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ORIGINAL ARTICLE

Changes in the Thresholds of the Electrically Evoked Compound Action Potential with Waveform Analyses After Cochlear Implantation

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Objectives: The electrically evoked compound action potential is one of the audiologic tools which is useful for early mapping. The errors must be considered at automated analysis.

Materials and Methods: We analyzed all waveforms and compared manual results to the automated waveforms: Fifteen cochlear implant users were enrolled in this study. Differences in the thresholds of manual neural response telemetry (NRT) and automated NRT were analyzed by repeated measures ANOVA test, and to analyze the statistical difference in the thresholds at each electrode, a paired t-test was used. The ANOVA test was used to analyze differences in the threshold between the basal turn, middle and apical turn.

Results: There was no statistical difference between the threshold of manual NRT and automated NRT ($p>0.05$). Each electrode was compared, a significant difference in threshold was studied, except two electrodes. Thresholds of approximately 2 current level (CL)~12 CL lower threshold of manual NRT was confirmed at each electrode ($p<0.05$). The mean differences in the threshold between automated NRT and manual NRT was approximately 4 CL at the apical turn, 8 CL at the middle turn and 6 CL at the basal turn($p>0.05$).

Conclusion: The thresholds analyzed with visual examination had differences from thresholds analyzed by the automated NRT. We recommend 4 CL in the apical turn, 8 CL in the middle turn and 6 CL in the basal turn electrodes lower than the threshold of automated NRT. These findings might lead to better speech perception and rehabilitation for patients.

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Introduction

For the last 10 years, cochlear implantation (CI) has helped rehabilitate hearing in patients with severe and profound hearing loss. Cochlear implant is a device which can change sound information into electric stimulation and it allows patients with hearing loss to hear sounds and distinguish them. In addition, this device can help patients to have normal conversations with other people. In order to understand sound information correctly, the survival rate and electrical acceptability of the spiral nerve must be estimated accurately, and should be reflected in the speech processor. This result will be most reliable and proper when the recipients can express sound sensations at each electric signal. However young patients who have had hearing problems for a long time or have several combined disorders will not be able to express their sensations of the sound correctly. This leads to the need for objective tests, which are the auditory evoked responses such as electrically evoked compound action potentials (ECAP) or electrically evoked auditory brainstem responses (EABR) and so on. EABR are greatly affected by myogenic potentials caused by the patient's movement so the patients must be asleep during the test. Because the recording electrode is near the stimulating electrode, ECAP are less affected by myogenic potentials and much easier to test compared to EABR. Thus ECAP is the most commonly used test.

ECAP can be recorded more stable than EABR by using the far field recording method. ECAP do not need patients to be asleep, and automatic tests are available. The stimulating electrode which has a strong electric current is beated at the site near the recording electrode. ECAP are greatly affected by artifacts of stimulation and the transformation of waveforms caused by the angle of the electric current or the malformation of the cochlea. Although it is affected less than the EABR, ECAP can be affected by motion artifacts caused by significant patient movement, which might lead to a change in the waveform. Despite

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several limitations, ECAP are more commonly used than EABR[1-3].

Automated neural response telemetry (Auto-NRT, Cochlear Corporation, Australia) analyzes each wave in terms of the N wave (negative peak) and the P wave (positive peak), according to the latent period time at the ECAP waveform, and calculates the amplitude between the N-P wave. This amplitude between N-P waves is calculated based on the threshold of the NRT (t-NRT), identifying changes according to the intensity of the stimulus. When the latent period time of the N wave and P wave is in a specific range, the artifacts are not considered, so that the t-NRT can include some errors. The adjustment of the speech processor should be based on the patient's subjective opinion regarding the sound (electricity) balance, but when the patient's assistance is not available, the t-NRT or EABR is required. This is why the accuracy of t-NRT is very important for mapping and input-output growth function.

In this study, the latent period time of N and P waves and the amplitude between the N-P waves were calculated from the auto-NRT which uses the forward masking paradigm. In addition, the threshold of the manual-NRT (manu-NRT) was determined from the waveform by an audiologic expert. The aim of this study was to compare the manu-NRT with auto-NRT and to make a reasonable standard for when it should be used for early mapping.

Materials and Methods

The subjects for this study were 15 patients who had a cochlear implantation at the department of Otolaryngology-Head and Neck Surgery between October 2006 and April 2009 at the Dong-A university Hospital (Table 1). All of the patients underwent the procedures by the same surgeon under general anesthesia, and 22 electrodes were inserted in all patients. The patients had the 24RE(CA) device (Cochlea Corporation, Australia) implanted in one ear. The radiologic images and medical documents of the patient's condition before surgery were studied retrospectively. All of the patients exhibited no abnormalities on radiologic findings. The mean age of the subjects was 29.7 years (range, 1-73 years) and the mean duration of deafness was 10.8 years (range, 1-33 years). Five males and ten females participated in the study.

