A Doctor of Philosophy Dissertation

상세 청각 특성을 평가하기 위한 ACC 반응을 이용한 객관적인 방법 연구

The electrophysiological approach to assess specific auditory property using the acoustic change complex response

The Graduate School
of the University of Ulsan

Department of
Biomedical Engineering

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The electrophysiological approach to assess specific auditory property using the acoustic change complex response

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[Abstract]

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The goal of this study was to evaluate the electrophysiological approach to assess specific auditory property using acoustic change complex response. The specific auditory properties evaluated in this study were the presence of cochlear dead region (CDR) and the spectral resolution. The acoustic change complex (ACC) as a type of auditory evoked potential is elicited by a change in an ongoing sound. Modified TEN stimuli and spectral ripple stimuli were used in the electrophysiological test for identifying CDR and assessing spectral resolution, respectively. In section 1, behavioral TEN test and electrophysiological TEN-ACC test were conducted to identify the presence of CDR. In section 2, behavioral spectral ripple discrimination (SRD) test and electrophysiological SR-ACC test were implemented to assess spectral resolution. The statistical analysis was conducted to confirm the effectiveness of the electrophysiological approach. In section 1, TEN-ACC thresholds in the CDR group were significantly higher (≥12 dB SNR) than those in the non-CDR group (NH and HI groups). There was a statistically significant correlation between TEN and TEN-ACC test. In section 2, HI group has the statistically lower threshold for the SR-ACC test than NH group. The correlation between SRD and SR-ACC test was statistically significant. These results suggest that the electrophysiological tests have a possibility to evaluate the auditory property objectively. Further studies are necessary to confirm the feasibility of this approach in clinical practice.

[Key Words] Auditory evoked potential, Acoustic change complex, cochlear dead region, spectral resolution, hearing loss

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1. Introduction

1.1. Background

Hearing is one of the traditional five human senses. Hearing is used to distinguish sound in our everyday life, communicate with each other, enjoy music and nature, share feelings of our valuable people, and so on.

The ear is the organ that is responsible for the hearing in our body. The ear converts the sound which is the change of air pressure to electrical signal and transmits to brain to enable that we could percept sound. Three main components of the ear are the outer ear, the middle ear, and the inner ear. Figure 1 shows the structure of the ear (adapted from [https://qph.ec.quoracdn.net/main-qimg-3b1864e435830af8ae88a6a4cebd1b8.webp]).

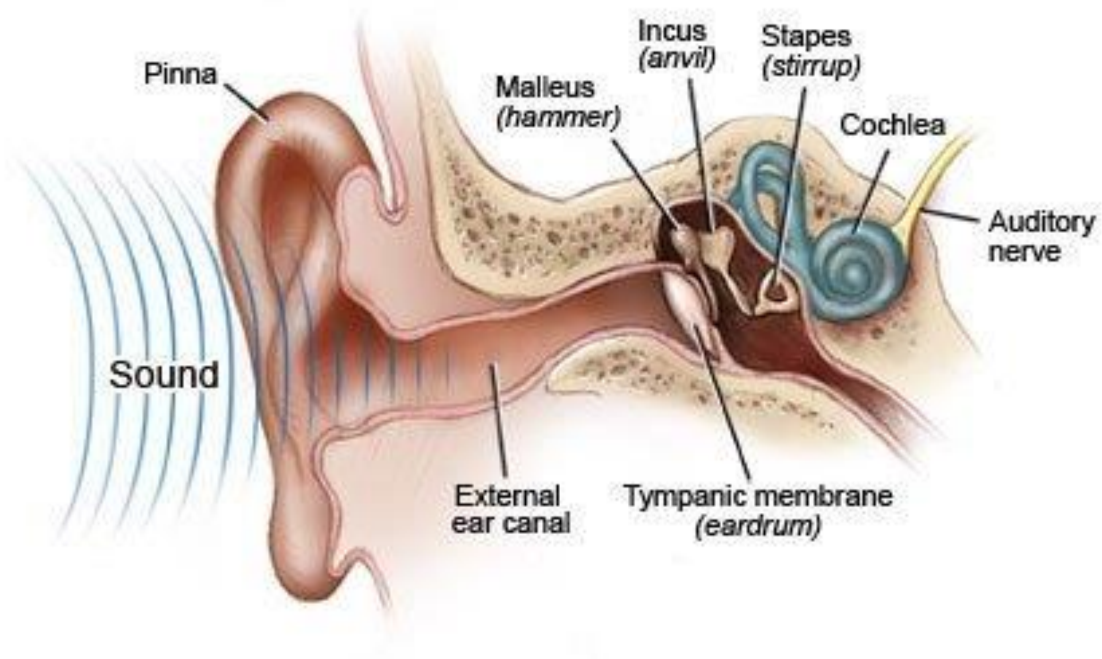

Figure 1. The structure of the human ear

The outer ear consists of pinna and ear canal. The middle ear includes eardrum also called tympanic membrane and ossicle which is composed of the malleus, incus and stapes. The inner ear consists of the cochlea. The sound waves is amplified in the outer ear and middle ear and transmitted to oval window of cochlea in inner ear. If a sound comes into the ear, it is amplified through the outer ear and middle ear. The amplified sound enters into the inner ear through the oval window. These sound waves stimulate hair cell on the basilar membrane in an organ of Corti by vibrating perilymph fluid in scala vestibuli. The activated hair cell convey the signal to the auditory cortex in the brain by transforming stimulus to the electrical signal. Finally, the brain recognizes the sound.

The basilar membrane in the organ of Corti has wider and more flexible characteristics as it reaches the end of the apex and narrower and stiffer characteristics as it reaches the end of the base [1]. The basilar membrane has frequency tonotopicity due to this physical characteristics. Each different part of the basilar membrane is in charge of each other frequency. Figure 2 shows the tonotopicity along the basilar membrane. The hair cells near the basal part of the basilar membrane are activated by sound with relatively high frequency, and the hair cells near the apical part of the basilar membrane are stimulated by sound with relatively low frequency. In other words, different frequencies of complex sound excite different places along the basilar membrane, which is called place theory [2]. Listeners could distinguish the speech and appreciated the music by discriminating information of frequencies included in sound. Hence, the ability to discriminate frequency information could affect performance for identifying the sound.

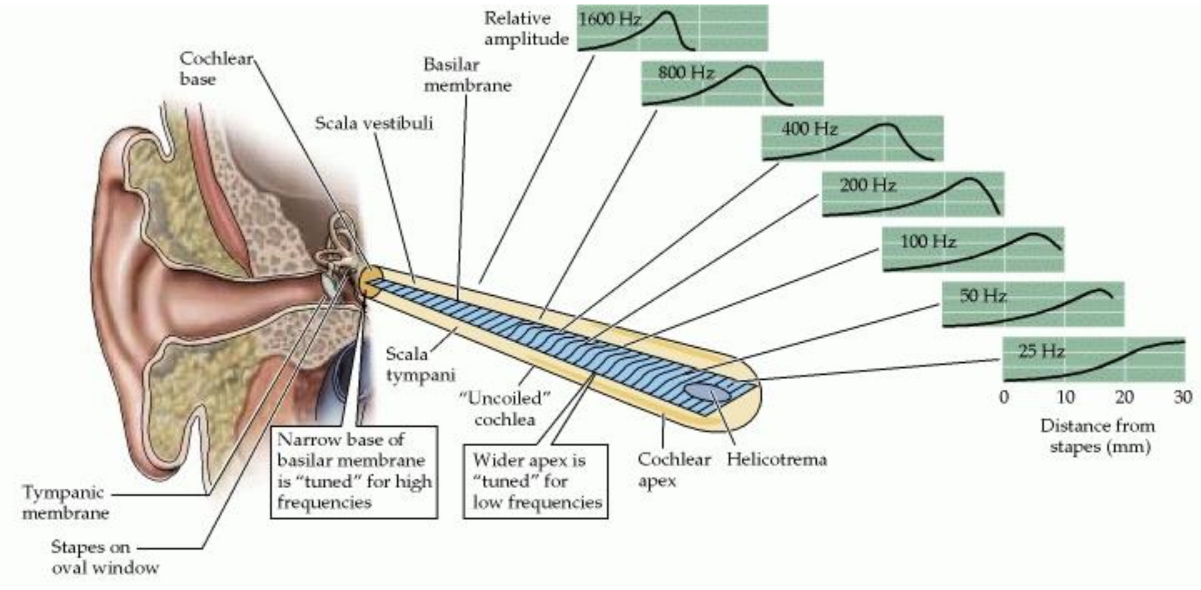

Figure 2. Frequency tonotopicity along the basilar membrane

It is known that if a listener has hearing loss, the aggravation of hearing function is generated. The damage to the cochlear hair cells has often resulted in the sensorineural hearing loss (SNHL). Depending on the degree of hearing loss, hearing aids or cochlear implants are recommended to compensate for the hearing loss. Finding the optimal fitting and mapping formula for the best improvement of speech performance is essential for listeners with hearing loss.

If hearing loss is relatively mild, only the outer hair cells may be damaged. If the hearing loss exceeds approximately 55 dB HL, both outer and inner hair cells will lose their function. The regions of inner hair cell loss or dysfunction on the basilar membrane are referred as "cochlear dead regions" (CDR) in the previous literature [3-5]. The vibration of the basilar membrane in the CDR is not transmitted to the auditory nerve. Therefore, the information in the sound related vibration could not be carried to the auditory cortex, or little information is transmitted. Individuals with CDR(s) often undergo difficulty understanding speech because of less sound information for frequencies of the CDR(s) and have limited effects of hearing aids benefit [6-11]. The information of CDR(s) is an important role in fitting. However, the presence of CDR(s) cannot be determined using standard audiometric testing. The presence of CDR(s) could be referred as specific auditory property related to speech performance which could not determine using pure tone audiometry.

The gold standard test to determine CDR(s) is psychophysical tuning curves (PTCs) [4, 12, 13]. A psychophysical tuning curve is drawn by measuring of masking thresholds that affect the ability of the listener to perceive a target signal. The tip of the PTC is defined as the frequency where the level of the masker signal that could mask the target signal tone is lowest. For subjects without CDR(s), the tip of the PTC (i.e., the frequency at which the level of masking threshold is lowest) falls near to the target signal frequency. For subjects with CDR(s), the tip is shifted away from the target signal frequency.

PTCs are time-consuming to obtain and are rarely conducted in clinical settings, although they are considered the gold standard for identifying CDR(s). The threshold-equalizing noise (TEN) test was introduced as a quick method of identifying CDR by Moore (2000) [3, 5, 14]. TEN is noise which is spectrally shaped so that, for subjects with normal hearing, the masked threshold of a pure tone is the same for all frequencies over the range 250 to 10,000 Hz. If listeners have a CDR, the masked threshold will be elevated because the TEN interferes off-frequency listening when a tone of frequency of a CDR is presented. That means inner hair cells and neurons with characteristic frequencies different from that of the signal frequency are used for decision of masked threshold. Thus, CDR(s) are identified when the masked threshold is much higher (e.g.,> 10dB higher) than both the absolute threshold for the tone and the normal masked threshold from an individual without a CDR(s) [4].

