et al. also reported that a majority of their 30 prelingually deaf children with cochlear implants did not master Mandarin tone production [5]. There is a growing body of literature that indicates that the age at cochlear implantation is crucial for development of language skills including both perception and production in pediatric cochlear implant recipients [6–13]. The present study was undertaken to evaluate the potential effects of age at implantation and duration of implant use on tone production in cochlear implant children.

2. Methods

2.1. Subjects

Fourteen prelingually deafened children (2.91–8.33 years old) who received cochlear implants from the Cochlear Implant Center of Beijing Tongren Hospital participated in the present study. The demographic information of the 14 cochlear implant children is summarized in Table 1. As controls, 14 age-matched

Table 1 Demographical information of the cochlear implant (CI) subjects

Subject number	Gender	Age at implantation (years)	Chronological age (years)	Duration of implant use (years)	CI system type
1	F	5.19	7.53	2.34	Clarion CII
2	M	1.50	3.60	2.10	N24M
3	M	1.32	3.38	2.06	N24M
4	M	3.90	5.50	1.60	Clarion CII
5	M	1.16	2.93	1.77	Clarion CII
6	M	2.60	2.91	0.30	N24R
7	F	2.59	4.41	1.82	N24M
8	F	2.05	4.27	2.22	N24M
9	F	3.10	5.51	2.41	N24M
10	F	5.56	6.53	0.97	N24R
11	F	4.55	5.35	0.79	N24R
12	M	7.09	7.67	0.58	N24R
13	M	1.70	4.27	2.57	N24M
14	M	5.73	8.33	2.60	N24M

normal-hearing children were recruited from kindergartens and elementary schools in Beijing. The age differences of the age-matched individuals in the two groups ranged from 0.1 to 3.5 months with a mean of 1.5 months. All children were native Mandarin Chinese speakers. The use of human subjects was reviewed and approved by the Institutional Review Boards of Beijing Tongren Hospital and Ohio University.

2.2. Speech recording

All children were asked to produce tones 1 through 4 of the following Mandarin Chinese monosyllables: ai, bao, bi, can, chi, du, duo, fa, fu, ge, hu, ji, jie, ke, la, ma, na, pao, pi, qi, qie, shi, tu, tuo, wan, wen, wu, xian, xu, ya, yan, yang, yao, yi, ying, you, yu, yuan, zan, zhi. All the 160 (40 × 4) monosyllables are real words in Chinese. Speech recording of the elicited tone production was carried out in quiet rooms. A Sony Portable DAT recorder (Model TCD-D100) with sampling frequency set at 44.1 kHz and an ElectroVoice omnidirectional microphone (Model RE50B) were used for the recording. The distance between the lips and the microphone was kept at around 10 cm.

The recorded speech materials were transferred to a personal computer hard disk using the same sampling frequency of 44.1 kHz and a 16-bit resolution. An acoustic analysis software, CoolEdit 2000 (Syntrillium Software, Scottsdale, AZ), was used to segment the recorded material into individual syllables and to save these as separate wave files. To assess the tone production performance, those wave files were used as tone tokens in the tone perception tests described below.

2.3. Tone perception tests

Seven normal-hearing native Mandarin Chinese speaking adults (26–32 years old) were recruited as listeners in the tone perception tests. All adult subjects had completed at least college-level education in China. A custom graphical user interface (GUI) was developed in MATLAB programming environment to present the tone tokens from the children speakers and to collect perception responses from the adult listeners. The tone perception test was performed in a double-walled sound-treated booth. The tone tokens from the 14 cochlear implant children and the 14 age-matched normal-hearing controls were pooled together, resulting in a total of 4480 tokens (160 × 28). These tokens were randomized and presented monaurally to the adult listeners at a most comfortable level via a circumaural headphone (Sennheiser, HD 265). The listeners were

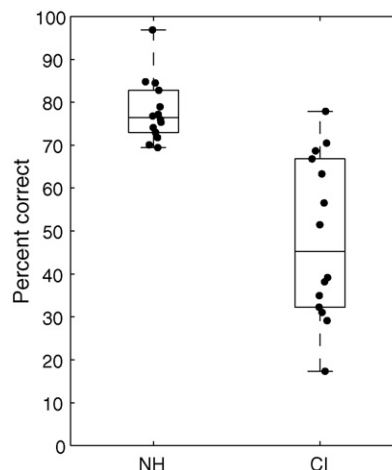


Fig. 1 Tone production performance of the normal-hearing (NH) and cochlear implant (CI) groups as assessed by the adult listeners' tone perception scores (percent correct). Each symbol represents the mean score for one child. Some jitters along the abscissa were applied to the data for better visual representation. The box plots have lines at the lower quartile, median, and upper quartile values. The whiskers show the extent of the rest of the data.

required to use a computer mouse to click on one of the GUI buttons labeled 1, 2, 3, or 4 to indicate the tone that they had heard. The responses along with the speaker identification numbers were stored in the computer for data analysis.

