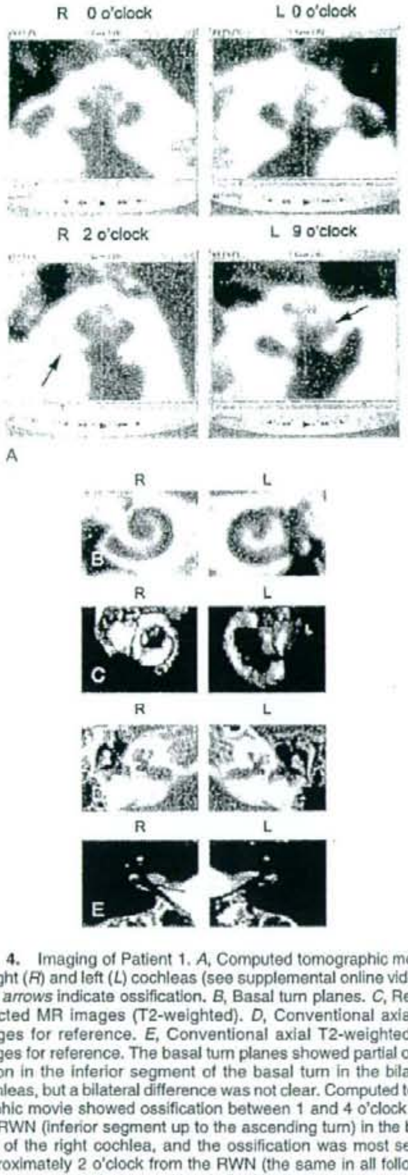

FIG. 4. Imaging of Patient 1. *A*, Computed tomographic movies of right (*R*) and left (*L*) cochleas (see supplemental online videos). The *arrows* indicate ossification. *B*, Basal turn planes. *C*, Reconstructed MR images (T2-weighted). *D*, Conventional axial CT images for reference. *E*, Conventional axial T2-weighted MR images for reference. The basal turn planes showed partial ossification in the inferior segment of the basal turn in the bilateral cochleas, but a bilateral difference was not clear. Computed tomographic movie showed ossification between 1 and 4 o'clock from the RWN (inferior segment up to the ascending turn) in the basal turn of the right cochlea, and the ossification was most severe approximately 2 o'clock from the RWN (the same in all following indications of clockwise positions). Ossification was also apparent in the right middle turn starting from 6 o'clock. The reconstructed MR image (T2) on the *right* showed fluid in the intracochlear spaces spared from ossification, indicating little soft tissue formation. On the *left*, the CT movie demonstrated slight ossification between 1 and 3 o'clock in the basal turn and severe ossification starting from 9 o'clock in the basal turn extending to the middle turn. The reconstructed MR image showed fluid in the intracochlear spaces spared from ossification.

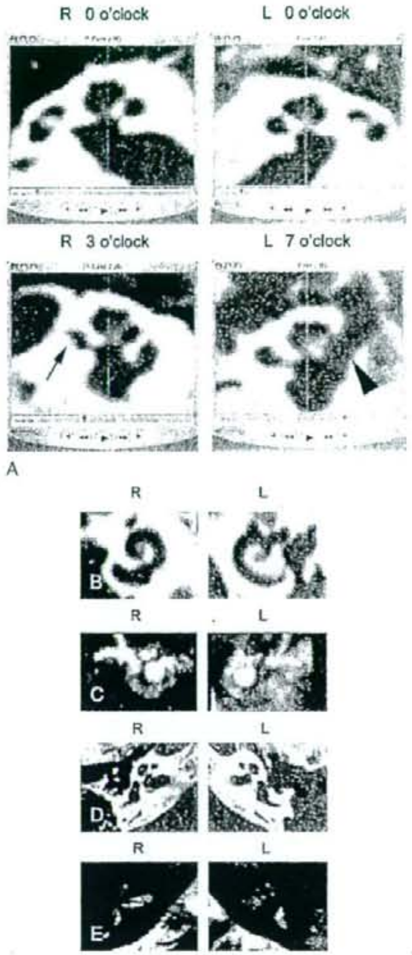

FIG. 5. Imaging of Patient 2. *A*, Computed tomographic movies of right (*R*) and left (*L*) cochleas (see supplemental online videos). The *arrow* indicates ossification. The *arrowhead* indicates communication of the basal turn space to the middle fossa. *B*, Basal turn planes. *C*, Reconstructed MR images (T2-weighted). *D*, Conventional axial CT images for reference. *E*, Conventional axial T2-weighted MR images for reference. The basal turn planes showed partial ossification at the ascending turn in the right cochlea, the boundary between the inferior and ascending segments, and possible slight ossification near the RWN in the left cochlea. In addition, the contour of the basal turn was disrupted in the superior segment on the *left*. On the *right*, the CT movie demonstrated ossification of scala tympani between 2 and 4 o'clock from the RWN. On CT movie, ossification was not apparent on the left cochlea, but connection of the intracochlear space to the cranial base was observed at 7 o'clock and that to the facial canal at 9 o'clock. Reconstructed T2-weighted MR images showed reduced intensity in the bilateral basal turns, especially in the inferior and ascending segments, indicating development of soft tissue.

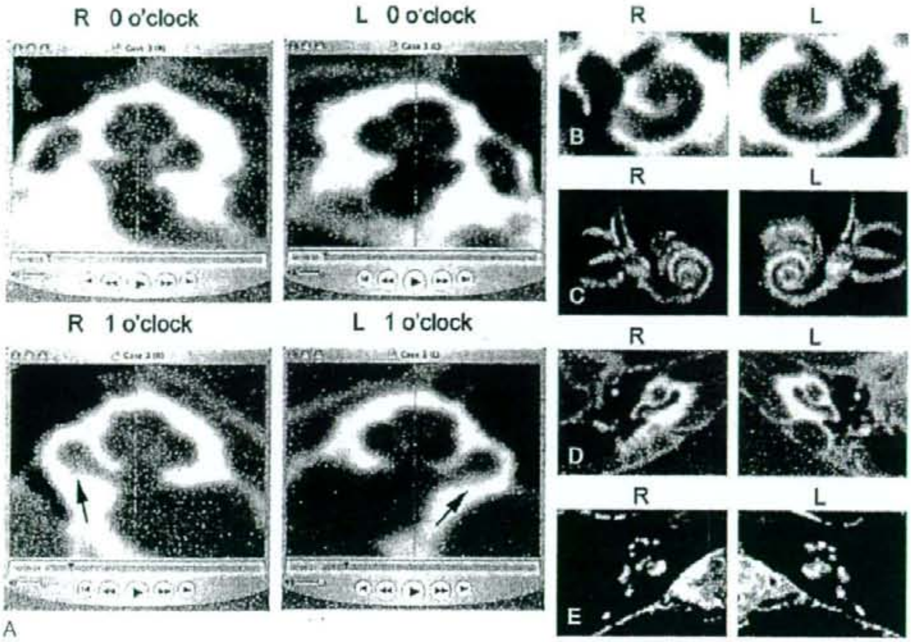

FIG. 6. Imaging of Patient 3. *A*, Computed tomographic movies of right (*R*) and left (*L*) cochleas (see supplemental online videos). The *arrows* indicate ossification. *B*, Basal turn planes. *C*, Reconstructed MR images (T2-weighted). *D*, Conventional axial CT images for reference. *E*, Conventional axial T2-weighted MR images for reference. The basal turn planes showed partial ossification in the inferior segment bilaterally. Computed tomographic movies demonstrated ossification of the scala tympani between 1 and 2 o'clock in the bilateral basal turns. The degree of ossification was slightly higher on the *right*. Reconstructed T2-weighted MR images showed slight narrowing of the fluid space on the *right* but an almost normal appearance on the *left*.

Patient 4

This patient was presented as "Case 2" in our previous article (15) and is reintroduced here to contrast with Patient 2 in the present article with regard to MRI findings and to demonstrate the limitations of our previous method. In brief, a 51-year-old man had become deaf after meningitis 1 year before cochlear implantation on the right side. All images in this article were newly reconstructed from the original DICOM images. The imaging findings are shown in Figure 7. The electrodes were inserted using the normal method, without transcanal drill out, by drilling a bit more around the cochleostomy, corresponding to the anticipation based on our newer method, the CT movie. Despite the reduced intensity of the cochlea in T2 images, the electrodes could be inserted smoothly without effort, in contrast to the present Patient 2.