The other of specific auditory property is spectral resolution. The sound has information for the time and frequency. Thus, the capability for the temporal discrimination and spectral discrimination is needed to recognize and understand sounds like speech and music. For the hearing impaired listeners with hearing loss in the moderate to profound range, not only audibility but also ability to perceive the spectral shapes of speech sounds may effect on accurate speech recognition [15, 16]. The method that is based on the ripple phase reversal test [17] was developed by Henry and Turner (2003) to directly evaluate the ability to spectral resolution [18]. The other study [15] showed results of spectral peak resolution obtained from individuals with various hearing like normal hearing listeners, hearing-impaired listeners, cochlear implant users. A significant relationship was reported between spectral peak resolution and speech performance in quiet across the three listener groups. These results suggest that efforts to improve spectral resolution via improved hearing aids, electrode arrays and speech processing strategies may lead to improved speech recognition. Other studies [19, 20] compared the relationship between spectral resolution and speech performance in CI user and hearing impaired listeners. Results showed that the spectral ripple discrimination test that assesses spectral resolution would be a useful tool to evaluate CI performance with different signal processing strategies and a promising clinical tool for diagnostic evaluations and for predicting amplification outcomes.

1.2. The necessity

The procedure of TEN test is similar to that of the pure tone audiometry. The difference is that the TEN test present threshold equalizing noise as background noise. Therefore, the TEN test is relatively straightforward and fast test to administer and an effective method to determine the cochlear dead regions in hearing-impaired listeners [3, 5, 14].

The spectral resolution test uses non-linguistic stimuli that go beyond the language in order to evaluate spectral resolution. Thus, this test could be administered to subject around the world. This test has good test-retest reliability and also has no learning effect [19]. The results of the test have good correlation with the amplified performance of hearing aids and cochlear implant performance [19, 20]. Thus, the test could be promising clinical tool for predicting outcomes of auditory devices, not only evaluate spectral resolution. These aspects of the spectral resolution test could overcome limitations of traditional speech audiometry. The limitations are as follows. Speech audiometry should conduct for subjects with the particular language, and because of limited materials for the test, it often has learning effect may lead to less reliable results. Therefore, the spectral resolution test is also effective method to evaluate the ability to spectral discrimination [15, 19, 20].

However, these two tests were inappropriate for infants, young children, individuals who are not inclined to cooperate or individuals with developmental delays or other cognitive challenges because the test requires the feedback from individuals. Because the noise-like sounds used in task could be a little boring, it could be difficult to young children who have the relatively short concentration that to conduct task which is required pressing button or identifying another sound among three individual sounds. In case of less concentration or understanding to the task, it is also difficult to lead the reliable results. Thus, the behavioral test could often lead unreliable results because depending on the feedback of subjects. It is known that sound exposure and appropriate hearing rehabilitation are important for listeners with hearing loss, particularly infants and young children. For this population, it could be difficult to obtain reliable information to help with their hearing compensation using behavioral test. Although it is not uncommon, the behavioral response test is performed by feedback from the subjects, so if the subjects conduct the test with impure intention, it could be difficult to obtain accurate results.

Therefore, an objective approach is needed to evaluate specific auditory property like cochlear dead region and spectral resolution. In this study, we propose a non-behavioral electrophysiological approach for identification of CDR and evaluation of ability to spectral discrimination. The electrophysiological method, which could overcome the disadvantages that difficult to conduct to a particular population and could bring out the merits by utilizing the same stimuli of the behavioral test, will be suggested in order to evaluate specific auditory property using electroencephalogram (EEG).

1.3. The index for objective method

An event-related potential is an electrophysiological response to a stimulus of specific sensory, cognitive, or motor event. The evoked potential is a subclass of event-related potential and is provoked by the presentation of a stimulus, as distinct from spontaneous potentials. In particular, auditory evoked potential is elicited by the signal generated by a sound [21]. When the sound enters the cochlea, an evoked action potential is generated and carried next phase at each delivery phase of the auditory pathway, and the signal is finally transmitted to the brain. Figure 3 (adapted from [http://www.cochlea.eu/en/audiometry/objective-methods/voies-et-centres]) shows the auditory pathway. Auditory evoked potential could be recorded from the electrodes placed on the scalp.

The auditory evoked potential could be divided as latency duration: short-latency response (~10ms), middle-latency response (15~70ms) long-latency response (90ms~). Figure 4 represents the diagram of auditory evoked potential components (adapted from [22]). The short-latency response includes electrocochleography (ECoG) and auditory brainstem response (ABR). ECoG is a technique for measuring electrical potentials occurring in the inner ear and auditory nerve using an electrode placed on a tympanic membrane or ear canal. The ABR is the response measured from the brainstem, and the origin of each peak of the waveform is shown in Table I below[23, 24]. ABR is currently being used as a primary tool in early childhood hearing screening in clinical settings. The auditory steady-state response (ASSR) is a kind of the middle-latency response. ASSR is measured using modulated pure tone, and the neural generator is dependent on the modulation frequency of the stimulus. It reflects the subcortical activation from the primary auditory cortex to the brainstem according to the frequency of stimuli [25]. ABR and ASSR is the effective method for estimating hearing threshold objectively.

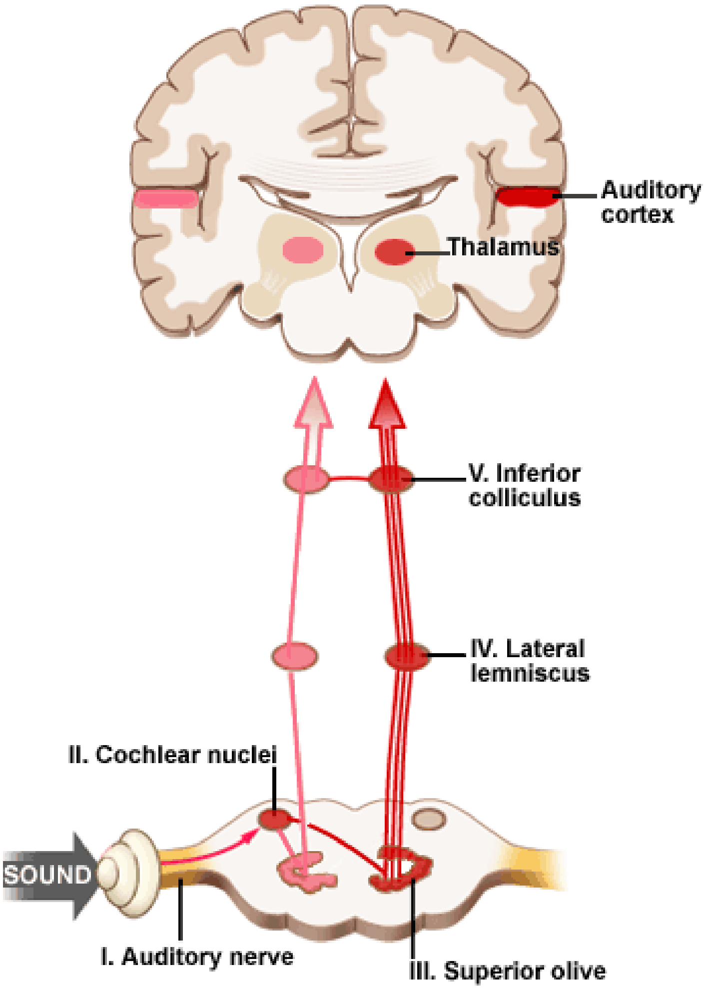

Figure 3. Auditory pathway

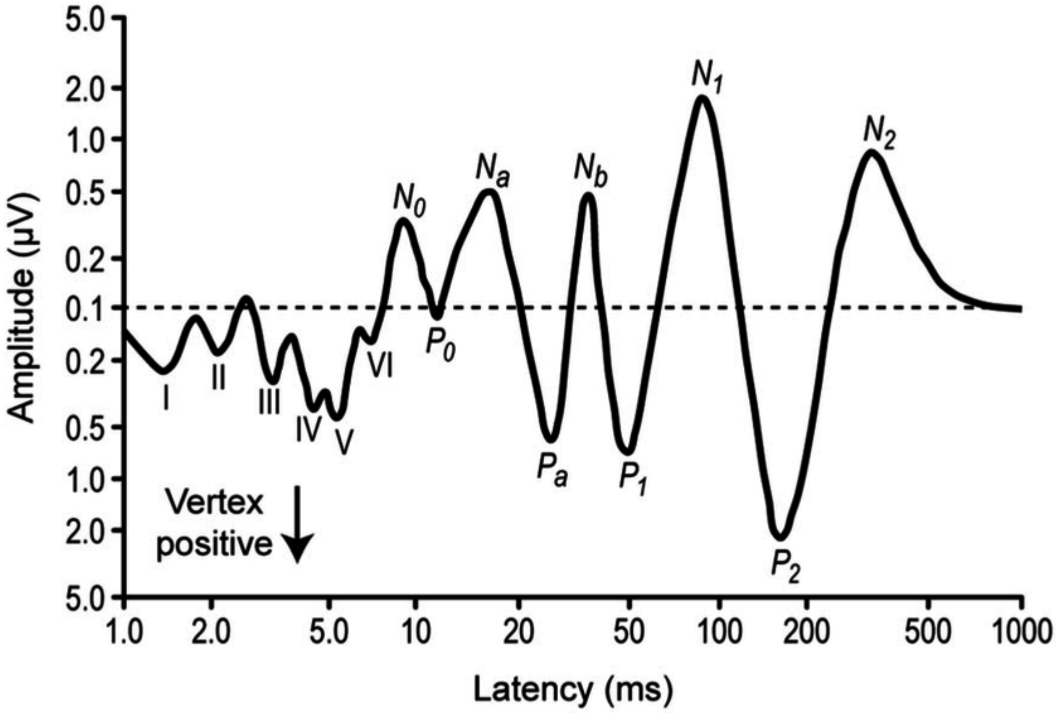

Figure 4. Auditory evoked potentials

	Jewett 1971	Moller
Wave I	Cochlear nerve	Distal cochlear nerve
Wave II	Cochlear nucleus	Proximal cochlear nerve
Wave III	Superior olivary complex	Cochlear nucleus
Wave IV	Lateral lemniscus	Superior olivary complex
Wave V	Inferior colliculus	Lateral lemniscus
Wave VI	Medial geniculate body	Inferior colliculus

Table I. Origins of auditory brainstem response

The late-latency response includes P1-N1-P2 complex, mismatch negativity (MMN), acoustic change complex (ACC), and P3 (P300). These EEG responses are measured at the cognitive level and originate from the brain cortex. MMN that was first reported by Naatanen et al. [26] in 1978 is elicited by an oddball paradigm in which occasional deviant stimuli embedded in a series of frequent standard stimuli. The auditory MMN is a negative potential with sources in primary and secondary auditory cortices [27]. MMN has a small amplitude waveform thus result in a poorer signal to noise ratio and relatively poor reliability [27, 28]. P3 also known as P300 was first reported by Sutton et al. (1965) [29]. P3 has positive potential at about 300 ms evoked by using oddball paradigm. The sources of auditory P3 are included auditory cortex, centroparietal cortex, hippocampus, and frontal cortex [27]. It is not suitable for uncooperative individuals, because it requires a behavioral response. Because of the limitation of MMN and P3, the ACC was taken into account as an index of recognition of a change in ongoing sound in this study.

P1-N1-P2 complex suggested as an index of acoustic signal as like onset or offset for sound [27, 30]. Similar to P1-N1-P2 complex, an auditory evoked potential that elicited by changes within an ongoing acoustic stimulus as spectral, temporal or loudness changes is the ACC [31-33]. It is a variant of the classic P1-N1-P2 complex and it is evoked when the listener is able to detect a change in some aspect of an ongoing sound. The ACC can also be evoked using speech stimuli [34]. Figure 5 shows the example of evoked ACC response after the sound changes from the /u/ to the /i/ [27].

