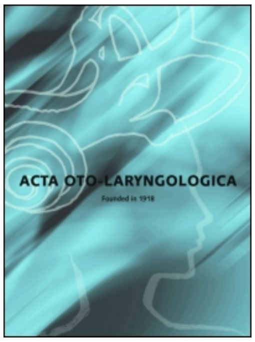

Acta Oto-Laryngologica

ISSN: 0001-6489 (Print) 1651-2251 (Online) Journal homepage: http://www.tandfonline.com/loi/ioto20

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To cite this article: Qiangyi Zhou, Zhijun Yang, Zhenmin Wang, Bo Wang, Xingchao Wang, Chi Zhao, Shun Zhang, Tao Wu, Peng Li, Shiwei Li, Fu Zhao & Pinan Liu (2018): Awake craniotomy for assisting placement of auditory brainstem implant in NF2 patients, Acta Oto-Laryngologica, DOI: 10.1080/00016489.2018.1424998

To link to this article: https://doi.org/10.1080/00016489.2018.1424998

Published online: 23 Jan 2018.

ACTA OTO-LARYNGOLOGICA, 2018
https://doi.org/10.1080/00016489.2018.1424998

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RESEARCH ARTICLE

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Awake craniotomy for assisting placement of auditory brainstem implant in NF2 patients

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ABSTRACT

Objectives: Auditory brainstem implants (ABIs) may be the only opportunity for patients with NF2 to regain some sense of hearing sensation. However, only a very small number of individuals achieved open-set speech understanding and high sentence scores. Suboptimal placement of the ABI electrode array over the cochlear nucleus may be one of main factors for poor auditory performance. In the current study, we present a method of awake craniotomy to assist with ABI placement.

Methods: Awake surgery and hearing test via the retrosigmoid approach were performed for vestibular schwannoma resections and auditory brainstem implantations in four patients with NF2. Auditory outcomes and complications were assessed postoperatively.

Results: Three of 4 patients who underwent awake craniotomy during ABI surgery received reproducible auditory sensations intraoperatively. Satisfactory numbers of effective electrodes, threshold levels and distinct pitches were achieved in the wake-up hearing test. In addition, relatively few electrodes produced non-auditory percepts. There was no serious complication attributable to the ABI or awake craniotomy.

Conclusions: It is safe and well tolerated for neurofibromatosis type 2 (NF2) patients using awake craniotomy during auditory brainstem implantation. This method can potentially improve the localization accuracy of the cochlear nucleus during surgery.

ARTICLE HISTORY
Received 17 October 2017
Revised 19 December 2017
Accepted 26 December 2017

KEYWORDS
Neurofibromatosis type 2; auditory brainstem implant; awake craniotomy

Introduction

Neurofibromatosis 2 (NF2) is an autosomal dominant disorder characterized by bilateral vestibular schwannomas. The disorder is genetically defined by a mutation of a tumorsuppressor gene on chromosome 22 coding for merlin, the lack or dysfunction of which leads to multiple nerve sheath tumors. Patients with NF2 always suffer bilateral hearing loss due to the surgical removal, progressive bilateral acoustic tumors, radiation therapy or other reasons [1]. Hearing loss is one of the main factors influencing quality of life and is difficult to handle in this condition. For bilateral auditory nerve injuries or disconnection in these patients, cochlear implant (CI) is not an appropriate option to reconstruct hearing. Auditory brainstem implant (ABI) can restore auditory function by bypassing the auditory nerve and directly stimulating the cochlear nucleus complex (CNC) in the brainstem [2–5]. However, auditory outcomes with ABIs are poor compared with those reported in CI users. Some ABI patients achieve open-set speech perception [6,7], but auditory benefits are limited to enhancing lip-reading for the majority of NF2 patients. Suboptimal placement of an ABI electrode array over the cochlear nucleus may be a crucial reason for poor auditory performance [8].

Electrically evoked auditory brainstem responses (EABRs) recorded intraoperatively are an important technique to guide the placement of the electrode array over the cochlear nucleus [9–12]. However, not all EABRs work well in assisting with ABI placement. First, EABRs cannot be elicited from some ABI recipients [10,13]. The correlation factors for response absence are not well studied. In addition, while the presence of an EABR is indicative of an auditory sensation, the absence of an EABR does not rule out an auditory perception [9,10,12,14]. Furthermore, the morphology of the EABR may vary obviously within test sessions, and the EABR threshold does not correlate with the behavioral measures of T and C levels [9,10]. Overall, these results bring into question the value of the EABRs as a tool for assisting placement of ABIs and the programming process in ABI recipients.