DISCUSSION

To summarize, the advantage of CT movie over sequential CT films was facility in understanding the 3D space in the cochlea. Evaluation of the extent of the ossified region on CT movie corresponded to the intraoperative findings in all 4 patients. In Patient 4, the CT movie corrected an erroneous evaluation based on conventional CT films. However, additional drilling over the extent of ossification was necessitated in Patient 2 because of scar tissue development. Although there have been not a few CT-based studies concerning cochlear implantation, most of these studies focused on the evaluation of electrode position after surgery (9–15). The present study is the first to compare preoperative evaluation and findings during surgery in multiple cases with partially ossified cochleas due to meningitis in the English literature.

Advantage of the CT Movie Over Conventional CT Films

The CT movie based on sequential sections enables the clinician to envision the extent of ossification and intuit the pattern of potential obstructing osseous lesions to a planned electrode array insertion. Presumably, the human brain can reconstruct the 3D image more efficiently from interactively watching the rotating movie than from viewing a large number of sequential static films. The intended correspondence of the time line in seconds

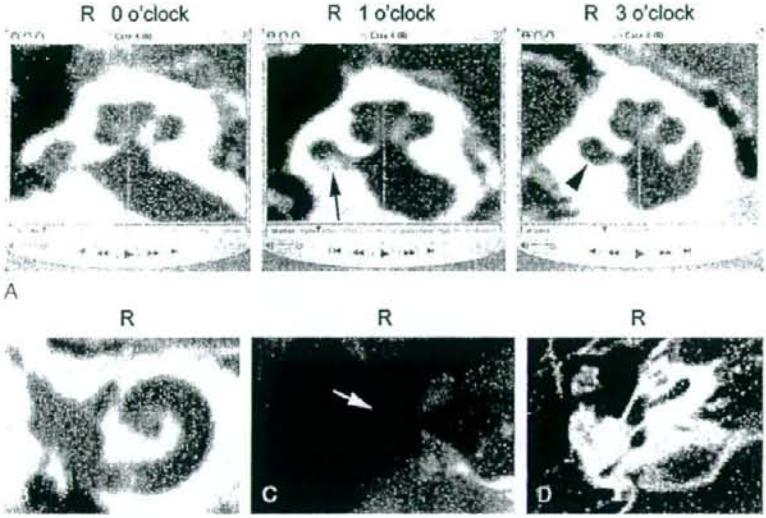

FIG. 7. Imaging of Patient 4. *A*, Computed tomographic movie of the right (*R*) cochlea (see supplemental online video). The *arrow* indicates ossification, and the *arrowhead* indicates the patent basal turn space. *B*, The basal turn plane. *C*, T2-Weighted conventional axial MR image showing reduced intensity in the cochlea (*arrow*). *D*, Conventional axial CT image for reference. The basal turn plane in our previous article (see Fig. 5B of Karino et al. [15]) showed ossification in the inferior segment near the ascending turn (3 o'clock from the RWN), and we considered that the cochlear cross planes confirmed this finding (see Fig. 5C of Karino et al. [15]). However, this finding was denied by the present study. The newly reconstructed basal turn plane showed ossified lesion obstructing the inferior segment near the RWN this time, and CT movie demonstrated only a small ossification in the scala tympani between 0 and 1 o'clock in the inferior segment. This example demonstrates limitation of the basal turn plane in evaluating intracochlear spaces: "ghost" ossification can appear, and it is not easy to deny such a ghost using multiple sequential cochlear cross planes, which cannot be easily reconstructed in the examiner's imagination. Another abnormal finding is the reduced intensity in the intracochlear spaces with T2-weighted MR images, which strongly suggests development of soft tissues.

(0–12 s) to the amount of rotation (0–12 o'clock) also contributes to the ease of understanding the rotating 3D model. As demonstrated in Patient 4, this facility in understanding can also reduce human errors.

Efficacy of CT Movie and MRI in Preoperative Evaluation of Partially Ossified Cochlea

Evaluation of the extent of ossified region by the CT movie corresponded to intraoperative findings in all cases (Table 1). Magnetic resonance imaging can discriminate between fluid (perilymph/endolymph) and soft tissue in the intracochlear spaces, which is not possible with CT. In Patients 2 and 4, MRI anticipated soft tissue development in the intracochlear spaces where ossification was not present. However, as demonstrated above, intraoperative findings differed between the 2 patients. This indicates that the intensity in T2-weighted MRI cannot predict the toughness of the soft tissue and resistance to electrode insertion.

TABLE 1. *Comparison between preoperative evaluation and intraoperative findings*

Case	Duration of deafness (yr)	Ossification evaluated by CT movie	Fluid space by MRI (T2)	Ossification demonstrated at surgery	Extent of bone drilling for device insertion	Additional drilling needed beyond that estimated on CT movie?
1	1.5	Inf Seg to Asc turn	High intensity (normal)	Same as CT movie evaluation	To Asc turn (Inf Seg and part of Asc Seg)	No
2	20	Inf Seg to Asc turn	Reduced intensity	Same as CT movie evaluation	To Sup Seg (Inf Seg, Asc Seg and part of Sup Seg)	Yes (because of scar tissue)
3	1	Inf Seg	High intensity (normal)	Same as CT movie evaluation	Inf Seg	No
4	1	Inf Seg	Reduced intensity	Same as CT movie evaluation	Less than half of Inf Seg	No

Asc indicates ascending; Inf, inferior; Seg, segment; Sup, superior.

In conclusion, CT movie was very useful for intuitive understanding of the position and degree of ossification in the intracochlear spaces, and for reducing human error. However, surgeons should always keep in mind that additional drilling may become necessary during surgery because of soft tissue proliferation.

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ORIGINAL ARTICLE

Vestibular evoked myogenic potentials evoked by multichannel cochlear implant – influence of C levels

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Abstract

Conclusions. This study showed that vestibular evoked myogenic potentials (VEMPs) evoked by cochlear implant (CI), could be related to the comfortable level (C level), particularly in the channels that are closer to the apical turn of the cochlea. *Objective.* The purpose of this study was to investigate the correlation between VEMPs and C level of each channel. *Subjects and methods.* We investigated 24 children who underwent cochlear implantation. VEMPs were recorded from the operated ears with the CI switched 'off' or 'on'. To investigate the correlation between VEMPs and C level, we selected 13 patients with Nucleus 24 (SPrint), and divided them into group A (normal VEMPs) and B (absence of VEMPs). In these children, all the 22 electrodes were active, and were mapped in the same frequency range for each channel. *Results.* Twenty children (83%) showed no VEMPs with the CI 'off'. Among them, 10 elicited VEMPs with the CI 'on', but the other 10 did not. In all channels, the mean C levels of CI were higher in group A than in group B. The p values in channels 1–12 were >0.10, in channels 13–16 were 0.06–0.09, and in channels 17–22 were 0.05–0.06, which were lower but not statistically significant.

Keywords: *Children, cochlear implant (CI), VEMPs, electrical stimulation, inferior vestibular nerve, C level*

Introduction

In patients with a multichannel cochlear implant (CI), electrical stimulation may not only stimulate the cochlear nerve, but may also partially spread to the facial nerve [1,2] or vestibular nerve [3]. Vestibular evoked myogenic potentials (VEMPs) are considered to be useful for evaluating the functions of the saccular [4], inferior vestibular nerve [5] and the tonus of the sternocleidomastoid muscle (SCM). In our previous study, we reported that there were no VEMPs during CI stimulation in eight children, but there were VEMPs in the other four children [3]. However, the differences in VEMPs in that study were still unclear.

The surgical procedures, CI devices, current intensity, stimulation schemes and testing paradigms used may be important for eliciting VEMPs. In this study, we selected 13 children with Nucleus 24 (SPrint), all the 22 electrodes of which were active and mapped in the same frequency range, and investigated the correlation between VEMPs and the C level of each channel.