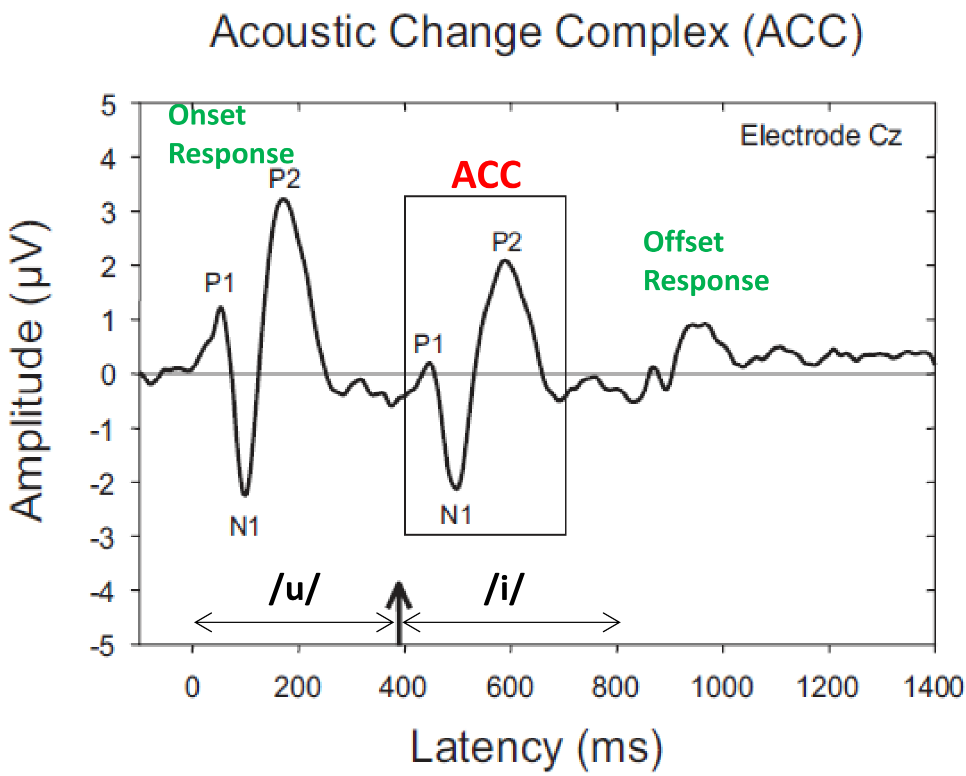

Figure 5. Example of evoked acoustic change response

The TEN test is a test to evaluate the ability to recognize pure tones presented when background noise is present. It could be said that there is a 'change' of sound as the pure tone presents at some point in the ongoing stimulation. The SRD test is a test to evaluate the ability to distinguish between standard ripple and inverted ripple. It could be said that the stimulus has 'change' from standard ripple to inverted ripple. To utilize this stimulation, the ACC response would be used as an index of the objective method to measure the recognition of 'change' in this study. The acoustic change complex (ACC) was utilized to use as an index of the objective approach in this thesis. The ACC can be measured from various clinical populations like adults or children in a passive listening paradigm [31, 35-38]. ACC responses have been recorded successfully from normal-hearing listeners[31, 39, 40], hearing-impaired listeners[27], cochlear implant users [41, 42], and patients with auditory neuropathy spectrum disorder [43, 44]. ACC responses have good test-retest reliability [45].

The ACC response is not only triggered when a change in ongoing sound is perceived but also depends on the magnitude of the change. He et al. (2012) showed that the magnitude of the change of stimulus that used stimulus shown in Figure 6. affects the ACC response [39]. The stimulus for temporal gap condition has a gap with durations of 5, 8, 10, 20, 50, and 100 ms between two broadband Gaussian noises. The stimuli for frequency change were made with the frequency increments of 5, 8, 10, 20, 50, and 100 Hz. For intensity changes stimuli, intensity increments were 2, 3, 4, 6, and 8dB. Figure 7 shows that the ACC amplitude decreases as the gap duration of the stimulus with the temporal gap decreases. Figures 8 and 9 also show that as the magnitude of the frequency increment and intensity increment decreases, the ACC amplitude also decreases. The figures were adapted from He et al (2012) [39]. Other studies that measured ACC response using Vowel showed that the magnitude of 'change' affects the ACC amplitude, and the ACC response was not observed in the absence of 'change' of stimulus [31]. Thus, the results of the studies show that the threshold of the ACC response could be determined by adjusting the magnitude of the change in stimulus. It is expected to be able to evaluate the threshold value through the magnitude adjustment of the change using the stimulus sound used in this study.