Awake craniotomy is a preferred approach in the resection of brain lesions in the eloquent cortex, which provides a unique opportunity for mapping sensorimotor, language, and cognitive functions, allowing the operator to optimize the extent of resection while preserving the patient's quality of life [15,16]. Regarding ABI surgery, we suppose that intraoperative cochlear nucleus mapping in awake craniotomy may assist the placement of the electrode array

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accurately. By stimulating the cochlear nucleus in awake patients, we can adjust the electrode array position to obtain more active electrodes. In addition, threshold levels and distinct pitches, which are thought to be related to high levels of speech recognition, may be achieved in the wake-up hearing test [6,7].

In the current study, we present a method of awake craniotomy with cochlear nucleus mapping in ABI surgery and hypothesize that the method can assist placement of ABI.

Methods

Patients and devices

From March 2016 to June 2016, awake surgery and hearing test via the retrosigmoid approach were performed for vestibular schwannoma resections and auditory brainstem implantations in four patients. Candidates were required to meet the following criteria: having received a diagnosis of NF2, being at least 12 years old, requiring either first- or second-side acoustic tumor removal, and having language competency, reasonable expectations, psychological suitability, and willingness to comply with the investigational protocol [2]. The study was approved by Beijing Tiantan Hospital Ethics Committee (No. QX2014-003-04). Written informed consent, which contained publication of identifying information/images in an online open-access publication, was obtained from patients before implantation. The study was performed in accordance with the approved guidelines and regulations.

As show in Figure 1, the ABI electrode paddle (Nurotron, Zhejiang, China) was comprised of slightly elliptical medical silicone, measuring 12 mm × 4 mm. 24 surface electrodes were attached to one side, and the other side was covered with a 1-cm-diameter polyethylene terephthalate mesh pad for stabilization purposes. The electrodes were composed of platinum and were circular with a 0.2 mm diameter.

Surgery and anesthesia

The retrosigmoid approach was used in all cases, and the operative technique is well described by other authors [17]. Facial and glossopharyngeal nerve monitoring were performed throughout the procedure. Intraoperative EABRs were recorded from the Bio-logic Navigator Pro diagnostic AEP system (Natus Medical, Pleasanton, CA) (Figure 2(B)). A detailed methodology for EABR recording and interpretation is described by O'Driscoll et al [9,10].

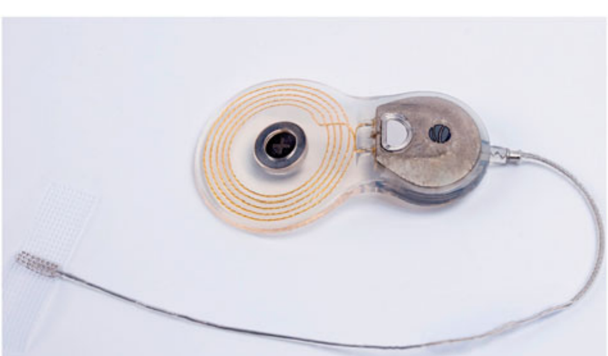

Figure 1. Photograph of Nurotron auditory brainstem implant device.

Intermittent general anesthesia was used during awake craniotomy, which is also known as the asleep-awake-asleep (AAA) technique [16]. The position used was the lateral decubitus. After anesthesia induction, the airway was secured using a laryngeal mask airway (LMA). Anesthesia was maintained using oxygen, nitrous oxide and sevoflurane, supplemented with an infusion of propofol and remifentanil. Once the craniotomy was completed, the dura mater was infiltrated with lidocaine. Twenty minutes before cochlear nucleus mapping, anesthesia was discontinued, and the LMA was removed. Before the closure of the dura, propofol was given, and the LMA was reinserted and remained in place until the end of surgery.