Subjects and methods

Subjects

The patients were 24 children who underwent CI surgery at the University of Tokyo Hospital. The mean age at VEMP recording was 5.4 ± 3.0 years (range 2–14 years). All the patients had normal inner ear structures, as demonstrated by computed tomography (CT) of the temporal bone. All the children showed improved hearing after surgery.

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Procedures and VEMP recordings

The children were placed in the supine position. The active electrode was placed on the upper half of SCM, the reference electrode on the upper sternum and the ground electrode on the midline of the forehead. During VEMP recording, the children were instructed to lift their head up or to turn their head to the contralateral side to induce hypertonicity in the SCM.

The electromyography signal from the stimulated side was amplified and averaged using a Neuropack evoked-potential recorder (Nihon Kohden Co. Ltd, Tokyo, Japan). Electromyographic activities at a constant level were recorded for each child. The head-phone was placed over the microphone of the CI behind the ear. Rarefaction clicks (0.1 ms; 95 dB normal hearing level) were presented through the head-phone (type DR-531; Elega Acous Co. Ltd, Tokyo, Japan) and were used to evoke the VEMPs. The stimulation rate was 5 Hz, the band-pass filter intensity was in the range of 20–2000 Hz and the analysis time was 50 ms. VEMPs in response to 100 stimuli were averaged twice. After the CI surgery, the VEMPs of all the 24 children were recorded from the operated ear with the CI switched 'off' or 'on'.

Definition of VEMP

We classified VEMP recordings into three types as follows. Type 1, normal: the amplitudes of VEMPs were $>50\ \mu V$. Type 2, small: the amplitudes of VEMPs were higher than $0\ \mu V$, but lower than $50\ \mu V$. Type 3, absent. Types 2 and type 3 were regarded as abnormal VEMPs.

Characteristics of CI device

The characteristics of CI devices are summarized in Table I.

CI device. All patients received multichannel cochlear implants; 21 children had Nucleus 24 and 3 children had Nucleus 22.

Speech coding strategy. All patients with Nucleus 24 were coded with ACE and all patients with Nucleus 22 were coded with SPEAK.

Speech processor. Two patients used ESPrit, and one child used Spectra. Among patients with Nucleus 24, 18 patients used SPrint, one used ESPrint and 2 used ESPrit 3G. Among patients with Nucleus 24, the electrodes of all the channels were active in

Table I. Profile of patients.

Patient no.	Sex	Age (years)	CI type	Speech processor	Strategy	Active electrode number	VEMP	
							Off	On
1	M	2	24M	SPrint	ACE	22	–	+
2	F	2	24M	SPrint	ACE	22	–	+
3	F	4	24M	SPrint	ACE	22	Small	+
4	F	5	24M	SPrint	ACE	22	–	+
5	F	7	24M	SPrint	ACE	22	–	+
6	M	3	24M	SPrint	ACE	22	Small	+
7	M	3	24M	SPrint	ACE	22	Small	Small
8	M	2	24M	SPrint	ACE	22	Small	Small
9	M	6	24M	SPrint	ACE	22	–	–
10	F	4	24M	SPrint	ACE	22	–	–
11	M	6	24M	SPrint	ACE	22	–	–
12	F	4	24M	SPrint	ACE	22	–	–
13	F	5	24M	SPrint	ACE	22	–	–
14	F	3	24M	SPrint	ACE	22	–	–
15	F	3	24M	SPrint	ACE	22	–	–
16	F	7	24M	SPrint	ACE	22	–	–
17	M	4	24M	SPrint	ACE	21	–	–
18	F	3	24M	SPrint	ACE	18	–	+
19	F	11	24M	ESPrit	ACE	20	–	+
20	M	7	24M	ESPrit 3G	ACE	20	–	+
21	M	7	24M	ESPrit 3G	ACE	20	–	–
22	F	9	22M	ESPrit 22	SPEAK	18	–	+
23	M	14	22M	ESPrit 22	SPEAK	17	–	+
24	F	8	22M	Spectra	SPEAK	16	–	+

16, and electrodes of a part of channels were active in 5 patients.

Correlation between VEMP and C level

To investigate the correlation between VEMP and C level, we selected patients with the same CI device, coded with the same strategy and programmed with the same frequencies in each channel. All of these patients had Nucleus 24 CI devices (SPrint) and were coded with ACE strategy, and programmed with the same frequency ranges in each channel. In these patients, the electrodes of all the channels were active. We divided these patients into group A (normal VEMP; $n=6$) and group B (absence of VEMP; $n=7$) when the CI was switched on. Groups A and B were compared in terms of the C levels of each channel. However, two patients with small VEMPs were excluded, and one patient who used a different stimulation rate was also excluded from this study.

Procedures for obtaining C level data

MAPs were created by audiologists for each subject using Cochlear Corporation's Nucleus R126 ver.2.1. All MAP data of Nucleus 24 were created using ACE of monopolar stimulation at a duration of 25 μs/phase. The default stimulus for the ACE processor is a 500 ms burst of 250 Hz biphasic pulse train. The 'current level' used in both the NRT software (for masker and probe levels) and the R126 programming software were represented in units that vary from 1 to 255 and span a nominal range of approximately 10.2 μA to 1.75 mA, respectively. To avoid confusion between actual current level of microamps and Cochlear Corporation's 'current level' units, we refer to the stimulus level in 'programming units', which correspond to Cochlear Corporation's 'current level' units [6].

The child would indicate threshold and the maximum stimulus level that was comfortable for each electrode stimulated. For younger children (approximately aged 2–6 years), minimal response levels were obtained using play audiometry. These levels were used to measure T level. T level would be set at a level that evoked a consistent change in behaviours, such as quieting or head turn. At connection, C levels were typically set from above T level uncomfortable level for each of the three or four MAPs loaded onto the speech processor. The child was sent home wearing the softest MAP, and the parents were instructed to work their child through each of the progressively louder programs during the first few weeks of implant use until they returned for the next programming session. This was done to ensure that the initial MAP would be comfortable for the first day of use. To investigate the correlation between VEMP and C level, we selected the data of C level at the same time as VEMP recording.

Statistical analysis

Data were analysed statistically using unpaired t test. A difference was considered to be statistically significant at $p<0.05$.

Results

VEMPs appearance rate with CI off and on

When patients were tested with CI off, VEMPs were absent in 20/24 and small in 4/24 children. When patients were tested with CI on, VEMPs were normal in 12/24, small in 2/24 and absent in 10/24 children (Figure 1).

Comparison of VEMPs in the same patients with CI off and on

The comparison showed the following results: 10/24 children among those with absent VEMPs with CI off showed VEMPs with CI on (Figure 2); 10/24

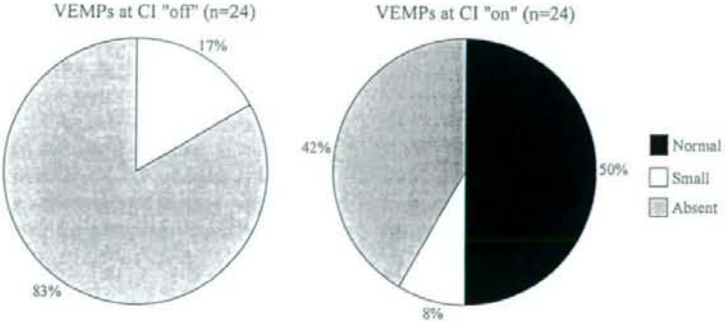


Figure 1. VEMPs appearance rate with CI off and on ($n=24$). Left: VEMPs with CI off ($n=24$). Right: VEMPs with CI on ($n=24$).