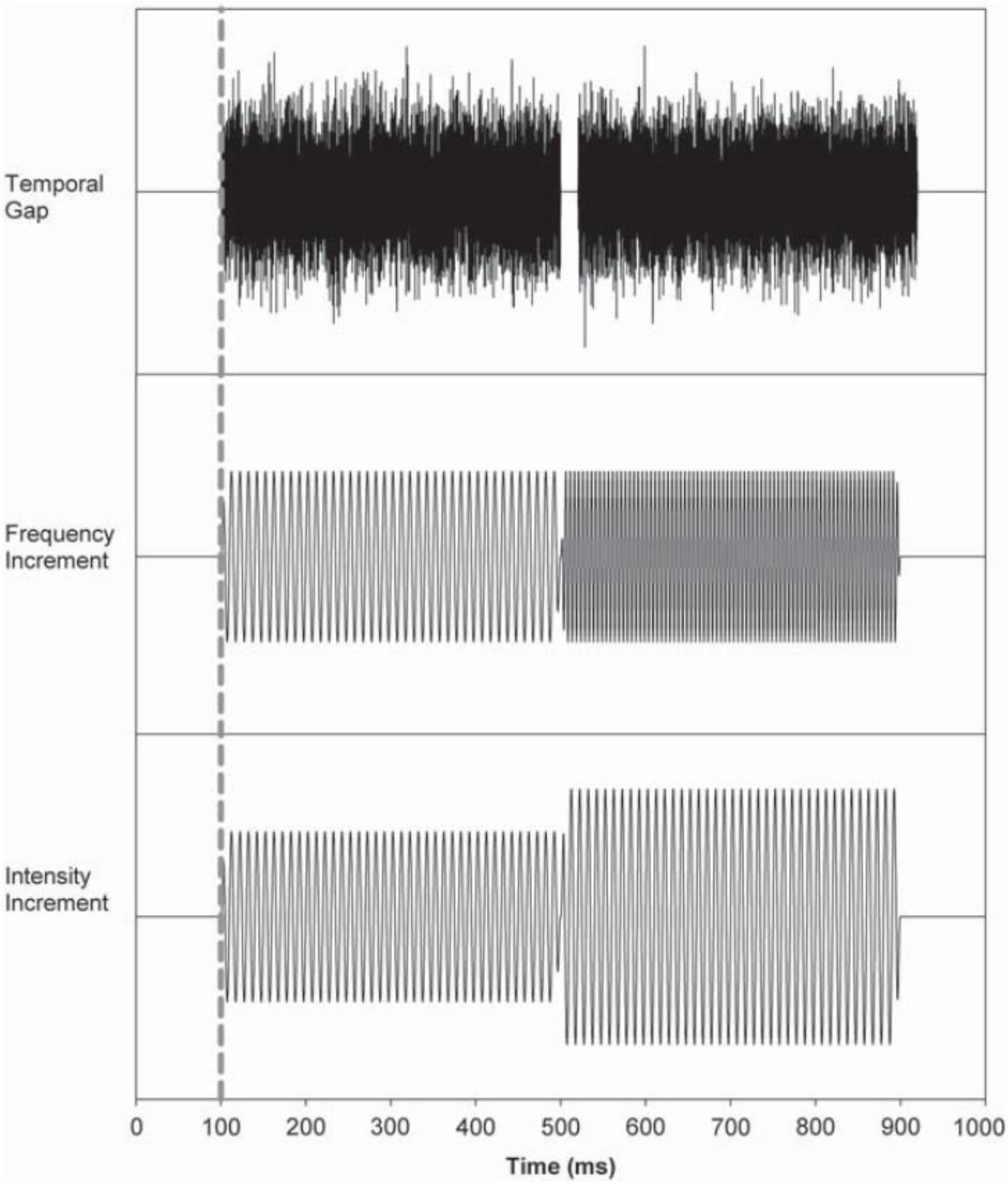

Figure 6. Stimulus schematic for temporal, frequency, and intensity changes

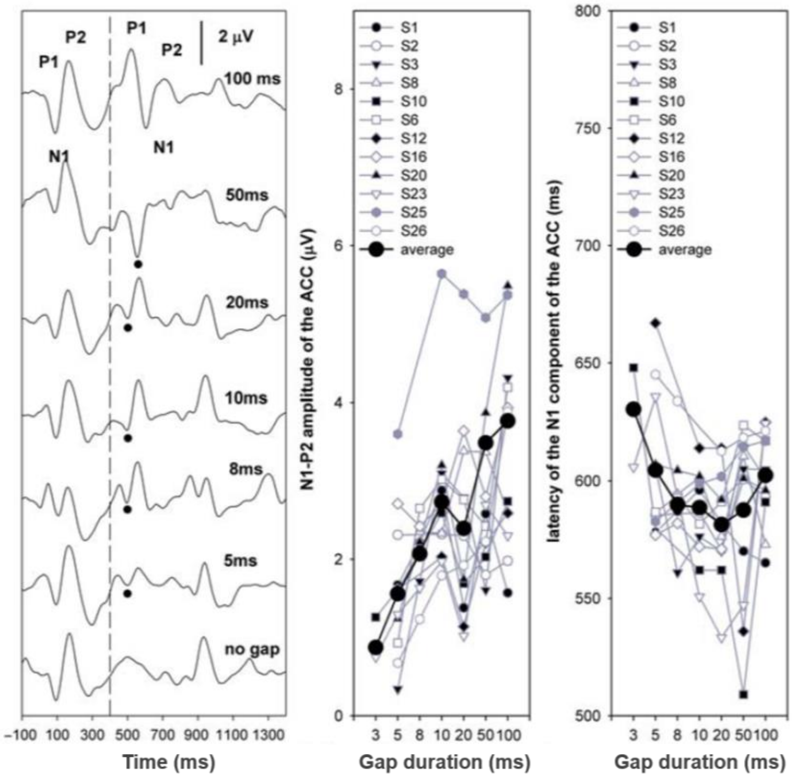

Figure 7. ACC responses evoked in response to temporal gap changes

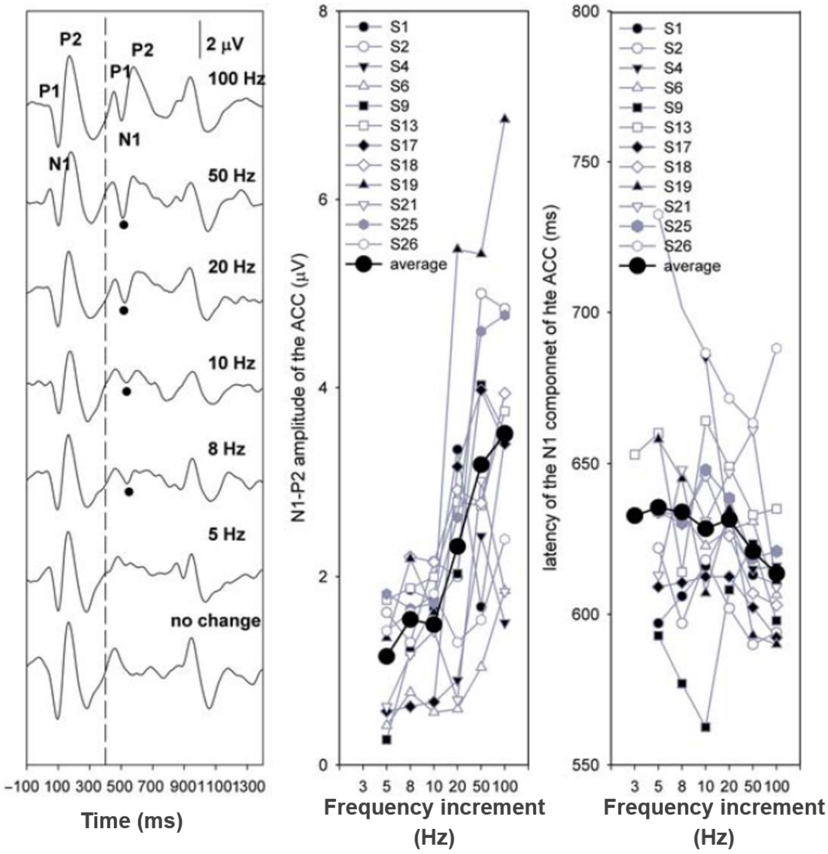

Figure 8. ACC responses evoked in response to frequency increment changes

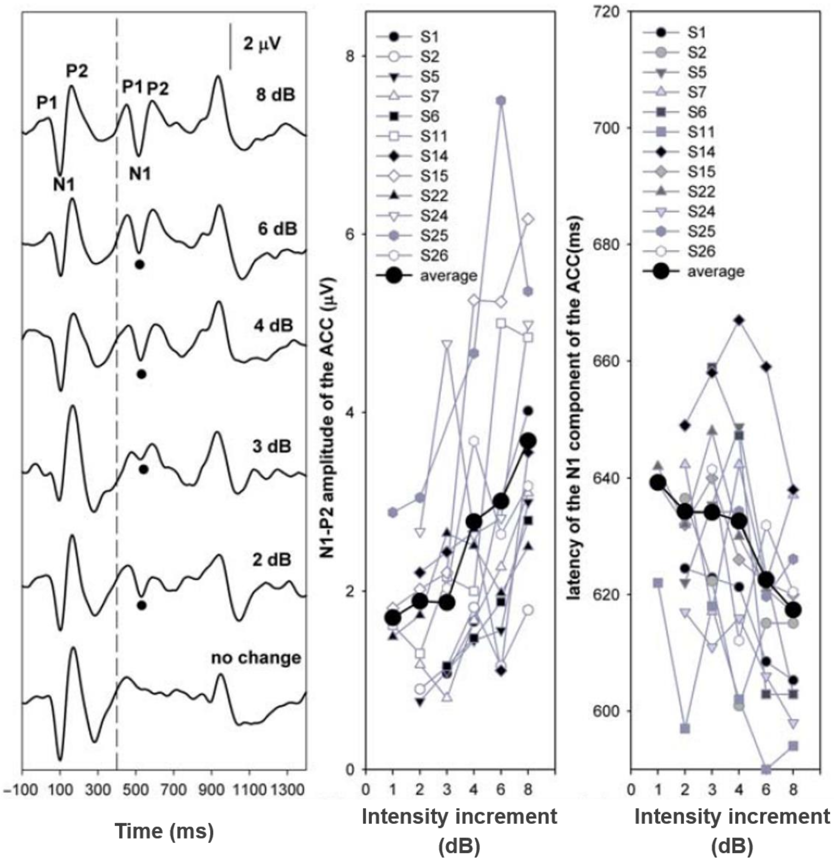

Figure 9. ACC responses evoked in response to intensity increment changes

1.4. Goal

In this study we describe methods for using the ACC to assess specific auditory property. This thesis describes results from two different studies to identify cochlear dead region and to assess spectral resolution. The goal of the study in the first section is to evaluate the feasibility of the electrophysiological approach using ACC response with TEN test stimulus to determine the presence of CDR(s). The goal of the study in the second section is to investigate the potential of the electrophysiological approach using ACC response evoked with spectral ripple stimulus to assess spectral resolution objectively.

2. Section1: TEN-ACC study

2.1. Methods

The study was approved by the Samsung Medical Center-Institutional Review Board. All participants signed an informed consent before conducting the study. The subjects were participated in both behavioral TEN test and electrophysiological TEN-ACC test.

2.1.1. Subjects

Ten normal hearing listeners (NH group, mean age = 24.1 years, SD = 1.97 years), 12 hearing impaired listeners without CDR (HI group, mean age = 52.42 years, SD = 11.30 years), and 4 hearing impaired listeners with CDR (CDR group, mean age = 46.00 years, SD = 9.42 years), a total 26 NH and HI listeners participated of which 11 were male.

All participants conducted pure-tone audiometry to identify hearing threshold levels of an individual. NH group has audiometric thresholds no worse than 25 dB HL for octave frequencies from 250 to 8000 Hz. HI and CDR group have audiometric thresholds worse than 40dB HL for octave frequencies from 250 to 8000 Hz. The test ear was selected randomly in the NH and HI groups. The test ear for the CDR group was selected based on the presence of the cochlear dead region that was identified using behavioral TEN test.

2.1.2. Behavioral TEN test

The TEN test that was developed and validated by Moore identify the cochlear dead region by measuring the level required for a listener to detect a pure tone presented in TEN.

The high interaural attenuation of the earphones reduces the necessity for better ear masking when the poorer ear is being examined [46]. Insert earphones avoid problems with collapsed ear canals and could more sanitary manage of test by changing the disposable tip of earphones. Thus, insert earphones, such as the Etymotic Research ER-3A, are often used to overcome some of the limitations of the headphones in clinical settings. The stimulus in a version of the TEN test for use with ER-3A insert earphones was utilized in this study [14]. The frequencies of test pure tone were limited to the range 500 to 4000Hz.

The test was conducted in a soundproof booth using an audiometer (Orbiter 922, Madsen Electronics, Minnetonka, MN) and ER-3A insert earphones. Figure 10 shows the equipment and environment for behavioral TEN test.

Three values are necessary for CDR decision: the audiometric threshold, TEN level, and masked threshold. However, TEN level set 10 dB higher than the audiometric threshold, for the diagnosis of CDR the audiometric threshold could ignore in this study. Therefore, only two values the TEN level and masked threshold need to be considered for a decision of CDR.

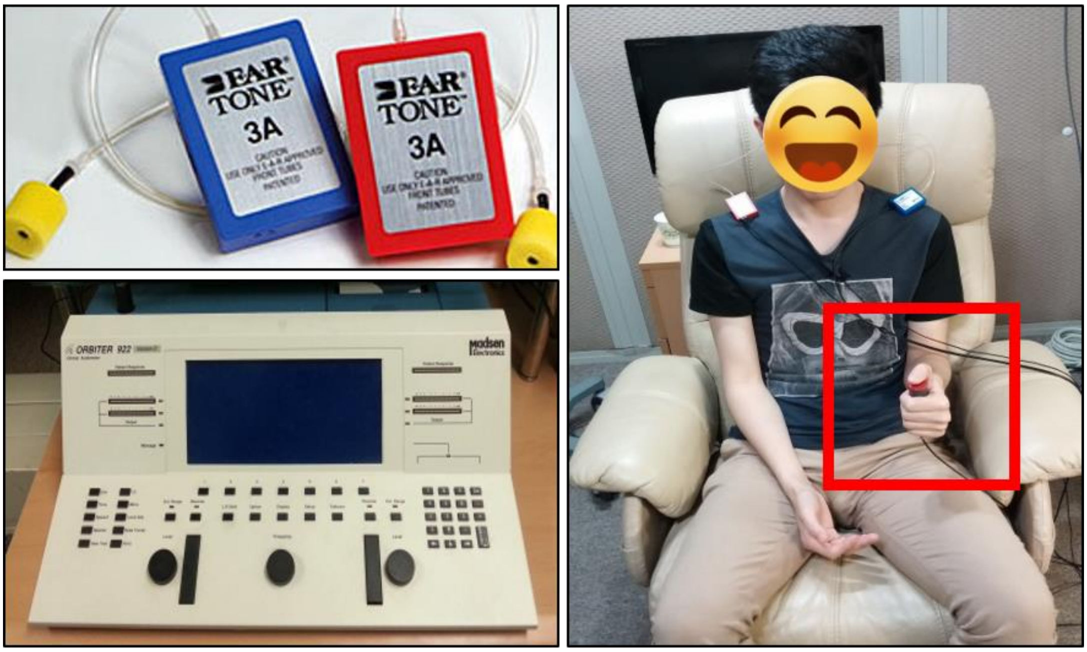

Figure 10. The equipment and environment for behavioral TEN test.

For the NH group, TEN level was fixed at 60 dB HL/ERB_N and 10 dB above the audiometric threshold of each pure tone frequency for the HI and CDR groups. Pure tone between 500 and 4000 Hz were presented in the presence of TEN. Masked pure tone threshold was decided using adaptive procedure. The level of pure tone was decreased by two steps when the listener had a correct response and increased by one step when the listener had an incorrect response. The step size was 2 dB. The masked threshold was determined as the minimum level which the listener detect the presence of pure tone in TEN. If the masked threshold was 10 dB higher than presented TEN level, that frequency region was determined as cochlear dead region.

2.1.3. Electrophysiological TEN-ACC test: Stimuli

The stimulation used in the electrophysiological TEN-ACC test was designed to suit the electrophysiological method using stimulation from the TEN test. The stimuli were presented using Neuroscan STIM2 system and ER-3A insert earphone. Figure 11 indicates example of stimulus for TEN-ACC test and evoked onset, ACC, and offset responses. The stimulus parameters are summarized in Table Ⅱ. The total duration of the stimulus is 1.5s. The stimulus consist of TEN part of 1s and pure tone embedded in TEN part of 0.5s. A rise and fall times of 5ms applied to the stimulus to avoid abrupt onset/offset artifacts. The inter-onset interval of stimulus was 3s. The TEN level was fixed at 60 dB HL in NH group. In the HI and CDR groups, the TEN level was presented at a level that was 10 dB higher than the audiometric threshold value. The stimulus level for pure tones level ranged from 0 to 21 dB signal to noise ratio (SNR). In one case for the CDR group, the pure tone level of 24 dB SNR was additionally recorded. The averaging waveform of each SNR condition was obtained from 120 presentations.