The auto-NRT was used 4~5 weeks after the operation just before the speech processor was put into operation, after a check for errors using the resistance between the electrode-tissue and monopolar 1+2 (MP1+2) and stimulograms with the common ground (CG) method current. The resistance between the electrode-tissue contact at this point was 15 kΩ at all electrodes except one (subject 2-E9), and the stimulograms showed no evidence of error such as waveforms diminishing or reversing form.

The auto-NRT was recorded by Custom Sound EP (version-1.3), NRT software(version-2.1) and the Nucleus freedom speech processor. The electric current stimulation probe and the masker were connected to the electrode at the cochlear implant site and the electrode(M1) was implanted outside the cochlea at the temporalis muscle and stimulated by 80

Table 1. Details of the subjects in this study.

Subject	Gender	Age (years)	Deaf duration (years)	Etiology	Excluded electrode
1	Female	18	10	Progressive	E3
2	Female	6	6	Congenital	E9
3	Female	30	25	Progressive	E1, E15, E17
4	Male	64	33	Meningitis	E8, E20, E22
5	Female	5	5	Congenital	
6	Female	58	20	Progressive	
7	Male	4	4	Congenital	E6
8	Female	50	10	Sudden	
9	Female	23	18	Progressive	
10	Female	13	5	Progressive	
11	Female	3	3	Congenital	E12
12	Male	73	2	Sudden	E16
13	Male	50	3	Sudden	
14	Female	1	1	Congenital	
15	Male	47	17	Trauma	

μs of +/- polarity with 25 μs of pulse width and 7μs of interphase gap(IPG). The masker was 100 Hz, with a 0.4 ms masker-to-probe interval (MPI) from stimulation. The electric current intensity of masker was 1 current level (CL) higher than the probe. T-NRT was determined by starting from the electric current stimulation of 100 CL, and adding 6 CL each time. Recording of the ECAP was done by the active electrode which was the second electrode from the apical turn of the stimulated electrode, and the electrode(M2) implanted at the receiver/stimulator unit was the reference electrode. The collected electric potential was amplified 50 decibels (dB), stimulated and repeated 35 times after 123 μs until 1.6 ms.

Analysis of the waveform to get manu-NRT was conducted at all of the electrodes. The selection standard of the N and P waves in this study was based on at a latent period time between 200~300 μs for the N wave and the mount form between 300~700 μs for the P wave. Waves showing the amplitude between the N and P wave less than 5μV were excluded.

Statistical analysis was performed using SPSS program (version 15.0). The differences between the threshold of the auto-NRT and manu-NRT were analyzed by the repeated measured ANOVA test. To analyze the statistical difference between the thresholds of each electrode, a paired T-test was used. The ANOVA test was used to analyze the differences of the threshold between the basal turn(E4~6), middle turn (E11~13) and apical turn (E19~21) of the cochlear. Value with a $p<0.05$ were determined to be statistically significant.

Results

Out of 330 electrodes 319 were studied. Electrodes without waveforms at auto-NRT or manu-NRT were excluded. Seven electrodes in auto-NRT and three electrodes in manu-NRT had no threshold. First of all, we investigated the trends of the changes in threshold for the auto-NRT and manu-NRT at each electrode. The difference between the threshold of the manu-NRT and auto-NRT ($p=0.764$) was not significant. Thus the threshold of manu-NRT can be applied to the threshold level for early mapping.

Each electrodes were compared, showing significant differences in the threshold, with the exception of the E18 and E21 (Table 2, Figure 1). The threshold of manu-NRT at each electrode was approximately 2 -12 CL lower than that of the auto-NRT($p<0.05$). The basal turn showed higher thresholds than those of the apical turn with both the auto-NRT and manu-NRT. The mean differences in the threshold between auto-NRT and manu-NRT were approximately 4 CL at the apical turn, 8 CL at the middle turn, and 6 CL at the

Table 2. The mean threshold of automated-NRT and manual-NRT at each electrode.