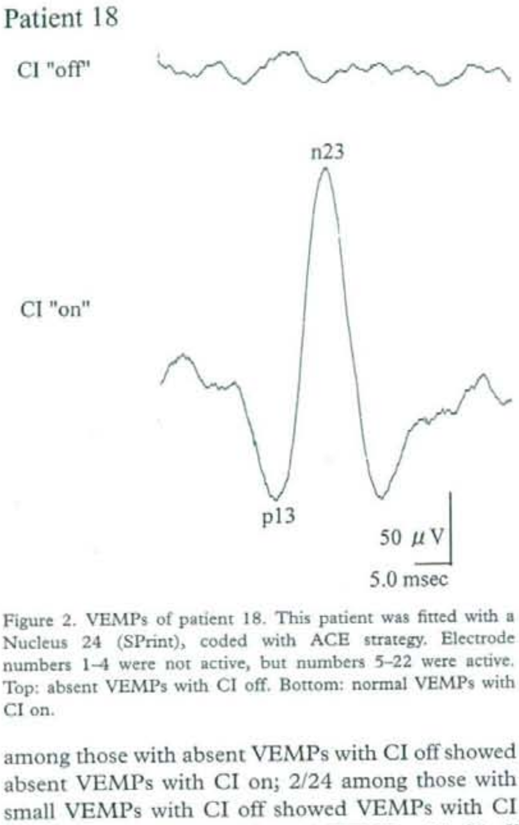


Figure 2. VEMPs of patient 18. This patient was fitted with a Nucleus 24 (SPrint), coded with ACE strategy. Electrode numbers 1–4 were not active, but numbers 5–22 were active. Top: absent VEMPs with CI off. Bottom: normal VEMPs with CI on.

among those with absent VEMPs with CI off showed absent VEMPs with CI on; 2/24 among those with small VEMPs with CI off showed VEMPs with CI on; 2/24 among those with small VEMPs with CI off showed small VEMPs with CI on.

The changes in VEMP amplitude before and after turning CI on are summarized in Figure 3. The mean amplitude with CI off and CI on were 6.5 ± 15.4 and 83.9 ± 102.9 µv, respectively.

Effect of C level on VEMPs

The mean time lapse after CI surgery in groups A ($n = 6$) and B ($n = 7$) were 13.3 ± 17.7 and 11.1 ± 10.1 months, respectively. There was no significant difference in the time lapse after CI surgery between groups A and B ($p = 0.7843$).

Figure 3. Changes in VEMP amplitude with the CI on ($n = 24$). Solid circle, patients have Nucleus 24 and all the 22 electrodes were active; empty triangle, other kinds of patients. n0 = 10: absent VEMPs with both CI off and on ($n = 10$).

The VEMPs in groups A and B are illustrated in Figure 4.

The lower and upper frequencies in each channel in group A (normal VEMP) and group B (absence of VEMP) are illustrated in Figure 5a.

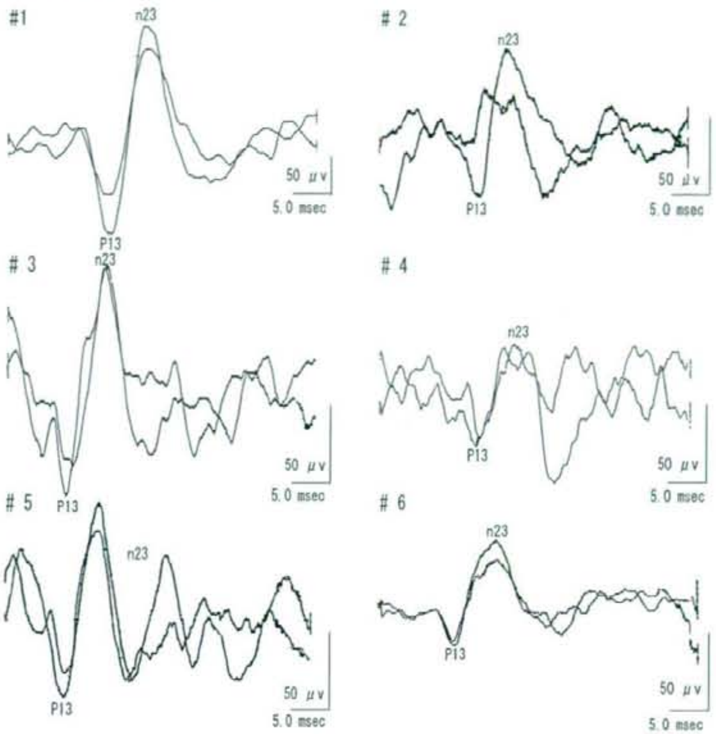
Mean C levels in each channel in group A and B are illustrated in Figure 5b. In all channels, each mean C level was higher in group A than in group B. The p values in channels 1–12 were >0.10, in channels 13–16 were 0.06–0.09, and in channels 17–22 were 0.05–0.06. Then, it was revealed that the C level that elicited VEMPs in group A was higher than in group B. The C level was higher than among those who had normal VEMPs (with CI on) and those who had no VEMPs, due to differences in channels 17–22.

Discussion

As regards saccular function after CI surgery, the insertion of an intrascalar electrode array causes immediate damage to the inner ear [7,8] and over time may cause additional changes, which can interfere with neuronal stimulation [9,10]. The postoperative dysfunction of the vestibular system in multichannel CI patients has been reported, such as dizziness [11], and reduction of caloric responses [12], and a vestibule-ocular response to rotation chair [13]. A decrease in VEMPs after CI surgery has also been reported [3,14]. In our previous study, we compared the VEMPs of the operated ear before and after CI surgery, and found that in 7 of the 12 children (58%), the VEMPs were abolished postoperatively without CI stimulation [3]. Ernst et al. demonstrated that VEMPs induced by bone-conducted acoustic stimuli are absent in 36% of patients before implantation, and that this percentage increases to 78% after the CI surgery [14]. These reports suggested that the saccule of these children must have been damaged after CI surgery in the operated ear.

In this study, we found that 20 patients (83%) did not show VEMPs without CI stimulation after surgery. This result is in agreement with those of previous studies [3,14]. In a pathological study of the human temporal bone, saccule collapse occurred in the operated ear [15,16], but the hair cell densities were the same as those in the non-operated ear [15]. Direct damage to the ductus reunions [17] or cochlear duct as a result of it being blocked externally by fibrous tissue or bone and internally by debris may result in saccule collapse [15]. Our

(a) VEMP in group A (n=6)



(b) VEMP in group B (n=7)

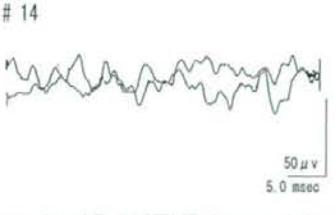


Figure 4. VEMPs in groups A and B. (a) VEMPs in group A ($n = 6$); (b) VEMPs in group B ($n = 7$).

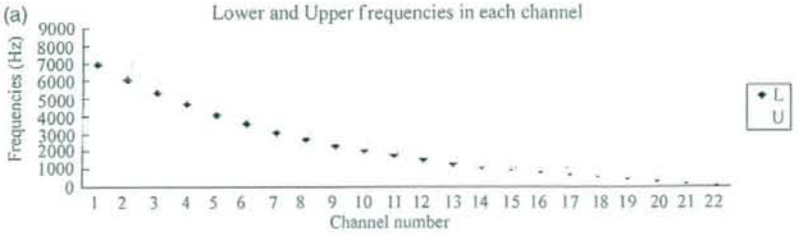
results also revealed that the functions of the saccule are lost after CI surgery.

Galvanic stimulation of the mastoid can stimulate the vestibular nerve [18,19], and elicit a sway response [20], eye movement [21] and VEMPs (galvanic VEMPs) [22,23]. Watson et al. reported that galvanic VEMPs are abolished by selective vestibular nerve section [22]. These studies suggest that galvanic VEMPs can stimulate the vestibular nerve and vestibular nucleus and elicit myogenic potentials in the SCM.

In our study, 20 children (83%) showed no VEMP response with the CI off, but 10 of these patients showed normal VEMP responses with the CI switched on. With the CI off, children with a CI were given only acoustic stimulation, but with the CI on, the acoustic stimulation changed to electrical stimulation. The VEMPs evoked by CI must be caused by the electrical stimulation of CI, which probably stimulates the inferior vestibular nerve. A human temporal bone pathological study demonstrated that Scarpa's ganglion cell count in the operated ear was the same as that in the non-operated ear [15]; however, collapse was only seen in the operated ear [15,16]. It is suggested that the vestibular nerve must be intact, although the functions of the saccule were lost in CI patients.