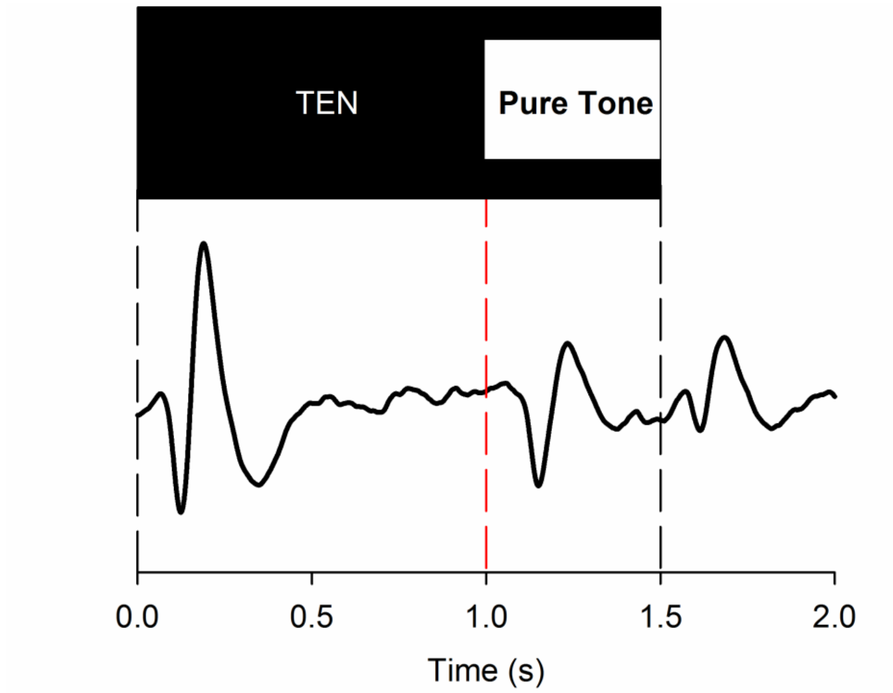

Figure 11. An examples of the stimulus used in TEN-ACC test

Group	NH	HI	CDR
TEN level	60 dB HL	Audiometric θ + 10 dB	
Pure tone level (1 and 4 kHz): 3 dB step	0 ~ 15 dB SNR	0 ~ 18 dB SNR	6 ~ 21 dB SNR
Total stimulus time		1.5 s	
Time for pure-tone stimulus		0.5 s	
Inter-stimulus interval		1.5 s	
Number of Sweeps		120	
Rise/fall time		5 ms	

Table II. The stimulation parameters used in TEN-ACC test

2.1.4. Electrophysiological TEN-ACC test: Recording

The electroencephalogram (EEG) was recorded using surface electrodes with Neuroscan Scan 4.5 and SynAmps2 system. The active electrode was placed at Cz, in accordance with the international 10-20 system. The reference electrode was placed at contralateral mastoid. The ground electrode was attached to the forehead. In the previous literature, this electrode site (Cz) had largest ACC amplitude recordings [31]. Thus, EEG response was measured only by one electrode at a site of Cz in order to reduce the setup time for the recording session. The artifacts from eye movements were also monitored using recording electrodes attached to above and below the ipsilateral eye and lateral both eyes. Electrode impedances and inter-electrode impedance differences were maintained below 5k and 2k ohms, respectively. EEG signal was amplified with ten times, band-pass filtered between 0.1 and 100 Hz and sampled at an analog-to-digital sampling rate of 1000 Hz.

The post process of EEG data was as follows. The ocular artifacts reduced from the EEG recordings. EEG epochs were created using the window that has 2900 ms in duration including a 100 ms pre-stimulus baseline for each stimulus condition. Sweeps including artifacts exceeding 100 μV were rejected. EEG epochs were baseline corrected (-100 to 0 ms) and band-pass filtered (1 to 30 Hz with 12dB/octave). The filtered epochs were averaged for each stimulus condition and each subject. The smoothing of the averaged waveform was conducted using a 40 ms moving average filter. Finally, the grand-mean average waveforms were created by averaging the data across subjects.

Two experienced researchers individually analyzed the waveforms and identified the presence of ACC responses and masked thresholds. The presence of ACC response was decided when two researchers had identical judgment. A root mean squared (RMS) amplitude ratio of ACC to noise floor was calculated to support the decision of the presence of ACC response. The window of the ACC response and noise floor were from 1050 to 1250 ms and from 2800 to 2900 ms after onset, respectively. If the RMS ratio was higher than at least 50%, the ACC response was determined to be present [47]. In summary, the presence of the ACC response was determined based on the visual decision of researchers and RMS ratio.

During the electrophysiological recording, subjects seated in a reclining chair in a soundproof booth. Subjects were instructed to be a comfortable posture and watch a captioned video to help them stay awake. The recording environment was observed using an infrared camera placed inside the soundproof booth.

2.2. Result

The EEG data were acquired from NH, HI and CDR groups. The time scale for plotting for waveforms extends from -100 ms to 2000 ms to display responses clearly. Figure 12A shows grand average waveforms obtained from NH and HI groups, and figure 12B indicates individual waveforms recorded from four individuals of CDR group. In the results of NH and HI group, grand average waveforms for both the 1 kHz and the 4 kHz stimuli are shown at each SNR condition. The grand average waveforms indicated that masked thresholds (TEN-ACC thresholds) for the 1 kHz and 4 kHz were 6 dB SNR and 6 dB SNR, respectively, for the NH groups and 6 dB SNR and 9 dB SNR, respectively, for the HI group. In the results of the CDR group, TEN-ACC thresholds ranged from 12 to 24 dB SNR. In case of a threshold of 24 dB SNR, there was no ACC response, but additional test for the higher SNR level didn't conduct because of the possibility of hearing damage for excessive input level. Hence, the maximum input value of 24 dB SNR was determined as the threshold. These thresholds are substantially higher than thresholds of NH and HI groups.

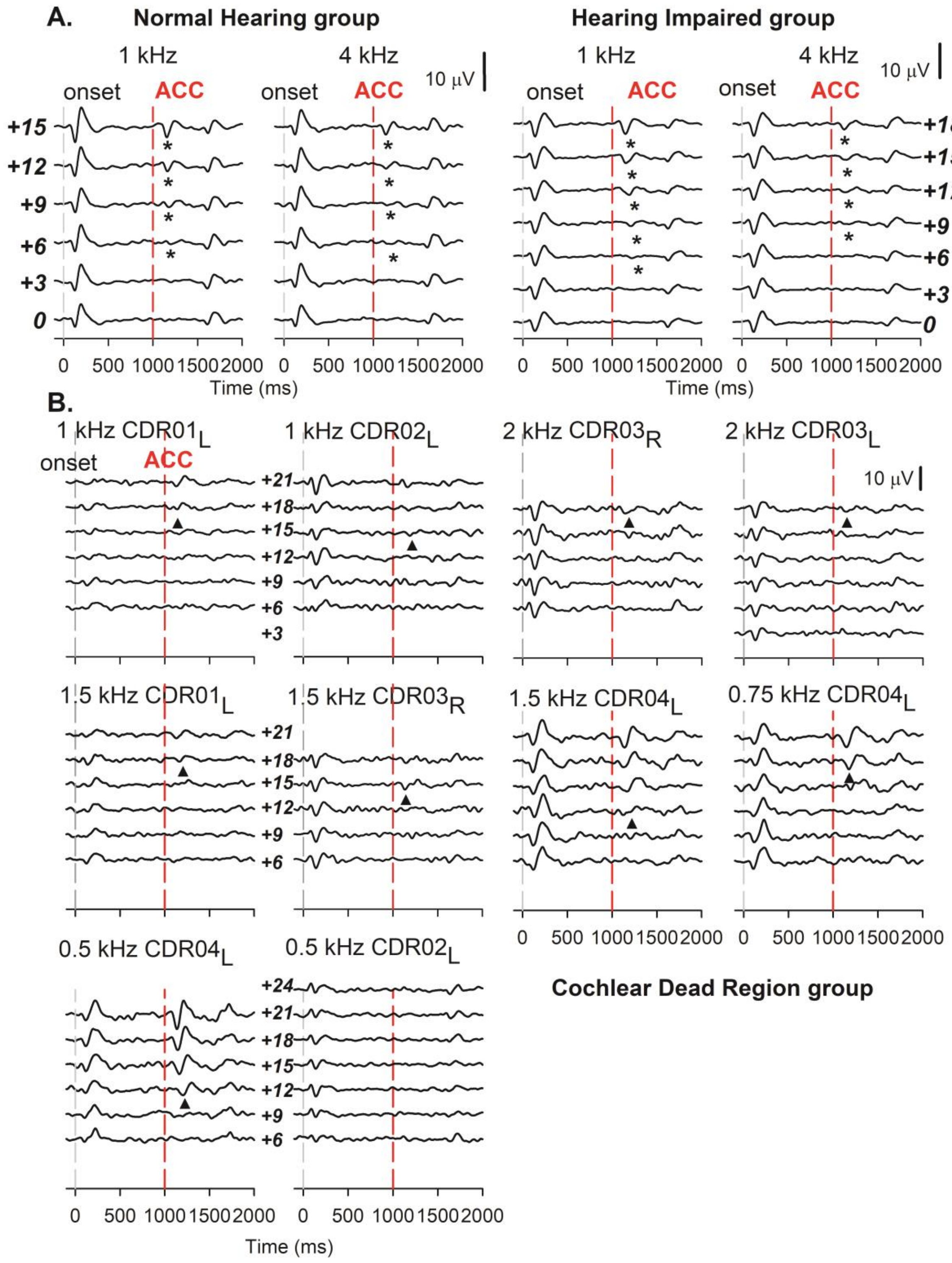

Figure 12. Grand average waveforms of NH and HI group (A) and Individual average waveforms of CDR group (B)

The comparison of behavioral (TEN) and electrophysiological (TEN-ACC) thresholds for all three groups were shown in Table Ⅲ. The 'e' represents the number of ears tested and number in parenthesis in CDR group refers to the number of subjects participated in each frequency condition of stimulus.

In the results for all groups, behavioral (TEN) thresholds are clearly lower than electrophysiological (TEN-ACC) thresholds. The TEN-ACC thresholds of NH group were 6.6 dB SNR and 8.4 dB SNR higher than TEN thresholds at 1 kHz (Wilcoxon signed rank test, $z=2.812$, $p=0.002$) and 4 kHz ($t=-7.145$, $p<0.001$), respectively. The TEN-ACC thresholds of HI group were 5.33 dB SNR and 6.08 dB SNR higher than the TEN thresholds at 1 kHz ($t=-4.959$, $p<0.001$) and 4 kHz ($t=-4.906$, $p<0.001$), respectively. These differences were statistically significant. For the CDR group, TEN-ACC thresholds were obtained using stimulation sound with frequencies in a CDR determined based on behavioral TEN test (i.e. 0.5, 0.75, 1, 1.5 and 2 kHz).

The electrophysiological thresholds for individual four participants were higher than behavioral thresholds. The mean difference between the masked thresholds across all stimulation sound measured using behavioral (TEN) and electrophysiological (TEN-ACC) tests was 5.2 dB SNR ($t=-7.839$, $p<0.001$).

Threshold (θ)		1 kHz		4 kHz	
		TEN (SNR)	TEN-ACC (SNR)	TEN (SNR)	TEN-ACC (SNR)
NH	Average	0.00	6.60	-1.80	6.60
(e =10)	SD	2.49	3.69	1.14	4.20
HI	Average	3.17	8.50	2.67	8.75
(e = 12)	SD	2.89	2.81	1.97	4.14

CDR		0.5 kHz(2)		0.75 kHz(1)		1 kHz(2)		1.5 kHz(3)		2 kHz(2)	
		TEN	TA	TEN	TA	TEN	TA	TEN	TA	TEN	TA
(e = 5)	Average	15	18	12	18	11	16.5	10	15	11	18

Table III. Comparison of the threshold of behavioral TEN test and electrophysiological TEN-ACC (TA) test for all subject groups

Figure 13 shows the scatterplot indicating the relationship between the results of the behavioral TEN test and the electrophysiological TEN-ACC test. Each symbol represents the results of each subject group: NH, HI, CDR group. The size of the symbol represents the incidence of the threshold. Linear regression analysis was used to examine the strength of the relationship between the electrophysiological and behavioral measures. The results used in this analysis were combined data of TEN test and TEN-ACC test for all three groups at all stimulus frequencies. The dashed line indicates the results of the linear regression analysis. The correlation between the two tests was found to be statistically significant (DF=53, r=0.60, p<0.0001). The two thresholds showed moderate-to-strong correlation.