Wake-up hearing test intraoperatively

After tumor excision, the location of the foramen of Luschka was verified with various landmarks, such as the seventh, eighth, ninth cranial nerves and choroid plexus (Figure 2(A)). During the awake phase, a wake-up hearing test was performed (Figure 2(C)). Stimulations would be given to the patients' cochlear nucleus by the ABI electrodes, and the intensity of stimulation was begun at 0.5 mA and went as high as 2 mA. After stimulation of the cochlear nucleus, the patients would be asked three questions by an assistant doctor. Whether they had heard sound, any uncomfortable symptoms did the patients experience, and the features of the sound they had heard, such as number, pitch and loudness. The assisting doctor communicate with the patients who still had useful residual hearing in the contralateral ears in oral language. The other two patients who had no useful hearing in both ears were communicated with a writing interpreter. Every time the patients were stimulated, the number of stimuli was variable and the patients would describe the number of sounds they had heard. The correct rate of the patients' answer for the number of stimuli was assessed.

The ABI device include 24 surface electrodes. If active electrodes were less than 12, the electrode array was thought in suboptimal placement, surgeon would adjust the position of the device. Threshold level and number of distinct pitches were also achieved in the test. Similar to the numeric pain rating scale, we use the numeric pitch rating scale to assess the pitches achieved from ABI. The 11-point numeric scale ranges from '0' representing extreme low pitch to '10' representing the other pitch extreme. The patient would describe the pitch they heard during the awake hearing test. For example, a patient reported 5 points represent moderate pitch he had heard.

Device fitting and speech assessment

Device activation was performed at 6 weeks after surgery. In patients with functional hearing in the contralateral ear, ABI implanted during first-side surgery (as a 'sleeper' device)