The basilar membrane of the inner ear is responsible for analysing the input signals into different frequencies. Low-frequency sounds create travelling waves in the fluid of the cochlea that cause the basilar membrane to vibrate, with the largest

(a) Lower and Upper frequencies in each channel



(b) Average of C levels in each channel

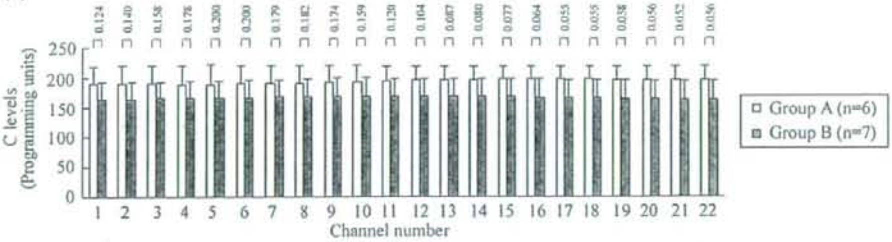


Figure 5. Average of C levels in each channel in group A ($n=6$) and B ($n=7$). (a) Lower and upper frequencies in each channel; L, lower frequency; U, upper frequency. (b) Average of C levels in each channel in group A ($n=6$) and B ($n=7$).

amplitude of displacement occurring at the apex of the basilar membrane. On the other hand, high frequency sounds create travelling waves with the largest amplitude of displacement occurring at the base of the basilar membrane. If the signals are composed of multiple frequencies, then the resulting travelling wave will show its maximum displacement at different points along the basilar membrane. This place theory for coding frequencies has motivated scientists to consider studying multichannel CIs and VEMPs. In multichannel CIs, the electrodes are located at different distances from the round window, and every channel shows different sensitivities to frequencies.

This study demonstrated that the C levels of CI were higher in group A than in group B. VEMPs stimulated by clicks are more sensitive to higher intensities, and the amplitudes of VEMPs increase with stimulus intensity [24,25]. The amplitudes of galvanic VEMPs also increase with current intensity [26]. It is suggested that the amplitudes of VEMPs are related to the current intensity of the C level.

In this study, the C level was higher among those who had VEMP (with CI on) than among those who had no VEMP, because of differences in channels 17–22 ($0.05 < p < 0.06$). The frequencies of channels 17–22 were 188–938 Hz. This difference in frequency range revealed that VEMPs evoked by CIs are easily elicited in the low frequency range. McCue and Guinan [27] reported that sound-sensitive vestibular afferents showed a broad, V-shaped tuning curve, with the ideal frequencies in the range of 500–1000 Hz. VEMPs evoked by short tone bursts (STBs) of 500 Hz, are used in clinical tests. These suggest that the saccular macula has its preferred stimulus frequency in the low frequency range. Our results suggest that the inferior vestibular nerve could be more sensitive to lower frequency ranges. The anatomic factor should be also considerable. Our results demonstrated that the p values in channels 1–12 were >0.10, in channels 13–16 were 0.06–0.09, and in channels 17–22 were 0.05–0.06. Channels 17–22 and channels 13–16 were further away from the inferior vestibular nerve endings than channels 1–13, so it may be that higher current intensities are needed to stimulate the inferior vestibular nerve in channels 17–22. This suggests that VEMPs evoked by CIs were correlated with C level, especially in the channels that are closer to apical turn of the cochlea.

In our study, 10 of the 24 patients showed no VEMP responses with the CI on. These patients may require higher current intensities to elicit VEMP responses. However, in children, it is difficult to increase the current intensity. Children feel pain or facial nerve stimulation when the current intensities are increased higher than those of the C level.

In conclusion, the presence or absence of VEMPs in children with CIs depends on the larger current intensities of the C level, particularly in the channels that are closer to the apical turn of the cochlea.

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ORIGINAL ARTICLE

Advancement in singing ability using The YUBA Method in patients with cochlear implants

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Abstract

Conclusion. Although overall improvement was not so dramatic due to a lack of retention, session by session advancement of matching pitch for targeted MIDI (Musical Instrument Digital Interface) sound was predominantly obvious. It was proved that The YUBA Method worked to improve singing ability for patients with cochlear implants. *Objectives.* This study sought to verify whether or not the Yuba theory and method improved the singing ability of patients with cochlear implants. *Subjects and methods.* Based on diagnosis, the instructor experimented to improve matching pitch of singing for three patients with cochlear implants using The YUBA Method. The mean fundamental frequencies and standard deviation of singing were then compared with before and after instructions to patients. The instruction was given for over 40 days at the University of Tokyo Hospital. *Results.* For each patient, the mean fundamental frequencies of their singing approached the mean MIDI specified frequencies as references for tests done in all three songs. Overall, the SD between fundamental frequencies of their singing and reference MIDI sounds became smaller.

Keywords: *Vocal folds, falsetto voice, vocal register shock, natural voice, vocal functional physiology, Yuba theory, tone deafness, music education, speech therapy*

Introduction

It is known that people with cochlear implants tend to sing off-key, monotonously, and flat [1]. Earlier results are the work of two separate research groups using the same unique technological singing voice method, The YUBA Method. One group tested 60 normal hearing subjects and found that the main effect of treatment was at the $p < 0.0001$ significance level [2,3]. Another group's results indicated a clear improvement in the singing ability of eight children with cochlear implants through the same method at the $p < 0.02$ significance level. The mean fundamental frequencies of their singing approached the mean MIDI specified frequencies as references. Secondly the deviation between fundamental frequencies of their singing and reference MIDI sounds decreased [4].

There are varying factors among the subjects that influence their singing ability, i.e. device and program of cochlear implants, the inner shape of the cochlea and the condition of the hair cells, musical background, implantation circumstances, cause of hearing loss or strong bradyacusia, and age at implantation. Therefore, it is necessary to evaluate the development of singing skills in individual cases rather than trying to examine their singing by standardizing the subjects' conditions.

In this study, we gave subjects several courses of individual singing voice instruction to teach them whole songs, while gradually increasing the degree of difficulty, so as to understand their singing ability.

This study asserts that if cochlear implant patients can recognize falsetto and natural voices, their singing ability, specifically pitch adjustment, can improve with the application of The YUBA Method. This method facilitates the subjects' intrinsic laryngeal muscular activities, which control their vocal folds, resulting in improved ability in matching pitch.

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With regards to the mechanism of pitch adjustment and pitch control in voicing, pitch is determined by the number of vibrations of the vocal folds. The main factor determining pitch is the function of intrinsic laryngeal muscles that control the length and thickness of vocal folds and the opening and closing of the glottis. Breathing muscles which adjust expiratory pressure can also influence pitch [5]; however, the influence of intrinsic laryngeal muscles is much stronger [6]. In the intrinsic laryngeal muscles there are specific functions of muscles such as the cricothyroid muscle which stretches the vocal folds and the closing muscle group which closes the glottis (interior thyroarytenoid muscle, posterior thyroarytenoid muscle, lateral cricoarytenoid muscle, transverse muscle, oblique muscle) [7–9]. In the production of the falsetto voice the cricothyroid muscle is more active than the closing muscle group, and in the production of the natural voice the closing muscle group is more active [10].

The contraction of the cricothyroid muscle narrows the distance between the cricoid cartilage and the thyroid cartilage; this results in stretching of the vocal folds. The number of vibrations increases not only because of the contraction of the cricothyroid muscle, but also because of the increase in expiratory pressure which elevates the subglottic air pressure [5–9]. The contraction of the closing muscle group closes the glottis, and as the cricothyroid muscle relaxes, the vocal folds are shortened. The number of their vibrations decreases not only because of the contraction of the closing muscle group but also because of decreasing expiratory pressure, which lowers the subglottic air pressure [5–9].

The mechanism for lowering pitch has not been fully revealed [10] in speech physiology. However, past experiments succeeded in lowering pitch by decreasing expiratory pressure, resulting in production of the natural voice [11,12].

Subjects and methods

Three young outpatients of the University of Tokyo Hospital were given therapeutic vocal instruction by The YUBA Method. Table I presents relevant information regarding the patients.

This study was conducted at a language training laboratory in the University of Tokyo Hospital. The mean laboratory base level during the treatment was around 40 dB. The patients were treated four times between 1 April and 13 May 2006. The patients did not have any medical illness that would affect singing performance (i.e. flu, cold, cough) during the treatment.