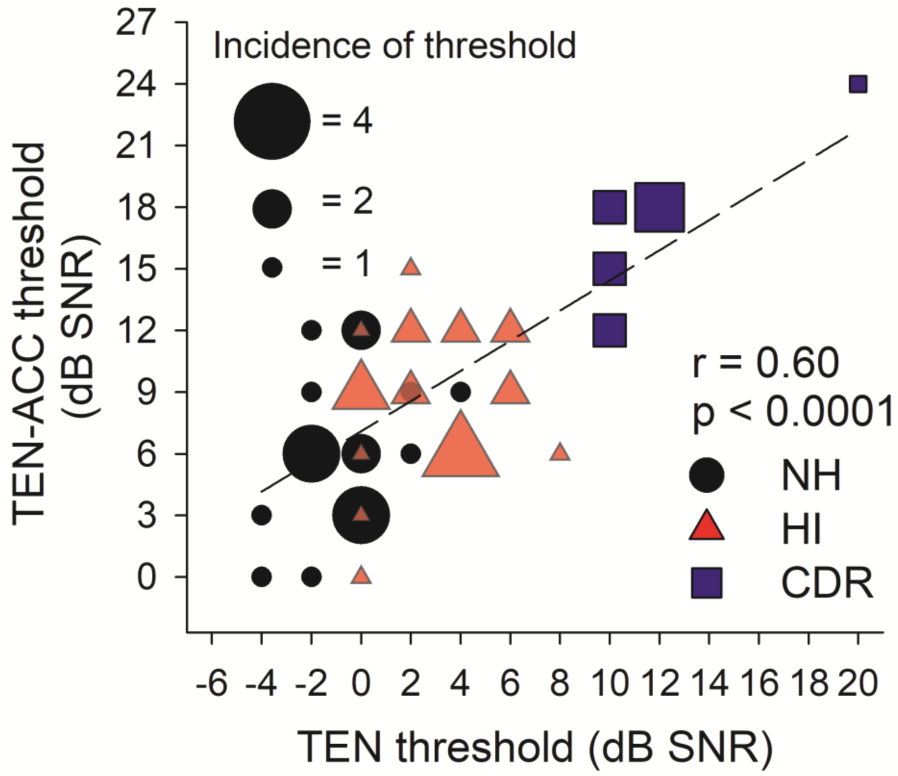

Figure 13. Correlation between behavioral TEN threshold and electrophysiological TEN-ACC threshold

The data used to plot figure 13 was rearranged in a box plot as like figure 14. The box plots show the threshold range along the different subject groups and two tests. The left and right panel indicate data obtained using TEN test and TEN-ACC test, respectively. The dashed lines on the figure indicate criterion to identify the presence of CDR in a behavioral TEN test and potential criterion to decide the presence of the CDR in an electrophysiological TEN-ACC test, respectively. The line in the box indicates median value and the black dot indicates outlier of data.

Statistical analysis using one-way analysis of variance was conducted to identify threshold difference for three groups. In behavioral TEN test (Kruskal-wallis one way ANOVA), difference of thresholds between the three groups were statistically significant ($p<0.001$). Post-hoc analysis revealed the mean TEN threshold of CDR group was larger than those of NH ($p<0.05$) and HI ($p<0.05$) groups. In addition, the mean TEN threshold of HI group was higher than that of NH group ($p<0.05$). For the TEN-ACC test, there was found to be statistically significant group effects ($p<0.001$). Post-hoc analysis indicated the mean TEN-ACC threshold of CDR group was larger than those of NH ($p<0.05$) and HI ($p<0.05$) groups. Though mean TEN-ACC threshold of HI group was greater than that of NH group, the difference was not statistically significant.

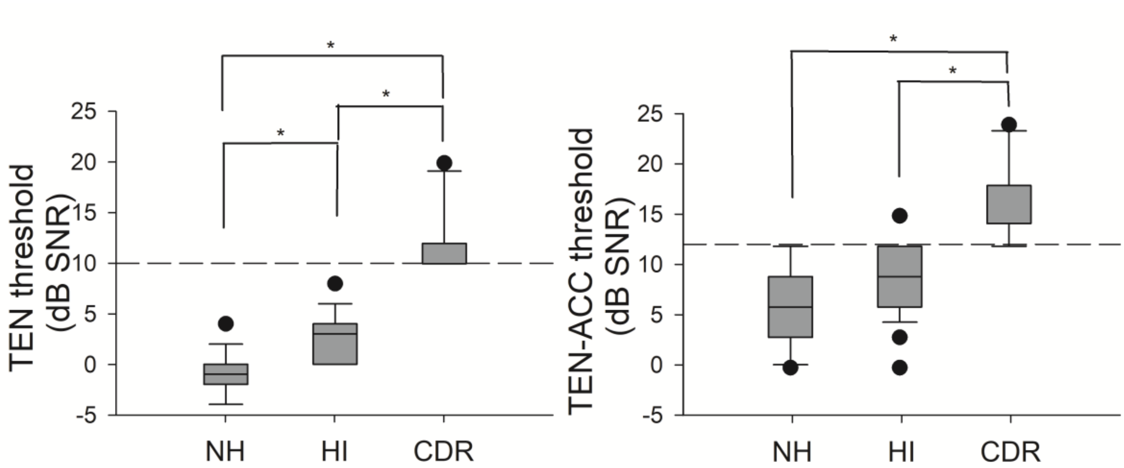

Figure 14. The box plots for the range of thresholds along the different subject groups and tests

Figure 15 shows the ROC curves of TEN test and TEN-ACC test. The ROC curve of the test signifies that performance of the diagnostic test is meaningful when curved to the left of the diagonal line represented a gray reference line. The area under the curve (AUC) has the maximum value of 1 means that the diagnostic test is perfect [48]. If AUC has 0.5, it means that the test has the chance level of performance for diagnosing. The AUC was 0.97 which was higher than the reference line, which could be a meaningful test for diagnosing CDR (95% confidence interval: 0.926-1.010, p<0.001).

Table Ⅳ shows the values calculated from the results of each stimulus condition in the TEN-ACC test: specificity, sensitivity, and the distance between (0,1) point and each condition point. The distance calculation formula is as follows:

$$\mathbf{d} = \sqrt{(\mathbf{1} - \boldsymbol{sensetivity})^{\mathbf{2}} + (\mathbf{1} - \boldsymbol{specificity})^{\mathbf{2}}}$$

The point with the minimum distance was 12 dB SNR. Thus, the optimal cutoff value for TEN-ACC test is 12 dB SNR.

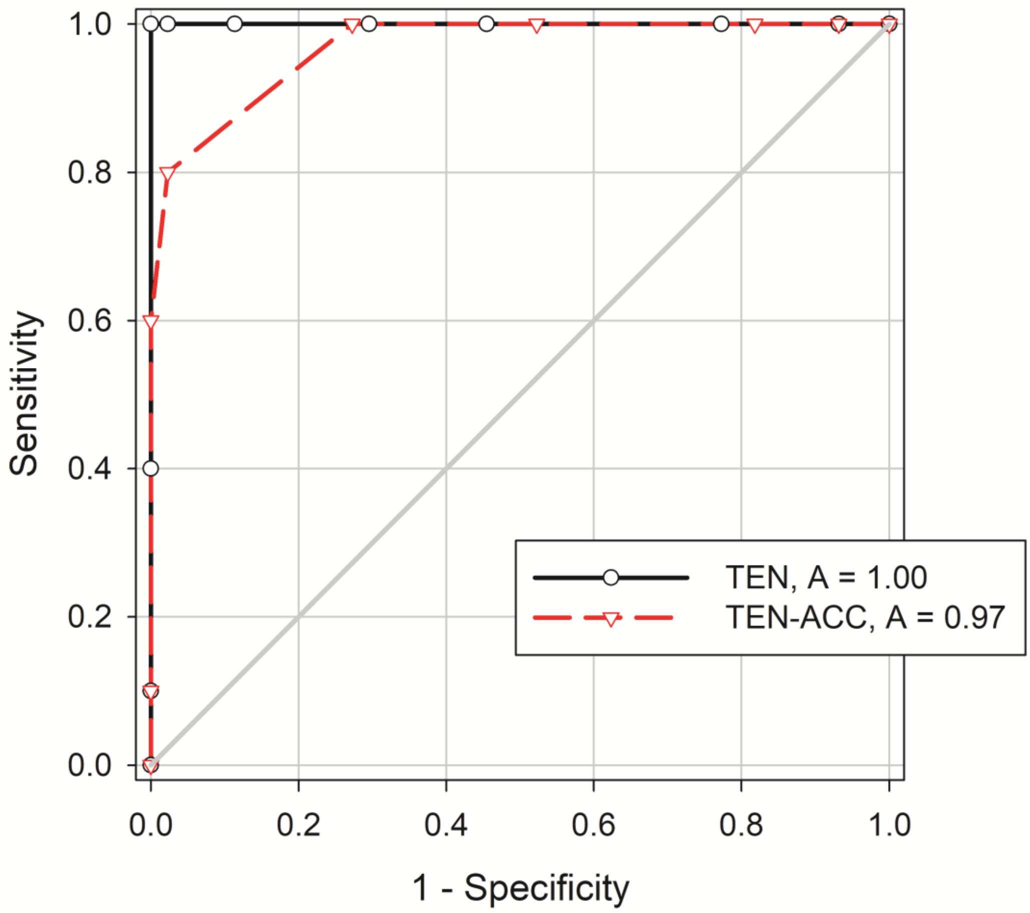

Figure 15. ROC curves of TEN test and TEN-ACC test

dB SNR	1-specificity	sensitivity	Distance between (0,1) and each point
0	0.931818	1	0.931818182
3	0.818182	1	0.818181818
6	0.522727	1	0.522727273
9	0.272727	1	0.272727273
12	0.022727	0.8	0.201287180
15	0	0.6	0.4
18	0	0.1	0.9
21	0	0.1	0.9

Table IV. Sensitivity and specificity of TEN-ACC test

Therefore, we suggest that the criterion of 12 dB for the electrophysiological TEN-ACC test to confirm the presence of the CDR. Only the thresholds of CDR group were higher than 12dB in the electrophysiological TEN-ACC test.

2.3. Discussion

Results of the study showed that ACC responses were able to measure from individuals of all three groups. The SNR level affected on the amplitude of ACC response. As the SNR level decrease, the amplitude of ACC response decrease, eventually the ACC response disappears. Therefore, we could determine the threshold.

The electrophysiological TEN-ACC threshold obtained from CDR group were significantly higher than those from other groups without CDR. The thresholds obtained from CDR group were higher than 12 dB in all subjects in CDR group. Therefore, we suggest that the 12 dB SNR of stimulus level is as the criterion for the decision of CDR in an electrophysiological TEN-ACC test. Figure 16 shows the individual and grand average waveforms for all three subject groups at 12 dB SNR stimulus level. The left panel shows the waveform of NH group, the middle panel displays the waveforms obtained from HI group, and the right panel displays the waveforms for CDR group. The thin gray lines are for the individual data, and thick black lines indicate the grand average waveforms obtained from each subject group. In the NH and HI groups without the cochlear dead region, there was ACC response in all participants except one participant at 12 dB SNR stimulus level. In the CDR group with the cochlear dead region, there was ACC response in only two out of ten participants. In other words, the electrophysiological TEN-ACC test has the specificity of 98% and the sensitivity of 80% for the decision of cochlear dead region.