Electrode number	N	Auto-NRT threshold	Manu-NRT threshold	Differences
E22	14	153 ± 24	145 ± 24	7 ± 4*
E21	15	159 ± 17	157 ± 14	1 ± 17
E20	14	158 ± 19	152 ± 18	6 ± 4*
E19	15	154 ± 21	148 ± 22	5 ± 6*
E18	15	163 ± 21	158 ± 21	5 ± 9
E17	14	169 ± 20	164 ± 19	4 ± 3*
E16	14	170 ± 25	164 ± 22	6 ± 8*
E15	14	168 ± 25	164 ± 25	4 ± 3*
E14	15	180 ± 20	173 ± 19	7 ± 8*
E13	15	174 ± 21	169 ± 22	5 ± 3*
E12	14	181 ± 20	172 ± 18	9 ± 4*
E11	15	180 ± 26	171 ± 23	9 ± 9*
E10	15	179 ± 18	171 ± 22	7 ± 11*
E9	14	190 ± 16	182 ± 15	7 ± 7*
E8	14	184 ± 19	172 ± 16	12 ± 15*
E7	15	178 ± 14	172 ± 15	6 ± 4*
E6	14	179 ± 20	172 ± 21	7 ± 6*
E5	15	171 ± 22	165 ± 22	5 ± 3*
E4	15	165 ± 27	160 ± 27	4 ± 3*
E3	14	162 ± 26	156 ± 27	6 ± 8*
E2	15	169 ± 32	162 ± 35	7 ± 5*
E1	14	185 ± 23	171 ± 28	9 ± 12*

*Values are the mean ± 1 standard deviation (current level), *: p<0.05*

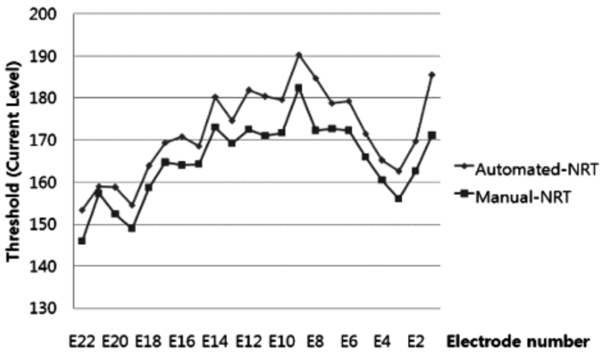

Figure 1. The mean threshold of automated-NRT and manual-NRT at each electrode.

basal turn. The differences in the electrode thresholds between auto-NRT and manu-NRT at the middle turn (E11-13) was greater than those of the apical turn (E19-21) and the basal turn (E4-6). There were no significant differences in the electrode thresholds between auto-NRT and manu-NRT at each turn ($p>0.05$).

Discussion

When a sensory organ is stimulated, a wave which has a large waveform and similar character to the stimulation is observed within a few μs to several ms and is presented as a stimulogram. This could be used to observe the total electric current condition such as the cochlear implant's failure by using phase and amplitude but it also makes it difficult to observe the waveform[1,2]. The short response, which is collected during the very short time of the latent period that occurs due to the stimulation of electricity, is affected greatly[4,5].

The ECAP is an electric potential produced at the end of the auditory nerve of the cochlear implantation. The waveform of the ECAP shows a mount form with low amplitude within 1 ms of the electrical stimulation, and then follows the N and P waves with a relatively large and specific amplitude (dozens μV). The survival state of the auditory nerve can be predicted from this electric potential, and its threshold for electric stimulation can be determined objectively for patients who cannot express their feelings about electric stimulation, such as young patients, patients with other disorders and patients who had hearing problem for a long time. The ECAP has been found to correlate significantly with the behavioral dynamic range of loudness limits (range from comfortable to threshold level) in cochlear implant recipients[6].

Even in the threshold stimulus or a weak impulse, a typical N wave of the ECAP showed a relatively long refractive period of N1. If the stimulus is gradually increased, an additional N0 appears. However, if the stimulation is increased to a point of sufficient stimulation, N_1 disappears and only the N0 remains. Changes in the N_1 at this point by the stimulation of the dendritic process will cause it to reappear and then both the N_1 and N0 appear in a refractory time less than 350 μs, suggesting that both signals are ECAP, which were derived from the terminal end of auditory nerves[7]. In this study, there were tendencies in which N waves were selected due to a more preferable higher base-to-peak amplitude of the N0 and N1. However these tendencies were ignored since the refractory differences were within 10μs and the difference of amplitude was 1μV or less. However, the tests showed that if a stimulogram bulges into the ECAP wave it produces a greater base-to-peak amplitude affecting the outcome of t-NRT.