Subjects were each given copies of three musical figures and three songs on separate sheets, totaling six sheets. We used a Sony PCM-D1 hard disk recorder to record singing data, instructions, and singing diagnosis, and an electric piano for melody and harmony accompaniment.

The nursery songs chosen for use in this study are well known to most Japanese people, including the subjects. We started out at an easy level and gradually worked up to higher levels. Song 1 'Frog chorus' and song 2 'Twinkle, twinkle little star' have an interval within the major 6th. Song 2 is a little more difficult than song 1, because in song 1, they can sing along with the scale, but song 2 has two jumps in the melody and is much longer than song 1.

Table I. Profile of patients.

Subject	Gender	Age	Device	Medical history	Speech perception test score	Musical background
Case 1	Female	23	Med-El Combi 40+	(Congenital bradyacusia) Hearing aid from 1 year 8 months until implantation of CI Cause of anacusis: vestibular aqueduct dilatation CI: since 20 years 3 months	Single note: 7% Single word: 20% Short sentence: 18% Post surgery time period to test: 1/2 years	No prior singing or instrument experience except school standard lessons. Violin lessons from 5 to 9 years
Case 2	Male	20	Cochlear Nucleus 22	(Congenital bradyacusia) Cause of anacusis: cold Hearing aid until 11 years CI: since 13 years 1 month	Single note: 60% Single word: 80% Short sentence: 88% Post surgery time period to test: 4 years	No prior singing or instrument experience except school standard lessons
Case 3	Male	20	Cochlear Nucleus 22	(Acquired anacusis) Age of loss: 9 years 4 months Cause of anacusis: Mycoplasma pneumoniae infection CI: since 10 years 5 months	Single note: 45% Single word: 72% Post surgery time period to test: 1 year	No prior singing or instrument experience except school standard lessons

Song 3, 'Sea', is much more difficult than the other two because it has a wider range and skips more frequently. The tonal range of the songs for a male voice is 131–294 Hz, and for a female voice is 262–587 Hz. To ensure consistency due to differences in vocal range, the key was adjusted according to individual vocal range.

Yuba theory and method

The Yuba theory is based on the 'Vocal functional physiology', which deals with the anatomic function of voicing in humans. This theory was originated by Toru Yuba, who has also named this field. It is mainly about controlling intrinsic laryngeal muscular activities, which in turn control the movement of the vocal folds in an effective and original way.

A part of this theory and method comes from the studies of Cornelius L. Read [13], based on the vocal pedagogy of eighteenth century Italy. The Yuba theory is rooted in the belief that humans do not possess any vocal organ. Instead, humans utilize the larynx, which is part of the digestive and respiratory systems, to produce voice. From the practical perspective of vocal functional physiology, humans only have two registers – falsetto and natural. Intrinsic laryngeal muscles are skeletal muscles responsible for making these two registers. However, Toru Yuba considers intrinsic laryngeal muscles as being simultaneously both *semi-voluntary* and *semi-involuntary muscles*. This is because producing falsetto voice or, more importantly, coordinating two registers to eliminate *vocal register shock* cannot be easily controlled like any skeletal muscle, i.e. flexing the arm by the biceps or moving the fingers. Basically, the singing voice is developed by strengthening and coordinating the functions making the two registers – falsetto and natural voices. The frequency of the vibration of the vocal folds determines pitch. We can control and train the intrinsic laryngeal muscles by imitating a modeled voice and at the same time correct motor-related off-key singing. The method based on this theory has facilitated the voicing correction of many off-key singers.

In this treatment The YUBA Method mainly focuses on: producing the falsetto and natural voice; singing both registers independently; interchanging between both registers smoothly; and coordinating the singing of the two registers. The YUBA Method also develops basic abilities for singing by following these essential steps: teaching subjects how to sing a one octave scale, arpeggio, and jump.

The three ways of targeting the pitch adjustment in singing with The YUBA Method are as follows. (1) In the case of the pitch being too low, it is possible to raise the pitch by balancing via instruction with the falsetto voice and increasing air pressure. (2) In the case of the pitch being too high, it is possible to lower the pitch by balancing via instruction with the natural voice and decreasing air pressure. (3) In the case of being off-pitch due to the register shock, it is necessary to coordinate the natural and falsetto voice registers.

Treatment procedure

First, we interviewed each patient to get their basic information: relevant medical and musical background, mental and physical health, and motivation for learning to sing.

In the singing diagnosis, we played the melody of the first two bars of 'Frog chorus' (song 1) as an introduction to each patient and then allowed them to sing the whole song from the first to the eighth bar a cappella (without accompaniment). The first four bars of 'Twinkle, twinkle little star' (song 2) were played as an introduction and the patients sang the complete song from the first to the twelfth bar a cappella. The last four bars of 'Sea' (song 3) were played as an introduction and the patients were asked to sing it from the first to the eighth bar a cappella. We diagnosed their singing acuity comparing their performance before and after each instruction. For one subject (case 2), we adjusted the key of song 1 and 2 to solve the problem of vocal range; the original key was too low for the subject to sing, therefore we raised the key for five semi-tones.

At the beginning of the instruction the instructor produced samples of both falsetto and natural voice several times, letting the subjects listen, while each time explaining to them about the difference in tone quality, i.e. 'This is the falsetto voice, that is the natural voice', to give them a clear concept of both voices. Secondly, for their falsetto voice instruction we made them imitate an owl call sounding like 'whoo', or a dog howling 'whoo', in a breathy high pitched voice. For their natural voice instruction, they produced 'ah—', in a less breathy, low pitched voice. These are vocal abilities necessary for elevating and lowering pitch. Third, we instructed them how to sing a one octave scale, a one octave arpeggio and a one octave jump in this order, until each sound pattern was sung nearly in tune. We instructed them to keep in tune by adjusting their generation of the falsetto voice and the natural voice, and adjusting their expiratory pressure according to the singing conditions of each subject. Lastly, we asked them to sing the same songs to compare their performance before and after instruction.

Method of measurement and analysis

We used the data recorder to compare the fundamental frequencies of the subjects' singing voices with the frequencies of each reference MIDI sound by time series to examine the accuracy of their singing. In this study, we used the frequencies of MIDI signals as the correct reference frequencies. We statistically processed the sequential differences of the vocal frequencies of the subjects' singing before and after the singing voice instruction. We eliminated most of the recording noise, adjusted the volume range per data, and presented the frequencies of each musical note by MIDI for ease of computer processing. For their vocal frequencies, we selected and adopted the fundamental frequencies of their singing voices to the exclusion of overtones. We then calculated the differences between the fundamental frequencies of their singing and the frequencies of the MIDI signals per sample.

Here, we use the frequency measurement unit 'cent', to compare each example of sampling data over MIDI reference frequencies. The mean ($\bar{x}$) of fundamental frequencies in each subject's singing is calculated by dividing the sum of x by the number of data (x) through singing and SD as a standard deviation with respect to x in each subject's singing. In spectrum analysis of the data, we used sampling period 1/86(Sec.) and 4096 points for the frequency resolution.

Data were processed as follows. We did not accept as voice data that which did not correspond to MIDI data. Therefore, the obtained data are somewhat short compared with the actual time series. The statistic for data analysis in this situation is made only when the data for both groups correspond.

In statistical processing, we compared each mean ($\bar{x}$) of singing of all cases and their SDs before and after the singing voice instruction. The changes of mean pitch of each subject's singing were indicated by the former ($\bar{x}$) and the change of the width of sound deviation were indicated by the latter (SD). We determined whether or not the SD of the frequencies was improved through these statistical tests.

We evaluated means, SDs, and p value (probability by Student's t test) in every singing sample of each case in the following way. As an example, we explain the procedure for song 1 of case 1. We used the same procedure for other songs and other cases.