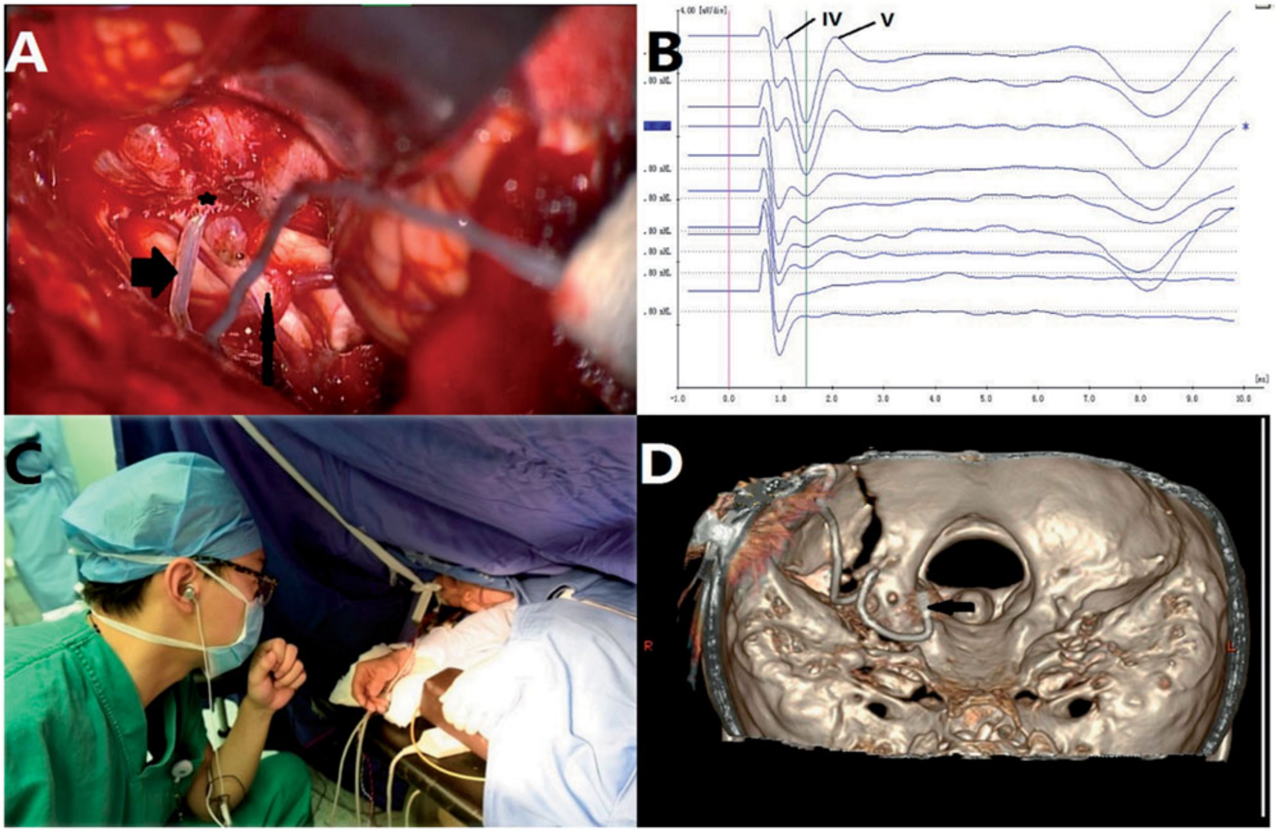

Figure 2. (A). Intraoperative view in an NF2 patient after a left versus removal and an auditory brainstem implantation through a retrosigmoid approach. The posterior groups nerve (long arrow) and the choroid plexus (*) helped in the identification of the lateral recess. The short arrow indicated electrode cable. (B). Typical recordings of intraoperative auditory evoked potentials stimulated by the auditory brainstem implant. (C). Intraoperative wake-up hearing test. (D). Three-dimensional CT scan after placement of a right-side ABI.

Table 1. Clinical demographic data of patients.

Patient	Sex	Age (years)	Side	Tumor size (cm)	Duration of hearing loss (months)	Preoperative PTA (L,R)	Device activation
P1	F	43	L	2.6	12	67, 48	Sleeper
P2	F	24	R	2.3	18	48, —	Sleeper
P3	M	46	R	5.0	12	75, —	Activated
P4	M	37	L	3.4	24	—, 77	Activated

PTA: pure tone test.

was not switched on until hearing was lost in the contralateral ear. Stimulation-related non-auditory side effects, if occurring at infra-threshold levels and if troublesome enough, were managed by disabling the offending electrode or electrodes. Refitting and reevaluation of the auditory performance were performed regularly over the first year. Computed tomography (CT) was routinely performed to postoperatively confirm array position within the lateral recess at 6 months (Figure 2(D)).

Speech and sound assessment measures were performed and recorded at 3 months, 6 months and 1 year postoperatively. The auditory measures included environmental sound recognition (20 sounds tested in an open-set mode) and simple rhythmic pattern reproduction. Speech perception tests were conducted in Mandarin in quiet listening conditions. Open-set speech perception tests were performed using a live voice at normal conversational levels in three conditions: (1) use of ABI alone without the help of lip-reading mode, (2) lip-reading alone without the use of ABI, and (3) lip-reading together with use of ABI (ABI + LR).

Results

Clinical demographic data of patients

The clinical demographic data of patients was show in Table 1. The mean vestibular schwannoma size at surgery was 33.1 mm (range, 23–50 mm). Deformation of the brainstem was present in 3 patients. The mean duration of hearing loss in operated ear at surgery was 16.5 months (range, 12–24 months). The mean patient age at the time of ABI implantation was 37.5 years (range, 24–46 years). All patients were Chinese and spoke Mandarin as their mother tongue. In all patients, implantation was performed in conjunction with removal of the tumor.

Outcomes of wake-up hearing tests

Outcomes of wake-up hearing tests in four patients who underwent awake craniotomy are summarized in Table 2. Three patients intraoperatively achieved auditory sensations

Table 2. Outcomes of wake-up hearing tests.

Patient	Auditory perception	Accuracy (%)	Number of active electrodes	Number of distinct pitches	Threshold levels (nC/phase)	Non-auditory sensation
P1	+	100	14	7	10.6	dizziness
P2*	/	/	/	/	/	/
P3	+	98	15	6	9.8	_
P4	+	95	17	8	11.6	_

*The patient was considered uncooperative in wake-up test.

Table 3. Adverse events and symptoms of discomfort of awake craniotomy ($N = 4$).

Adverse event or discomfort	No.
Cardiovascular (Hypotension, Hypertension, Arrhythmia)	0
Pulmonary (Airway obstruction, Respiratory depression, Pulmonary aspiration)	0
Neurological (Brain swelling, Seizure, Air embolism, hemorrhage)	0
Laryngeal/pharyngeal traumatism	0
Nausea	1
Postural pain	1
Uncooperative patient	1

in the hearing test, and one patient was considered uncooperative. When the number of sound stimuli changed, the patients could distinguish it accurately. The precision could reach 100%, 98%, and 95%. In the three patients completed awake hearing tests, the numbers of effective electrodes were 14, 15 and 17. The threshold levels for the three patients ranged from 4.0 to 64.0 nC/phase, and the mean threshold levels were 10.6, 9.8 and 11.6 nC/phase. As stimulus level increases above threshold, loudness of the sound increased monotonically. The number of electrodes that provided distinct pitch sensations were 7, 6 and 8. A wake-up test lasted approximately 60 minutes on average.