3. Results

Fig. 1 shows the tone production performance of both the normal-hearing and cochlear implant children groups as assessed by the mean percent-correct scores of the perception tests performed by the adult listeners. The tone production performance of the normal-hearing children ranged from 69.4 to 96.9% correct (mean ± S.D., 78.0 ± 7.3% correct). The tone production performance of the cochlear implant children ranged from 17.4 to 77.9% correct (mean ± S.D., 48.4 ± 18.9% correct). The differences of the mean tone production performance between the two groups were statistically significant (*t*-test, $p < 0.0001$). The variation in tone production performance was greater for the cochlear implant children than the normal-hearing children. Note that four or five of the cochlear implant children reached a level of tone production performance comparable to the normal-hearing children even though a majority of the cochlear implant group scored much lower and a half of the group scored less than 50% correct.

From the 15,680 (i.e., 160 tone tokens × 14 implant children × 7 adult listeners) tone perception

Table 2 Tone confusion matrix of tone production of the cochlear implant children

Target	Responses			
	Tone 1	Tone 2	Tone 3	Tone 4
Tone 1	71.7	8.5	7.3	12.5
Tone 2	43.7	19.4	25.1	11.8
Tone 3	32.6	10.2	48.1	9.1
Tone 4	37.5	2.9	4.3	55.3

Each of the values represents the percentage of responses for a particular target (total $N = 15,680$).

responses of the adult listeners using the cochlear implant children's tone tokens, a tone confusion matrix was constructed to illustrate the error patterns of the tone production of the cochlear implant children (Table 2). The production of tone 1 (the high level tone) by the cochlear implant children was perceived as tone 1 the highest percentage of the time, 71.7%. In contrast, tone 2 (the rising tone) was perceived as tone 2 only 19.4% of the time, which suggested that the cochlear implant children had the greatest difficulties producing the rising tone pattern. The production of tone 3 (the low and dipping tone) and tone 4 (the falling tone) yielded 48.1 and 55.3% correct responses, respectively. The confusion matrix also revealed that the most frequent responses to all target tones were tone 1, indicating that the tones produced by the cochlear implant children were typically invariant in F0.

Fig. 2 depicts the relationship of the tone production performance of the cochlear implant children and the age at implantation, chronological age, and duration of implant use. Pearson's correlation showed that the tone production performance of the cochlear implant children was negatively correlated with their age at implantation ($r = -0.57$, $p = 0.034$) and positively correlated with the duration of implant use ($r = 0.56$, $p = 0.038$).

However, the correlation between the tone production performance of the cochlear implant children and their chronological age was not statistically significant ($r = -0.37$, $p = 0.204$).

4. Discussion

The present study confirmed our previous findings [4] that there is a remarkable deficit in tone production in Mandarin Chinese speaking children who have received cochlear implants. Furthermore, we found that the age at implantation was negatively correlated with the tone production performance, whereas the duration of implant use was positively correlated with the tone production performance.

When the 15,680 tone perception responses by the adults to the tone tokens of the cochlear implant children were analyzed for tone confusion matrix, we found that tone 2 (the rising tone) was the least accurately produced tone by the cochlear implant children. In a previous study based on an acoustical analysis of tone production of cochlear implant children, we also found that the rising Mandarin tone (tone 2) was the most difficult for the cochlear implant children. Three out of the four children could not produce the tone 2 correctly [4]. Using a tone intelligibility paradigm in their study of tone production of cochlear implant children, Peng et al. [5] showed a similar finding that tone 2 was judged to be the least accurately produced tone. The confusion matrix analysis used in the present study also showed that when the adult listeners were presented with the tone tokens from the cochlear implant children, the most frequent responses to all target tones were tone 1, indicating that the tones produced by the implant children were typically flat. Thus, it gives a monotonic characteristic to the speech by cochlear implant children.