1. We collected all fundamental frequency data in a singing session that correspond to some MIDI note frequency (e.g. C note). As for song 1, its MIDI tone sequences are like C, D, E, F, E, D, C, . . ., where each tone is included multiplicatively. In this case, for example, we collected data of the first C and of the seventh C as same group data (e.g. C is included eight times in song 1). Then we evaluated the mean of a singing fundamental frequency in a song for C from the data with the 'cent' unit.
2. By the same process described above, we can evaluate all means of singing fundamental frequencies that should be equal to each reference MIDI tone frequency in the song. We calculated the mean for each voice corresponding to MIDI's six notes, from C to A, in song 1.
3. We applied this processing to song 1–B1 [singing data before instruction (first day)] and song 1–A4 [singing data after instruction (fourth, last day)]. Then we obtained the mean of all fundamental frequency data in a singing session as for before and after instruction.
4. Using data from (3), we tested the difference of mean of fundamental frequencies of a song between before and after instruction. Here we used Student's paired t test, with $\alpha = 0.05$.
5. We also evaluated mean of SDs of a song with the same processing as described above using SDs that correspond to each MIDI tone frequency in a song. The value of each SD corresponds to scattering measure of each singing session in this study.
6. We applied the same procedure to song 1, song 2, and song 3 for every case (1, 2, and 3). As well as simple statistical analysis, we calculated quantitatively the variation between the results and the target MIDI frequencies.

Results

Here we use following abbreviations. B1, before instruction [1st time]; A1, after instruction [1st time]; A2, after instruction [2nd time]; A3, after instruction [3rd time]; A4, after instruction [4th time]. Table II shows mean ($\bar{x}$), $\pm$SD [unit: cent] and p (T <t) before and after the singing voice instruction. p (T <t) is probability by Student's t test with $\alpha = 0.05$ to B1 and A4 pair and All. 'All' are evaluated by simple average of all cases or songs. A function of statistical data processing in MS-EXCEL was used.

Figure 1 shows means ($\bar{x}$) of fundamental frequency of voice of singing for three songs (1, 2, and 3) for each case. Figure 2 shows the absolute values of mean ($\bar{x}$) by gray bar and $\pm$SDs by vertical bold line for every song for each case.

Table II. Mean ($\bar{x}$), ±standard deviation (SD) [cent] and p (T <t).

		Case 1			Case 2			Case 3			All
Song	Parameter	B1	A4	p	B1	A4	p	B1	A4	p	p
Song 1	$\bar{x}$	−317.4	−2.1	0.0058	609.4	−19.3	0.0002	−258.9	−7.1	0.0005	0.0022
	±SD	272	219.7	0.0588	264.4	211.5	0.0399	127.9	150.2	0.1307	0.0765
Song 2	$\bar{x}$	−382	−183.3	0.0266	447.1	−204.2	0.0018	−339.8	−64.9	0.0008	0.0097
	±SD	256.9	247.4	0.0008	305.2	207.1	0.9893	153.3	148.2	0.0108	0.3336
Song 3	$\bar{x}$	−739.6	−452.8	0.0026	178.1	128.9	0.3858	−749.4	−221.5	0.0027	0.1304
	±SD	261.8	272.4	0.0469	289.8	270.7	0.7409	145.6	210.2	0.0014	0.2631

Average pitch after the singing voice instruction was improved

As shown in Table II, we obtained a level of significance of 5% p $(T < = t) = \{0.002$ (song 1), 0.01 (song 2), 0.13 (song 3)$\}$ by t test for $\bar{x}$ from averaging all cases. As a result, we could conclude that the average of frequencies of all subjects' singing was improved after instruction, because the average pitch after the instruction approached the best value (0). We found that the average of frequencies of all subjects' singing was improved remarkably by a few periods of instruction. Figures 1 and 2 show the same behaviors.

Scattering of pitch (SD) was improved slowly by instructions

From the table, we found that the average pitch of singing of all cases was improved soon after each instruction, although the SDs of singing were improved slightly. Overall, the SD between fundamental frequencies of their singing and reference MIDI sounds became smaller by instruction, although the pace of the improvement of scattering of pitch was slow. We found that improvement for the scattering of pitch needs continuous instruction. This shows the difficulty in curing the scattering of pitch of singing. Figure 2 illustrates this statement.

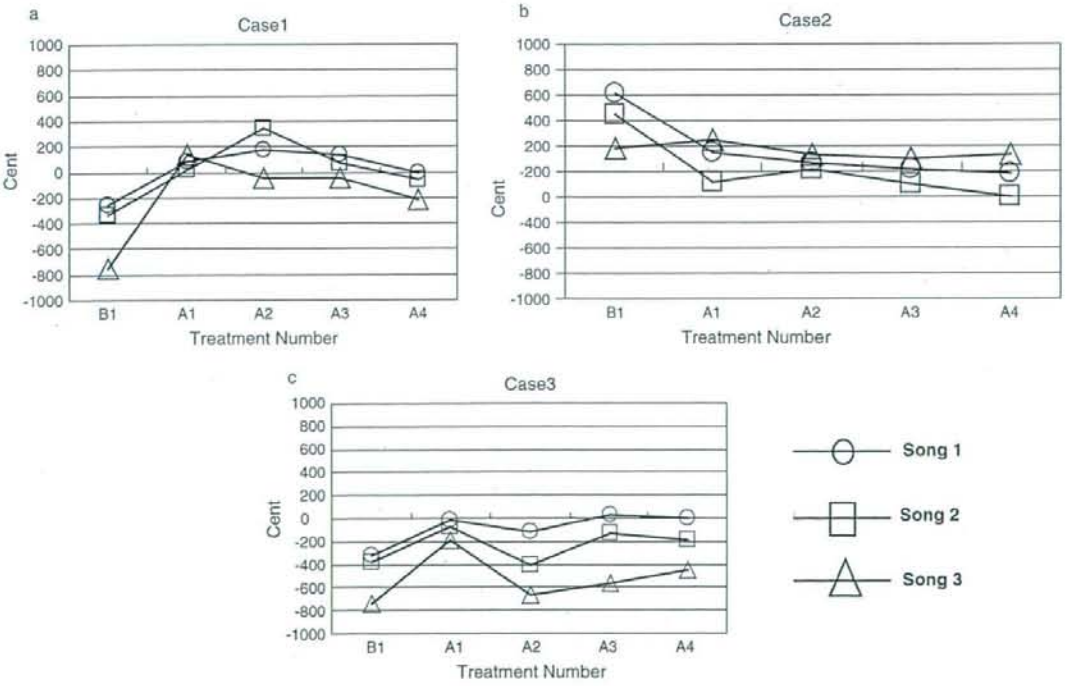

Figure 1. Means ($\bar{x}$) of singing in (a) case 1, (b) case 2, and (c) case 3 for every song (1, 2, and 3). B, before instruction; A, after instruction.

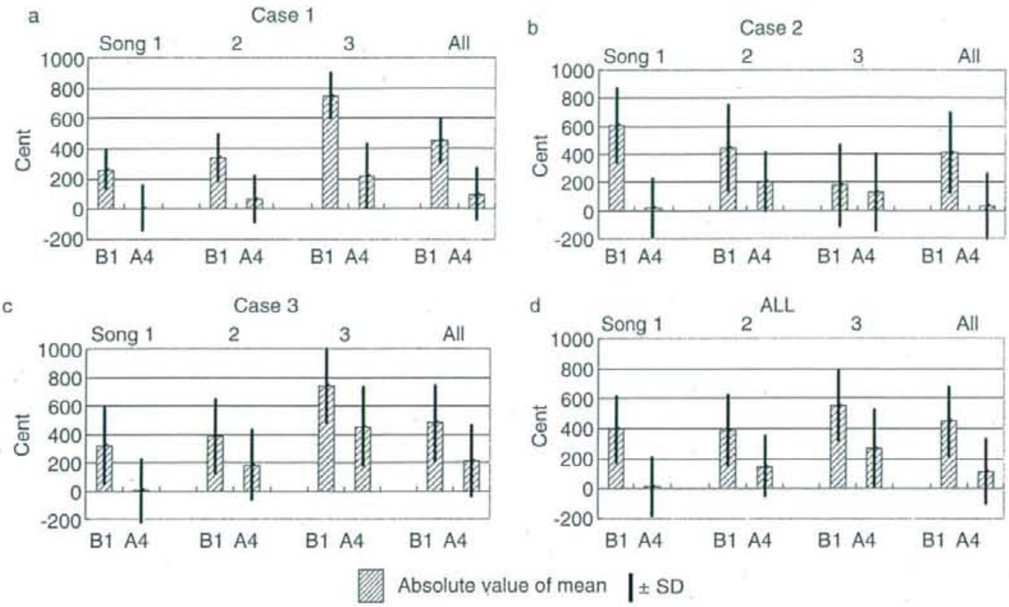

Figure 2. Means and SDs of singing for three songs (1, 2, and 3); (a) case 1, (b) case 2, (c) case 3, (d) all. B, before instruction; A, after instruction.