The adverse events and patient reports of discomfort recorded during the awake phase of the protocol are summarized in Table 3. Electrocardiogram (ECG) was monitored closely, and no cardiovascular or pulmonary abnormalities were observed during the awake phase. There was one case of postural pain without the need to abort the awake phase. To investigate the personal experiences of patients during the awake phase, we postoperatively carried out a qualitative survey. The uncooperative patient had no recollection of being awake, and the other three were satisfied with the experience.

Auditory outcomes

Two of the four ABI patients (P3 and P4) used the processors on a daily basis, whereas the other two still had useful residual hearing in the contralateral ears and used the processors only in the laboratory. Sound and speech assessment measures were performed at 3 months, 6 months and 1 year postoperatively in the two patients whose devices were used daily. As shown in Figure 3, environmental sounds could be differentiated in both patients after 1 year of ABI use (scores of 62.5% and 49.6%). Closed-set word identification was possible in both patients at 1 year (scores of 42.5% and 33.8%). None of them demonstrated open-set speech recognition with ABI alone. With the combination with lip reading, open-set words could be differentiated at 1 year postoperatively (scores of 75% and 58%). It was well accepted for both patients by using ABI in their daily life.

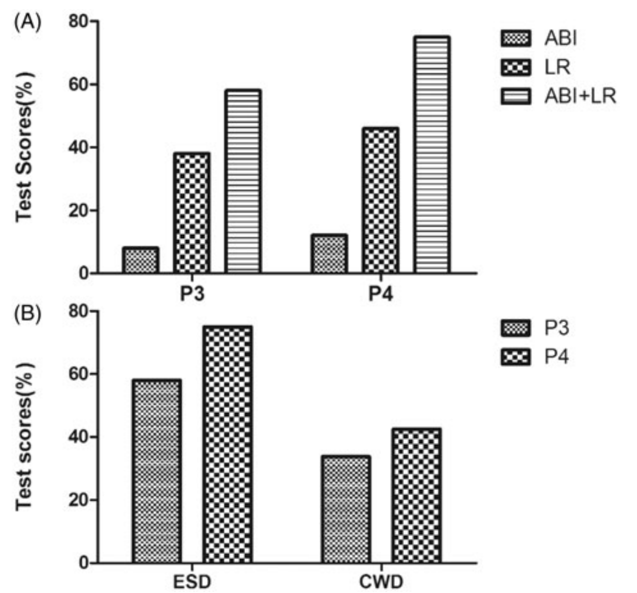

Figure 3. (A). Open-set words discrimination scores in patients after 1 year. ABI indicates sound only; LR, vision only; ABI + LR, sound and vision. (B). Environmental sound discrimination scores and closed-set words discrimination scores in patients after 1 year. ESD, environmental sound discrimination; CWD, closed-set words discrimination.

Surgery complications

No severe intraoperative and postoperative complications were observed in patients with ABI devices. No paddle migration was observed by computed tomography scan at 6 months postoperatively. Two patients experienced non-auditory effects including dizziness and facial spasm, which were managed by disabling the related electrodes.

Discussion

The ABI was developed to provide auditory percepts for adults with NF2 for almost 40 years [4]. However, only a very small number of individuals achieved open-set speech understanding and high sentence scores [6,7]. Suboptimal placement of the ABI electrode array over the cochlear nucleus may be one of the main factors for poor auditory performance [8]. As many studies bring into question the value of the EABRs as a tool for assisting placement of ABIs, we applied awake craniotomy to ABI surgery in four NF2 patients. One year after implantation, the devices were effective in providing auditory benefits that can help recognize environmental sounds and facilitate lip reading.

Awake craniotomy and intraoperative mapping are indispensable parts of modern neurosurgery. Provided that careful preoperative and perioperative counselling is given, the procedure is feasible in many patients. The authors applied awake craniotomy to ABI surgery in four NF2 patients for the first time. Reproducible auditory sensations, satisfactory numbers of effective electrodes, threshold levels and distinct pitches were achieved in the wake-up hearing test. In addition, relatively few electrodes produced non-auditory percepts. All patients were satisfied with the experience, which was in consonance with those that underwent removal of supratentorial brain tumors.