The N wave is easily stimulated by a strong electrical stimulus. The eI wave of EABR is essentially the same wave form as the N wave, although the title is different. If the patient is affected by independent static or another stimulus, stimulation of head and neck muscles affects the amplitude of the eI wave by dramatically increasing it. Most of the time the eI wave is recorded in the same direction as the stimulus (ipsilateral recording), which is mixed with the eII wave creating a shoulder on the eI wave, thus creating a trough between the eI wave and the eII wave. The P wave of ECAP should be concluded to the same point. In the study, waveforms that were created by strong stimuli in the eII wave trough were selected instead of the eI wave trough, as occured in the selection of P waves. The highest vertex was selected by the auto-NRT instead of the trough next to the shoulder of the N wave. In these cases, the strong stimulation range of the auto-NRT showed an abnormally high N-P amplitude. An abnormally high N-P amplitude will give rise to a change in the amplitude of the input-output function (amp-I/O) gradient, which gives a different NRT threshold as well as giving an unpredictable viability factor in the spiral nerve.

In the electrically stimulated dynamic range (eDR), the change of intensity in the electric stimulation based on loudness perception might not be sensed although pulse width was increased from 8 to 58 μs and when the IPG was narrowed from 100 μs to a maximum of

8.4 μs, the difference in the sound was only 1 dB or slightly more for the implant recipient. The sound difference in the recipients is affected by the electric intensity, which is an exponential relationship, and the development of the neurologic fiber is effected by the electric intensity, also having an exponential relationship[8]. As stimulation in eDR gets close to the saturated MAL, the sound sensation becomes saturated.

Because of this, the electrically loudness growth function (eLGF) according to the electric current intensity becomes a 'ʃ' shape. The slope of the eLGF is affected by the development of the spiral nerve fiber when there is no interference of stimulograms or myogenic potentials. When the development of the spiral nerve fiber gets low, the amp-I/O becomes gentle[9]. But when stimulograms or muscular tone interferes, the slope might become shallow, and visual examination of the waveform by an expert is very important in this case.

There was one electrode (subject 2-E9) which was not determined at the threshold of the auto-NRT and manu-NRT. No error was found from the electrode, which showed 0 kΩ for resistance between electrode-tissue contact. This was observed continuously and the resistance at subject 2-E9 started to decrease 3 months after the operation and ended at below 15 kΩ after 6 months. It is thought that this electrode's resistance between electrode-tissue contact became low because of some electrical interference such as bone dust during the operation.

The unstable wavelength of the N-P wave caused by interference of stimulograms resulted in no statistical graphs for t-NRT and this led to non observation of the ECAP threshold during analysis of the automatic wave. In this case, when similar electric currents to the close electrode were active, the manu-NRT was observed by visual observation. When the wavelength of the t-NRT observed by automatic analysis was examined visually, the manu-NRT did not appear. This situation was caused by the auto-NRT's decision based on other waves generated by the low electric current, and also by stopping experiments on corresponding electrodes. Thus, when t-NRT is very low or high compared to close electrodes, the waveform should be examined visually or the electrode should be re-examined.

In this study, the determination of the manu-NRT thresholds was after on the auto-NRT. So the manu-NRT thresholds were lower than auto-NRT. But the results showed significant differences compared to those of the auto-NRT. The dynamic range is determined between the threshold and comfortable levels. If the manu-NRT thresholds are applied to the threshold level, the dynamic range changes, so the speech perception gets better than the auto-NRT thresholds.

The EABR and ECAP recorded after cochlear implantation at all ages showed electric potential with a larger amplitude and a shorter latent period when stimulated by an electrode at the apical turn than when stimulated by electrodes at the basal turn[10-14]. In this study, the thresholds were higher in the basal turn than the apical turn. Because worsening thresholds in the apical to basal direction could also be the result of greater degeneration of spiral ganglion cells at the base of the cochlear as compared with the apex[15]. The electrode is closer to the modiolus of the apical turn than the middle turn[15]. The results of larger differences between the thresholds at the middle turn than the apical turn seems to be caused by this reason.

In this study, the patients using contour-type electrodes only were subjects, so there was a limit to mapping considerable differences between the thresholds of auto-NRT and manu-NRT for all patients. Further studies should be conducted by having patients with the straight type electrodes as subjects to see if there is a difference between the thresholds of the auto-NRT and manu-NRT, if there is a difference in the deaf duration or previous rehabilitation period, and whether there is a difference between pre and post-lingual patients.

Conclusion

The NRT threshold is dependent on a mechanical value, and when there is interference such as noise, the threshold is determined more inaccurately or it is higher or lower compared to the thresholds of nearby electrodes. Although the auto-NRT is an easy and time-saving method, the waveforms should be analyzed visually in this case. In this study, the thresholds analyzed with visual examination had some difference from thresholds analyzed by the auto-NRT. These differences were significant. The amplitude input-output function of the cochlear is affected by the thresholds level. At the early mapping, we determined 4 CL in the apical turn, 8 CL in the middle turn and 6 CL in the basal turn electrodes lower than the threshold of the auto-NRT. Together, these findings might lead to better speech perception and rehabilitation for patients.

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