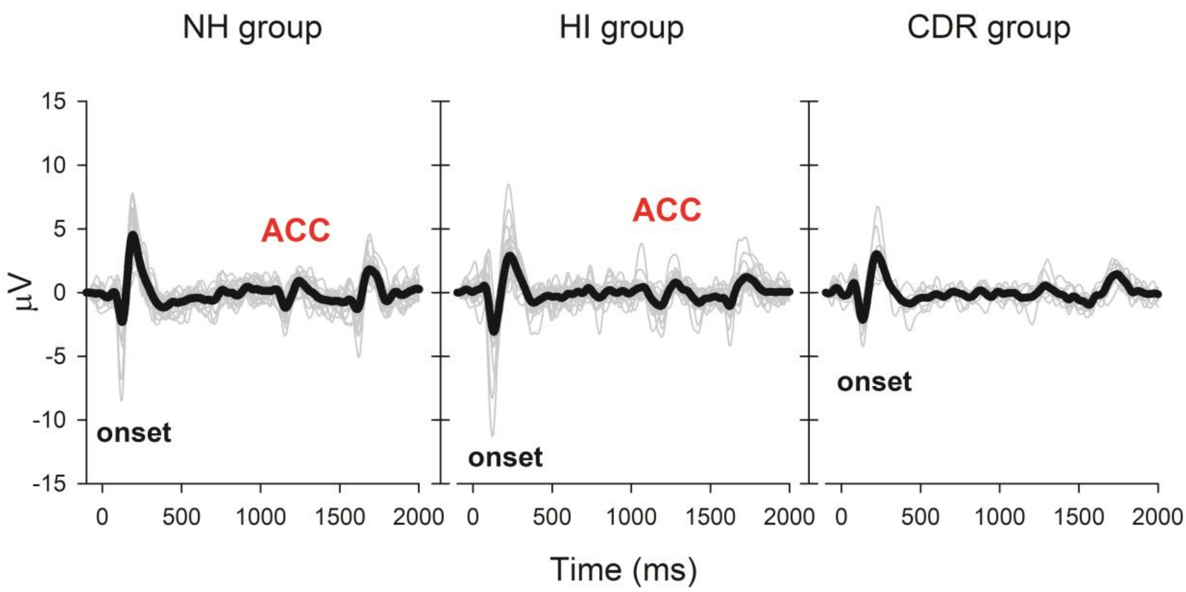

Figure 16. The individual and grand average waveform graphs for all three groups at 12 dB SNR stimulus level.

Various studies research prevalence of cochlear dead regions. Preminger et al. study[49] showed presence of cochlear dead region of 29% prevalence in a typical clinical population with binaural hearing aid users who had at least two pure-tone thresholds greater than 50 dB HL and lesser than 80 dB HL. Vinay and Moore study [50] reported a prevalence of 57.4% for a large number of adults (308 subjects) with sensorineural hearing loss. The presence of a cochlear dead region could not be predicted reliably from the audiogram and the slope of the audiogram, and was regardless of age. Therefore, TEN test is useful tool for determining CDR. We expect the TEN-ACC test may be promising tool to identify CDR objectively for who cannot conduct the behavioral TEN test.

Though the subject that was participated in this study was cooperative adults, in general, objective measures are more applicable for difficult-to-test or pediatric populations. The presence of CDR is relatively common in adolescents with a longstanding hearing impairment [51]. Almost 70% of adolescents who participated Moore's study met the criteria for CDR at medium to high frequencies in at least one ear. Generally, the aging and hearing impairment affects the morphology of auditory evoked potentials. The ACC, a type of evoked potentials, could also have the different morphology depending on age or hearing impairment. Martinez and colleague [52] showed that obvious ACC response to vowel change has appeared in children with or without hearing impairment ranging from 2 years and 3 months to 6 years and 3 months. Therefore, we anticipate that the ACC response to the stimuli used in the TEN-ACC test could occur in young children with or without hearing loss.

Previous literature shows a study that tried to objectively measure PTCs using auditory brainstem response (PTC-ABR). The PTC-ABR method has a minimum of two hours recording time to obtain a physiological tuning curve per frequency. This was quite time-consuming. The TEN-ACC test requires approximately 40 minutes to obtain data per frequency. The time can be further decreased by conducting the test at one condition. For example, the test can be measured at a single 12 dB SNR that is criterion suggested in this study to determine CDR objectively as a way of screening rather than a full TEN-ACC test that measured at several SNRs. If an ACC response is recorded, it would determine that frequency region has non-CDR. If an ACC response does not exist, it would indicate the existence of CDR at that test frequency region. A single SNR condition of TEN-ACC test needs just about 6 minutes. Therefore, the TEN-ACC test seem to be more feasible in a clinic in terms of time-efficiency.

The sample size required for group-to-group mean comparisons could be obtained by the following formula:

$$\mathbf{N} = \frac{2 \cdot \left(Z_{\alpha/2} + Z_{\beta}\right)^2 \cdot \sigma^2}{\delta^2}$$

The Greek latter α means that the type 1 error rate or significance level, that is the probability of rejecting the null hypothesis when it is true. The rate of the type 2 error is denoted by the β and associated to the power (which equals 1-b) of a test. The required sample size of each group is 10 when α is 0.05, β is 0.05, that is the power is 0.95, the variance (σ^2) is 40, and the average difference (δ) is 10. The variance and delta values were referenced from the TEN test results. The subjects recruited in this study were ten normal subjects, 12 hearing loss groups, and 4 CDR groups. Normal and HI groups met the required sample size, but the number of subjects in the CDR group did not meet the required sample size. Additional recruitment of CDR group is needed to have significant statistical power.

The sample size required for the correlation analysis could be obtained by the following formula:

$$\mathbf{N} = \left(\frac{Z_{\beta} + Z_{\frac{\alpha}{2}}}{W_{ES}}\right)^2 + 3, \quad W_{ES} = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$

The required sample size is 13 when the significance level alpha is 0.05, the beta is 0.2, that is the power is 0.8, and the correlation coefficient r is 0.7. Correlation coefficients referred to coefficients obtained from the correlation analysis between behavioral test and electrophysiological test for frequency discrimination of the previous literature [39]. The sample size of 54 used in the correlation analysis in this study satisfies the required sample size.

Because the TEN-ACC test is used to evaluate the presence or absence of CDR, the recruitment of subjects in the CDR group with the smallest number of subjects is considered to be the most necessary in order to support the effect of the test. The audiometric threshold for the TEN-ACC test was limited under the 75 dB HL because of clipping for stimulation output, and subjects with audiometric thresholds above this level could not participate. The stimulation was designed that TEN level to be 10 dB higher than the audiometric threshold in order to satisfy the criterion about the audiometric threshold among CDR criterion. If the TEN level adjusted to be 5 dB higher than the audiometric threshold, both criteria should be taken into consideration for judging the CDR, but the test could be carried out up to 80 dB HL.

As far as we know, this study is first attempt to determine CDR using the ACC response. Results of this study suggest that it is possible to determine CDR using electrophysiological approach. If the TEN-ACC test performed only under a 12 dB SNR criterion stimulus level as a screening step, the test time will be sufficiently reduced so that it could proceed in the laboratory but also the clinic. However, further studies with the larger population, using finer step sizes of SNRs, and testing more frequencies are needed to confirm the feasibility of objective TEN-ACC test.

3. Section2: SR-ACC study

3.1. Methods

The study was approved by the Samsung Medical Center-Institutional Review Board. All participants signed an informed consent before conducting the study. The subjects participated in both behavioral spectral ripple discrimination (SRD) test and electrophysiological SR-ACC test.

3.1.1. Subjects

Ten normal hearing (NH) listeners, aged between 22 and 30 years (NH group, mean age=25.1 years, SD=2.02 years) of which five were female and five were male, participated in this study. Seven hearing impaired (HI) listeners, aged between 47 and 70 years (HI group, four females and three males mean age=60.6 years, SD=8.94 years) have participated. NH subjects had audiometric threshold less than 25 dB HL at all octave frequencies from 250 to 8000 Hz. HI subjects had more than the moderate sensorineural hearing loss in both ears. The audiometric thresholds average for 500, 1000, 2000, and 4000 Hz was worse than 40 dB HL. All HI subjects were using bilateral hearing aids of RIC (receiver in the canal) type more than three months. Individual HI subject information is listed in Table Ⅴ. One of the participants in HI group did not complete behavioral SRD test hence the data was excepted.

Subject	Sex	Age	Hearing Aids Type (Duration: years/month)	
			Rt	Lt
HI1	M	69	GN Resound Linx 2 LS561-DRW RIC (3y/1m)	GN Resound Linx 2 LS561 DRW RIC (1y/10m)
HI2	M	70	WIDEX vnique v-pa RIC (2y)	WIDEX vnique v-pa RIC (2y)
HI3	F	64	Phonak audeo Q50 RIC (2y/8m)	Phonak audeo Q50 RIC (2y/8m)
HI4	F	60	GN Resound AL 461-DRW (7y)	GN Resound AL 461-DRW (5y)
HI6	F	50	GN Resound Al461-DRW (3y/1m)	GN Resound Al461-DRW (5y)
HI7	M	47	GN Resound LS561 RIC (11m)	GN Resound LS561 RIC (7m)
HI8	F	64	Phonak audeo Q50 RIC (1y/11m)	Phonak audeo Q50 RIC (1y/11m)

Table V. The HI subject characteristics

3.1.2. Behavioral SRD test

One of the behavioral methods to assess spectral resolution is the spectral ripple discrimination (SRD) test. The SRD test was followed in the procedure that is described in earlier literature [19]. Behavioral SRD test use ripple sound that has the full-wave rectified sinusoidal spectral shape that showed in figure 17[19]. The logarithmic amplitude is closer to the perceptual scale of loudness hence Logarithmic amplitude ripples were used in the test. Two thousand five hundred fifty-five pure-tone frequency components were summed to generate the ripple stimuli. The stimuli had a bandwidth of 100-5000 Hz and depth of 13 dB.

The SRD test measures the threshold value of the maximum ripple per octave (rpo) level distinguishing ripple sound from inverted ripple sound that is 90° phase shifted. The spectral ripple resolution threshold is determined using a three-interval forced-choice, two-up and one-down adaptive procedure, converging on 70.7% correct [53]. The ripple densities of stimuli differed by ratios of 1.414 and started with 250 rpo. The density level was increased by 2 steps when subjects had a correct response and decreased by 1 step when the subjects had an incorrect response until the threshold was identified. Subjects randomly listen to three sounds consisting of the standard ripple and the inverted ripple sound with a phase shift of 90 degrees and then conduct the task of picking the one button for different sound. The test screen for the SRD test is like figure 18. The threshold was determined by averaging the values of ripple density for the final 8 of 13 reversals in a trial. The final threshold were decided by averaging the thresholds obtained from three trials.

The stimulus level was 65 dBA for NH subject and most comfortable level (MCL) which was determined using half-gain rule based on frequency amplitude for HL subject. The stimuli were presented at an average level of 65 dBA through a loudspeaker located 1m away from the subject at zero degrees azimuth in the sound field for NH subject. For HI subject, the stimuli were presented bilaterally via ER-3A insert earphones at MCL.