A certain number of active electrodes is necessary for speech understanding. Some authors found that 60%–75% of available electrodes were related to good auditory results [7]. In a systematic review related to hearing rehabilitation in patients with NF2, 50.1% of ABI electrodes showed auditory stimulation [18]. The mean active electrodes in our series is 63.9% (15.3/24). With respect to electrodes causing non-auditory sensation, the mean electrodes ranged from 24% to 42% [7,18]. However, there was only one patient, and five electrodes were reported to cause non-auditory sensation intraoperatively in our study. Overall, our results demonstrated that the wake-up hearing test in awake craniotomy may increase available electrodes and diminish electrodes with nonauditory sensations, which is consistent with our hypothesis. As only two patients use the device daily, no conclusions can really be drawn.

To program the speech processor of an ABI, it is necessary to estimate the threshold levels (T levels) for multiple stimulating electrodes. It has been demonstrated that the T level is critical for speech understanding in CI users. In ABI users, Behr et al. found that threshold level was correlated with high level of speech recognition [6]. Therefore, determining T level by wake-up hearing test would be especially useful for ABI recipients. The mean T level was 10.7 nC/phase in our series, which is obviously lower than that reported in previous studies [19]. After adjusting the position of electrode, the distance from electrode to cochlear nucleus may be decrease, which may lead lower T-levels in our series. In addition to T level, the number of electrodes that provided distinct pitch sensations achieved intraoperatively was also correlated with a high level of speech recognition [6]. By achieving a T level and distinct pitches intraoperatively, awake craniotomy has the potential to improve the auditory outcomes of ABI. One notable weakness of this article is that the acquisition of pitches depends on the judgment of the patients intraoperatively. The subjective approach may result in an inaccurate assessment of pitch from the ABI.

Most studies demonstrated that NF2 patients could benefit from the ABI for differentiating environmental sounds [2,19]. Both patients who used ABI daily in our study could differentiate environmental sounds, which is in concordance with the published studies. Regarding improvement in lip reading for speech understanding, Otto et al. reported that lip reading combined with ABI improved auditory sensations by an average of 30% [2]. Both patients who used ABI daily in our series showed an obvious improvement in speech recognition scores in lip reading combined with ABI after 1 year, which is also in concordance with the literature.

None of the patients in our study achieved open-set speech understanding with ABI alone. Many factors are thought to be related to the functional outcomes of the auditory brainstem implant, such as surgical position, length of deafness, the number of distinct pitch electrodes, perceptual levels, and ABI stimulation rate [6,7]. In addition to the possible factors stated above, Thong et al. supposed that tonal language may be related to poor auditory outcomes. Differentiating between the tones is essential for speech understanding in tonal language, such as Mandarin [5]. Current common speech-processing strategies of the CI and ABI may not be adequate for tonal languages. This have been inferred from studies on CI patients in Cantonese and other tonal languages, who have been found to improve tone recognition and speech perception by adjustments to speech processing parameters [20]. All patients in our study were Chinese and spoke Mandarin as their mother tongue, which may be another possible explanation for our seemingly poor outcome compared with published literature. More research is needed to improve ABI speech-processing strategies for tonal languages.

Conclusions

In the present study, awake craniotomy was applied in NF2 patients during ABI surgery. Satisfactory numbers of effective electrodes, threshold levels and distinct pitches were achieved in the wake-up hearing test. We demonstrated that awake craniotomy for ABI placement is safe and well tolerated, no obvious extra surgical risk was found due to the awake craniotomy. This method can potentially improve the localization accuracy of the cochlear nucleus during surgery. In addition, this is the only published study in Mandarin-speaking Chinese NF2 patients with ABIs. Open speech understanding is improved with the combination of ABI and lip reading in our series. More research is needed to investigate the potential benefits of awake craniotomy and improve ABI speech-processing strategies for tonal languages.

Acknowledgments

We thank Ruquan Han, Dexiang Wang and Shuo Zhang for their invaluable help. This work has been funded by the following grants: The National Science Foundation of China (grant number: 7112049), the National Science and Technology Support Program of the 12th Five-Year Plan of China (grant number: 2012BAI12B03), Beijing Program Foundation for the Talents (grant number: 2016000021469G216) and the Capital Health Development and Research Special Projects of Beijing (grant number: 2011-1015-01).

Disclosure statement

The authors declare no competing financial interests.

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