Discussion

It is known that people with cochlear implants tend to sing off-key, monotonously, and flat. Former results have been the work of two separate research groups using The YUBA Method. One subject group in Hawaii tested 60 elementary students attending the normal level of hearing classes and found that the main effect of treatment was at the $P<0.0001$ significance level. In 2004 the latter group tested eight pediatric patients with cochlear implants and found a clear improvement in their singing ability and that the main effect of treatment was at the $p<0.02$ significance level.

This latest research method was improved to provide more of a wide spectrum of results with the patients. This time we conducted the research at a patient's individual level, with four exposures over 40 days as opposed to an individual exposure. We also had the patients sing three whole songs instead of four bars of one song, to provide a larger base of data to process for the results. The three sample songs were deliberately picked for varying levels of difficulty and singing patterns for the same reason. The songs were also chosen because they are well known, to maximize realism within the research. An instructor's voice and electric piano sound were used as reference sounds to clarify the pitch and melody for the patients.

Based on earlier research, we expected that the mean fundamental frequencies of their singing would approach the mean MIDI specified frequencies as references for this study. Also, we thought that the deviation between fundamental frequencies of their singing and reference MIDI sounds would decrease. We expected that these factors would remain constant despite the longer period of exposure and variation in level of difficulty.

Initial consultations with the three patients showed that they could almost distinguish between falsetto and natural voices. Building on this ability, the application of The YUBA Method allowed them to control their laryngeal muscular activities, as demonstrated in their improved ability to produce both the falsetto and natural voices; to sing a one octave scale, arpeggio, and jump guided by an electric piano; to sing the three songs a cappella; and to raise or lower pitch in the rendition of songs. After every instruction, the singing ability, particularly matching pitch, of each patient was diagnosed.

Before instruction, the first patient (case 1) sang monotonously and lower than the targeted pitch. After receiving instructions regarding the falsetto voice, the patient sang higher than the targeted pitch, resulting in off-key singing. Furthermore, she had vocal register shock when shifting from the natural to the falsetto voice and vice versa. When instructed to coordinate the two registers, the improvement in her singing pitch was apparent despite not being able to erase the vocal register shock completely.

The second patient (case 2) sang monotonously and higher than the targeted pitch at the outset, thereby exhibiting a narrow vocal range manifested in singing a higher key when asked to sing in a low note and vice versa. Based on this diagnosis, instructions were given regarding the two registers to expand his vocal range and to introduce the concept of high and low pitch. In addition, the key of songs 1 and 2 was changed from C to F to adapt to the patient's high-pitched male voice. Although the patient still found difficulty in producing definite falsetto and natural voices, he showed an expansion of his vocal range, with a tendency to produce the falsetto and natural voices when prompted.

Originally, the third patient (case 3) sang monotonously and lower than the targeted pitch. After receiving instructions, he was able to produce the falsetto voice. However, he could not produce the falsetto voice constantly until the end of the fourth instruction. Diagnosis revealed an improvement in his singing pitch but his pitch still registered below the target.

If the second and third patients (cases 2 and 3) produced two registers constantly, there would be a better improvement of matching pitch for their singing.

Science is relentlessly in pursuit of improving human quality of life through research. Science is finding that the human body, while fallible, may be repaired and updated through technology. As medical research technology allows us to repair our 'hardware' (the body) through surgery, prosthetic parts, pacemakers, cochlear implants, etc., we invariably have to update the 'software' (technological method) simultaneously. This unique technological method will serve to better the quality of life for the hearing disabled.

In this study, we were able to improve significantly the singing abilities of people with cochlear implants by The YUBA Method. This is an example of how technology developed by research has compensated for the inadequacy of the body's hardware.

In the case of acquired deafness it is known that hearing and speaking abilities can be regained quickly and certainly after implanting an artificial cochlea. This means that even if people lose their hearing ability through some disorders such as senile hearing loss, disease, or accidents, they can regain the pleasure of verbal communication.

We felt that the results of this research were encouraging; however, two uncontrollable factors contributed negatively to our work. First we were unable to use headphones during the experiment due to the subjects' medical condition. Consequently, our results were recorded with electric piano accompaniment and voice simultaneously, making it more difficult to analyze than in the case of normal-hearing subjects. Second, we believe that the various psychological profiles of the subjects detracted from our results and analysis. They were affected during the recording by the performance anxiety based on both prior teasing and having to sing in front of several adult persons in the laboratory. We believe that for these two reasons our results have been adversely affected and we wish to minimize these two factors as much as possible in future work.

This unique technological method can be used as an alternative method for speech therapy rehabilitation. Intonation is positively affected via this method over a larger vocal range than traditional speech therapy alone.

We conjecture that the patients might improve matching pitch better with accompaniment than unaccompanied.

Conclusion

Although overall improvement was not so dramatic due to a lack of retention, session by session advancement of matching pitch for targeted MIDI sound was predominantly obvious. It was proved that The YUBA Method worked to improve matching pitch for the singing of patients with cochlear implants. At this research stage, we cannot conclude with absolute certainty that this technology will work with all people with cochlear implants. However, we are positively encouraged by the results of this, our second study. The same technological method used in an earlier study had similar results. Therefore we feel confident that this unique technological voice method works well.

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小児内耳奇形に対する人工内耳埋込術と術後成績

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要旨：当科で人工内耳埋込術を施行した小児内耳奇形14例の内耳奇形の形態分類，術前聴力と補聴器装用下聴力レベル，手術内容，また術後の聴取能力と言語獲得について検討した。内耳奇形の内訳は1例が外側半規管低形成，4例が両側前庭水管拡大症（EVA），2例がcommon cavity（CC），7例がincomplete partition（IP）であり，IP 7例中2例に両側内耳道狭窄，1例に両側前庭水管拡大症が認められた。人工内耳術後の顔面神経麻痺，髄膜炎，電極脱落例は無かった。両側内耳道狭窄例は2例とも人工内耳装用下の語音聴取能改善が難しく，言語発達のために術後に視覚言語を併用していた。CCの2症例のうち1例は術後語音聴取能，言語表出が良好となったが，1例は言語獲得不良であった。IP，外側半規管低形成，両側前庭水管拡大症例は，全例術後の音声言語コミュニケーションが良好となった。

ーキーワードー
先天性高度難聴，小児内耳奇形，人工内耳埋込術，術後聴取能，言語発達

はじめに

内耳奇形に対する人工内耳埋込術は海外では1980年代半ばより報告され，その有用性が知られている。我が国においても1998年に改定された「人工内耳適応基準」により必ずしも内耳奇形例は禁忌の対象にならないとされ1)，近年内耳奇形を伴う高度難聴児の人工内耳埋込術に対する結果が各施設より報告されている。これまで海外ではIP（incomplete partition：蝸牛不全分離），Partial SCC（外側半規管低形成），両側前庭水管拡大症例では術後の語音聴取テストにおいて内耳奇形のない児と変わりないほどの良好な結果が得られている一方で，CC（common cavity deformity），HC（hypoplastic cochlea）の症例はIP，外側半規管低形成，両側前庭水管拡大症例よりも成績が劣ることが報告されている2)3)。また，両側内耳道狭窄例は術後成績が内耳奇形の中でも極めて悪いことも報告されている2)3)4)5)。今回我々は小児内耳奇形14例の内耳奇形の形態分類，手術，副損傷の有無，術後聴取能力および言語発達についてこれまでの報告と比較した。そして，内耳奇形の形態別にどの程度まで聴取能が改善したか，言語発達が認められたかを検討し，術前の補聴効果，人工内耳手術の時期が与えた影響などについても考察したので報告する。

対象と方法

東京大学医学部付属病院耳鼻咽喉科で1999年5月から人工内耳手術を施行し，観察期間が6ヶ月以上であった症例のうち，小児内耳奇形14例（男児9例，女児5例）を対象とした。これら14例の内耳奇形の形態分類，術前聴力と補聴器装用下聴力レベ