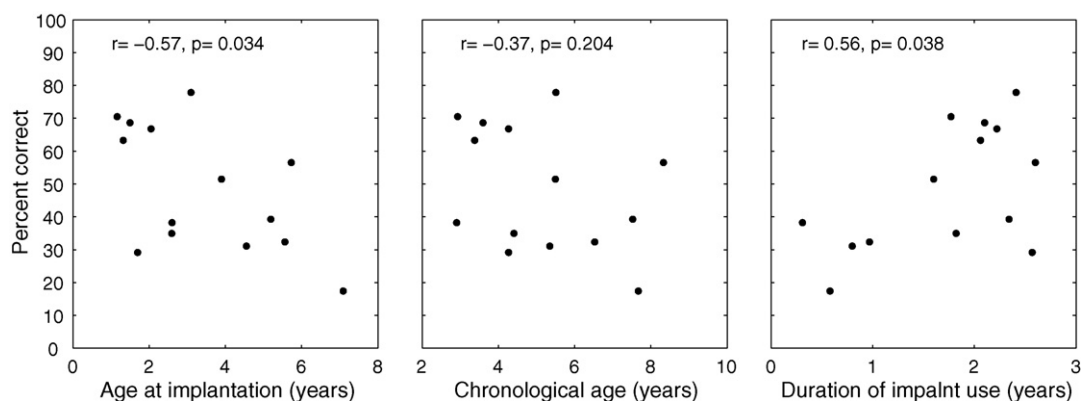


Fig. 2 Relationship between tone production performance of the cochlear implant children and age at implantation, chronological age, and duration of implant use. Each symbol represents the mean score for one child. The correlation coefficient (r) and the p -value are shown in the upper left corner of each panel.

Many studies have demonstrated that children implanted at an early age showed improvements in both expressive and receptive language abilities [6–13], thus advocating for early implantation for prelingually deafened children. In a recent report, Connor et al. [13] demonstrated an additional value for earlier implantation over and above advantages attributable to longer length of use at any given age. They showed that cochlear implants could provide an early burst of growth in both speech and vocabulary outcomes if children receive their implants prior to age 2.5 years old. The added advantage (i.e., burst of growth) diminishes systematically with increasing age at implantation. However, not all studies showed a negative correlation between the age at implantation and the language outcomes. In a series of comprehensive studies involving 181 prelingually deaf children with cochlear implants, Geers and colleagues failed to find a significant effect of age at implantation on both speech perception and speech production abilities of the children [14–16]. Note that a vast majority of the 181 children received cochlear implantation at the ages of 2–4 years old. Such a narrow range of ages at implantation might have obscured any potential significant effects of age at implantation on speech perception and production performance of the children.

There are relatively fewer studies on the effects of age at implantation and duration of implant use on speech perception and production of tone languages. Wu and Yang demonstrated that age at implantation is negatively correlated to the improvement of closed-set Mandarin-Chinese speech perception during the period of 1 and 2 years after implantation [17]. In a follow-up study during the period of 4 and 5 years after implantation, Wu et al. again demonstrated that children who receive cochlear implantation before 3 years of age have significantly better speech perception than those who receive cochlear implantation after 3 years of age [18]. Lee et al. also found that both age at implantation and duration of implant use contribute to Cantonese tone perception [2]. However, studies on effects of age at implantation and duration of implant use on tone production have yielded inconsistent results. Peng et al. [5] reported that the subjective judgment scores of tone production of the cochlear implant children were negatively correlated with the age at implantation. Huang et al. [19] showed a trend of negative correlation between the tone intelligibility and the age at implantation. However, the correlation did not reach the statistical significance. Both of the above-mentioned papers did not show a positive correlation between the tone intelligibility and duration of implant use.

Using a tone perception paradigm to assess the tone production performance of the prelingually deaf children with cochlear implants, we found a statistically significant correlation between tone production and the age at implantation and duration of implant use in the present study (Fig. 2). Both correlations were not particularly strong, each accounting for about 30% of the variance in the tone production performance of the cochlear implant children. It should be noted that the age at implantation and duration of implant use are intrinsically related to each other. A multiple regression analysis should be ideal to evaluate the separate and combined contributions of these two factors to tone production performance [20]. The sample size of the present study is inadequate for such an analysis due to the lack of statistical power. Future studies with a much larger sample size are warranted to further elucidate the contributing factors for tone production in cochlear implant children.

Acknowledgements

We are grateful to Erin Furman, Hui-Hui Li, Shuang Liang, Chessy Seebom, Jessica Wolfanger, and Yunfang Zheng for their technical support. The study was supported in part by NIH NIDCD Grant R03-DC006161.

References

- [1] W.I. Wei, R. Wong, Y. Hui, D.K.K. Au, B.Y.K. Wong, W.K. Ho, et al., Chinese tonal language rehabilitation following cochlear implantation in children, *Acta Otolaryngol.* 120 (2000) 218–221.
- [2] K.Y.S. Lee, C.A. van Hasselt, S.N. Chiu, D.M.C. Cheung, Cantonese tone perception ability of cochlear implant children in comparison with normal-hearing children, *Int. J. Pediatr. Otorhinolaryngol.* 63 (2002) 137–147.
- [3] V. Ciocca, A.L. Francis, R. Aisha, L. Wong, The perception of Cantonese lexical tones by early-deafened cochlear implantees, *J. Acoust. Soc. Am.* 111 (2002) 2250–2256.
- [4] L. Xu, Y. Li, J. Hao, X. Chen, S.A. Xue, D. Han, Tone production in Mandarin-speaking children with cochlear implants: a preliminary study, *Acta Otolaryngol.* 124 (2004) 363–367.
- [5] S.C. Peng, J.B. Tomblin, H. Cheung, Y.S. Lin, L.S. Wang, Perception and production of mandarin tones in prelingually deaf children with cochlear implants, *Ear Hear* 25 (2004) 251–264.
- [6] R.S. Tyler, H.F. Teagle, D.M. Kelsay, B.J. Gantz, G.G. Woodworth, A.J. Parkinson, Speech perception by prelingually deaf children after six years of cochlear implant use: effects of age at implantation, *Ann. Otol. Rhinol. Laryngol.* 109 (Suppl. 185) (2000) 82–84.
- [7] S.B. Waltzman, N.L. Cohen, R.H. Gomolin, J.E. Green, W.H. Shapiro, R.A. Hoffman, et al., Open-set speech perception

- in congenitally deaf children using cochlear implants, *Am. J. Otol.* 18 (1997) 342–349.
- [8] A.K. Cheng, G.D. Grant, J.K. Niparko, Meta-analysis of pediatric cochlear implant literature, *Ann. Otol. Rhinol. Laryngol.* 108 (Suppl. 177) (1999) 124–128.
- [9] K.I. Kirk, R.T. Miyamoto, C.L. Lento, E. Ying, T. O'Neill, B. Fears, Effects of age at implantation in young children, *Ann. Otol. Rhinol. Laryngol.* 111 (Suppl. 189) (2002) 69–73.
- [10] C. O'Neill, G.M. O'Donoghue, S.M. Archbold, T.P. Nikolopoulos, T. Sach, Variations in gains in auditory performance from pediatric cochlear implantation, *Otol. Neurotol.* 23 (2002) 44–48.
- [11] S. Hassanzadeh, M. Farhadi, A. Daneshi, H. Emamdjomeh, The effects of age on auditory speech perception development in cochlear-implanted prelingually deaf children, *Otolaryngol. Head Neck Surg.* 126 (2002) 524–527.
- [12] T.A. Zwolan, C.M. Ashbaugh, A. Alarfaj, P.R. Kileny, H.A. Arts, H.K. El-Kashlan, et al., Pediatric cochlear implant patient performance as a function of age at implantation, *Otol. Neurotol.* 25 (2004) 112–120.
- [13] C.M. Connor, H.K. Craig, S.W. Raudenbush, K. Heavner, T.A. Zwolan, The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: is there an added value for early implantation? *Ear Hear* 27 (2006) 628–644.
- [14] A.E. Geers, C. Brenner, Background and educational characteristics of prelingually deaf children implanted by 5 years of age, *Ear Hear* 24 (2003) 25–145.
- [15] A.E. Geers, C. Brenner, L. Davidson, Factors associated with development of speech perception skills in children implanted by age five, *Ear Hear* 24 (2003) 245–355.
- [16] E.A. Tobey, A.E. Geers, C. Brenner, D. Altuna, G. Gabbert, Factors associated with development of speech production skills in children implanted by age five, *Ear Hear* 24 (2003) 365–455.
- [17] J.L. Wu, H.M. Yang, Speech perception of Mandarin Chinese speaking young children after cochlear implant use: effect of age at implantation, *Int. J. Pediatr. Otorhinolaryngol.* 67 (2003) 247–253.
- [18] J.L. Wu, C.Y. Lin, H.M. Yang, Y.H. Lin, Effect of age at cochlear implantation on open-set word recognition in Mandarin speaking deaf children, *Int. J. Pediatr. Otorhinolaryngol.* 70 (2006) 207–211.
- [19] C.Y. Huang, H.M. Yang, Y.J. Sher, Y.H. Lin, J.L. Wu, Speech intelligibility of Mandarin-speaking deaf children with cochlear implants, *Int. J. Pediatr. Otorhinolaryngol.* 69 (2005) 505–511.
- [20] M.J. Strube, Statistical analysis and interpretation in a study of prelingually deaf children implanted before five years of age, *Ear Hear* 24 (2003) 155–235.

Available online at www.sciencedirect.com