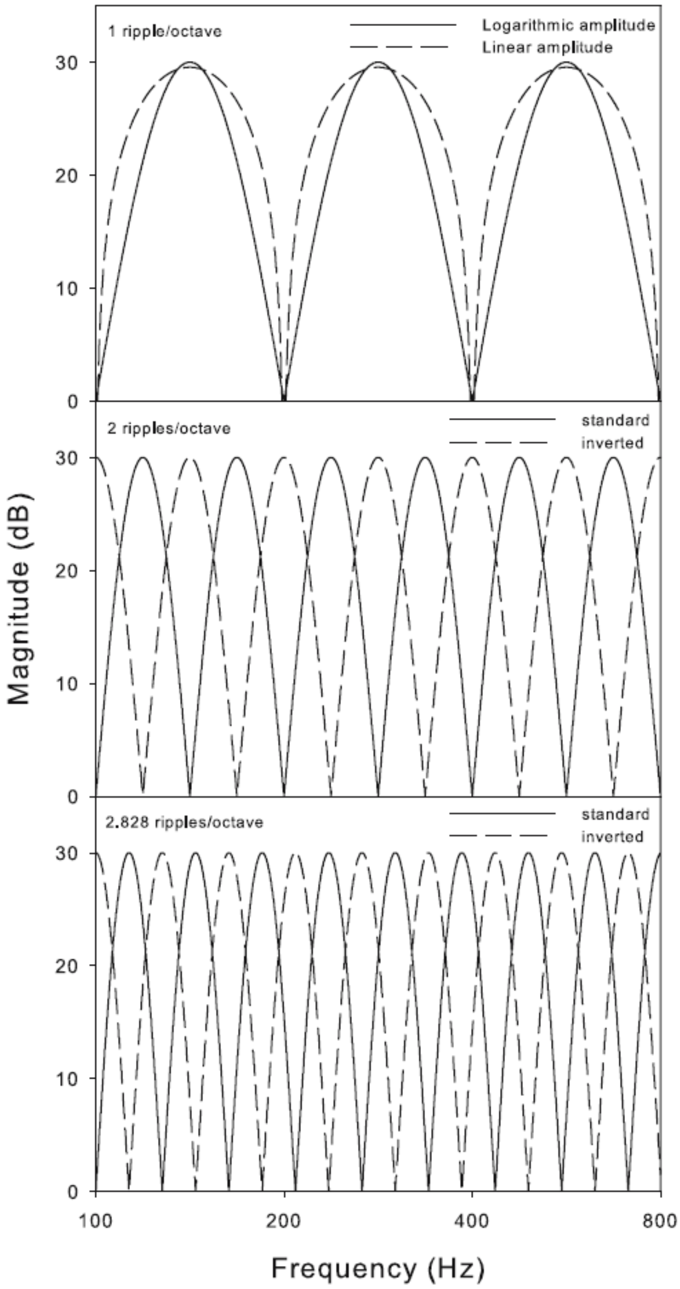

Figure 17. The spectra of spectral-ripple stimulus

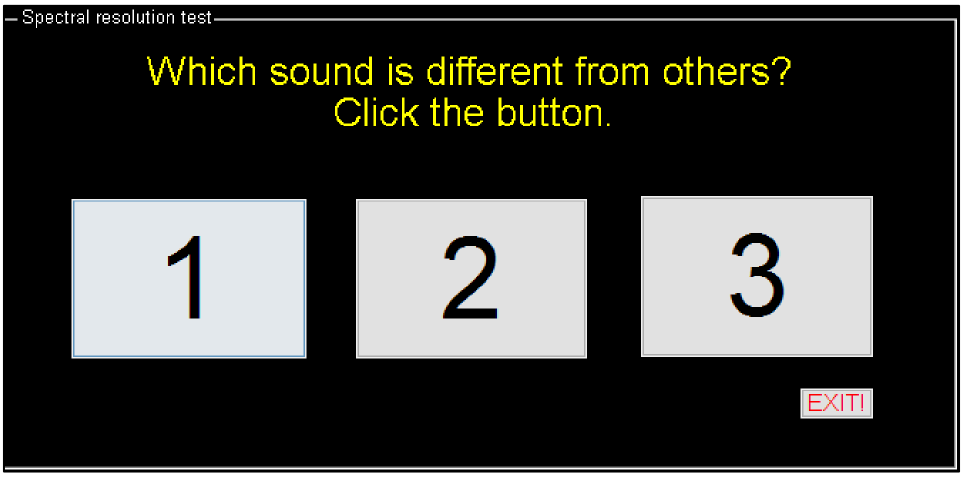

Figure 18. The test screen for the SRD test.

3.1.3. Electrophysiological SR-ACC test: Stimuli

Figure 19 shows waveforms and spectrogram for stimulus for the 1 rpo case.

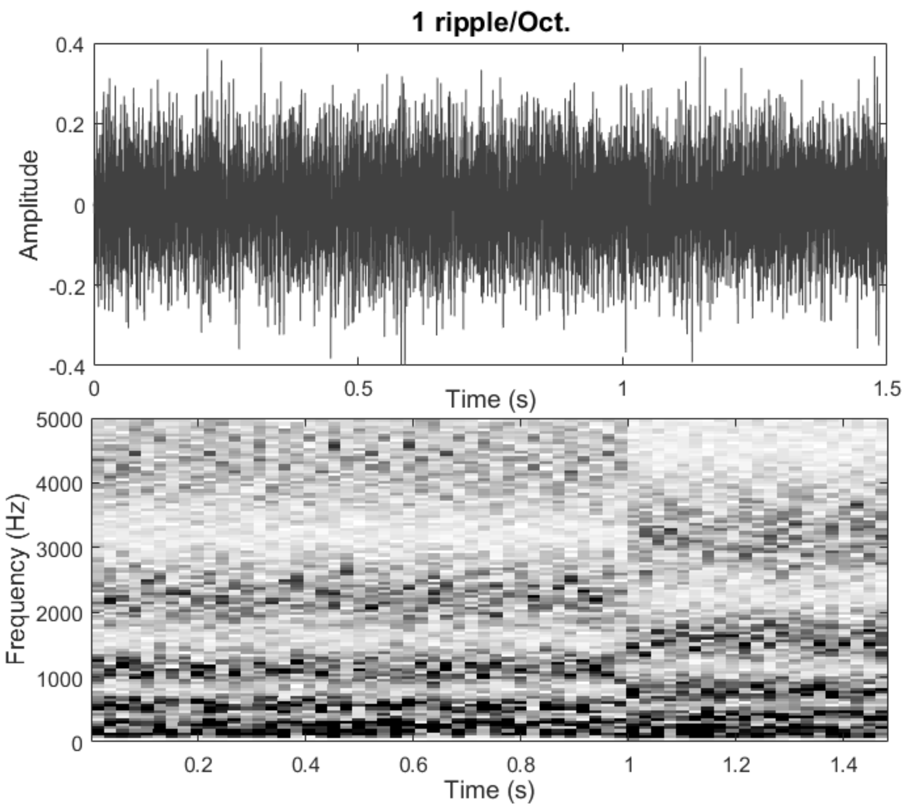

Figure 19. An example of stimulus used in SR-ACC test (1 rpo)

The total duration of the stimulus is 1.5 s consisting of the standard ripple of 1 s and inverted ripple of 0.5 s. The first 1 s of stimulus consisted a standard ripple and the last 0.5 s contained an inverted ripple. There was a spectral change at the 1s point. Each part of the stimulus was individually created and concatenated. The normalization of the stimulus was applied to eliminate the loudness change at the 1s point by matching the root mean square of each part. After normalization, the whole stimulus was ramped with 5 ms rise/fall times to abrupt onset/offset artifacts. A 5 kHz low-pass filter was applied to entire stimulus in order to reduce frequency components beyond 5 kHz at the 1s point generated because of the concatenation. The inter-stimulus interval was one second, and the stimulus level is the same as the behavioral test. The ER-3A insert earphones connected with a Neuroscan STIM system (NeuroScan, Inc., Herndon, VA) were used to present the stimuli bilaterally. The ripple densities of stimulus ranged from 0.5 to 6 rpo.

3.1.4. Electrophysiological SR-ACC test: Recording

During the recording session, subjects were seated in a reclining chair in a soundproof booth as like study of section 1. The subjects were requested to relax and watch a captioned video to help them stay awake. The recording environment was monitored using an infrared camera placed inside the soundproof booth. If the subject moved or dozed off during the recording session, that specific condition was ceased and repeated after re-instruction. The EEG was recorded using surface electrodes with Neuroscan Scan 4.5 and SynAmps2 system. The active electrode on Cz was placed according to the international 10-20 system (Jasper 1958). An electrode on the forehead served as ground, and the electrodes on the bilateral mastoid served as reference. Vertical and horizontal eye movements and eye blinks were monitored via recording electrodes attached to above and below the left eye and lateral both eyes. Electrode impedances and inter-electrode impedance differences were kept below 5k and 2k ohms, respectively. Individual ACC recording for each condition represented the average 200 stimulus presentations consisting of blocks of 100 sweeps.

During the data acquisition, the EEG signal was amplified with ten times, band-pass filtered between 0.1 and 100 Hz and digitized at an analog-to-digital sampling rate of 1000 Hz. After the data were acquired, ocular artifact reduction were conducted. EEG epochs were created using a window ranged from −100 to 2900 ms. EEG epochs in which voltage exceed absolute value of the 75 μV were rejected and baseline corrected (−100 to 0 ms). After that, the band-pass filtered ranged 1 to 30 Hz with 12dB/octave was applied. The filtered epochs were averaged for each stimulus condition and each subject. The smoothing of the averaged waveform was conducted using a 40 ms moving average filter. Final grand-mean average waveforms were created by averaging the waveforms across subjects.

The experienced researcher analyzed the waveforms and determined the presence of ACC responses and thresholds. An RMS amplitude ratio of ACC to noise floor was supported to determine the presence of ACC response. The window of the ACC response and noise floor were ranged from 1050 to 1250 ms and from 2800 to 2900 ms after onset, respectively. If the RMS ratio was higher than at least 50%, the ACC response was determined to be present. In summary, the visual decision of researcher and RMS ratio value were used to determine the presence of the ACC response.

3.2. Results

Figure 20 shows the grand average waveforms obtained for each rpo condition from NH and HI groups. The left panel indicated average waveforms for the NH group, and the right panel displayed average waveforms for the HI group. The time window of waveforms extended from - 100 ms to 2000 ms to display the responses more clearly. The gray dashed line indicates stimulus onset and the red dashed line indicates the point of change from standard ripple stimulus to inverted ripple stimulus. The robust onset responses were shown in all conditions of two groups. After one second point, the ACC responses were observed at the rpo conditions of supra-threshold level. The stimulus was turned off at 1500 ms, and offset responses also provoked in the grand average waveforms. The graph shows that amplitude of ACC increases, as the rpo level of the stimulus increases from 0.5 to 6 rpo. The thresholds for the NH and HI group were five rpo and 1.414 rpo, respectively.

The mean thresholds of behavioral SRD test and electrophysiological SR-ACC test for the NH and HI groups were indicated in Table Ⅵ. The difference of thresholds obtained from SRD test for two groups is 5.16. There was a statistically significant difference between the groups ($t=11.708$, $p<0.001$). The difference of thresholds resulted in the SR-ACC test for two groups is 3.439. There was a statistically significant difference between the groups ($t=10.240$, $p<0.001$).

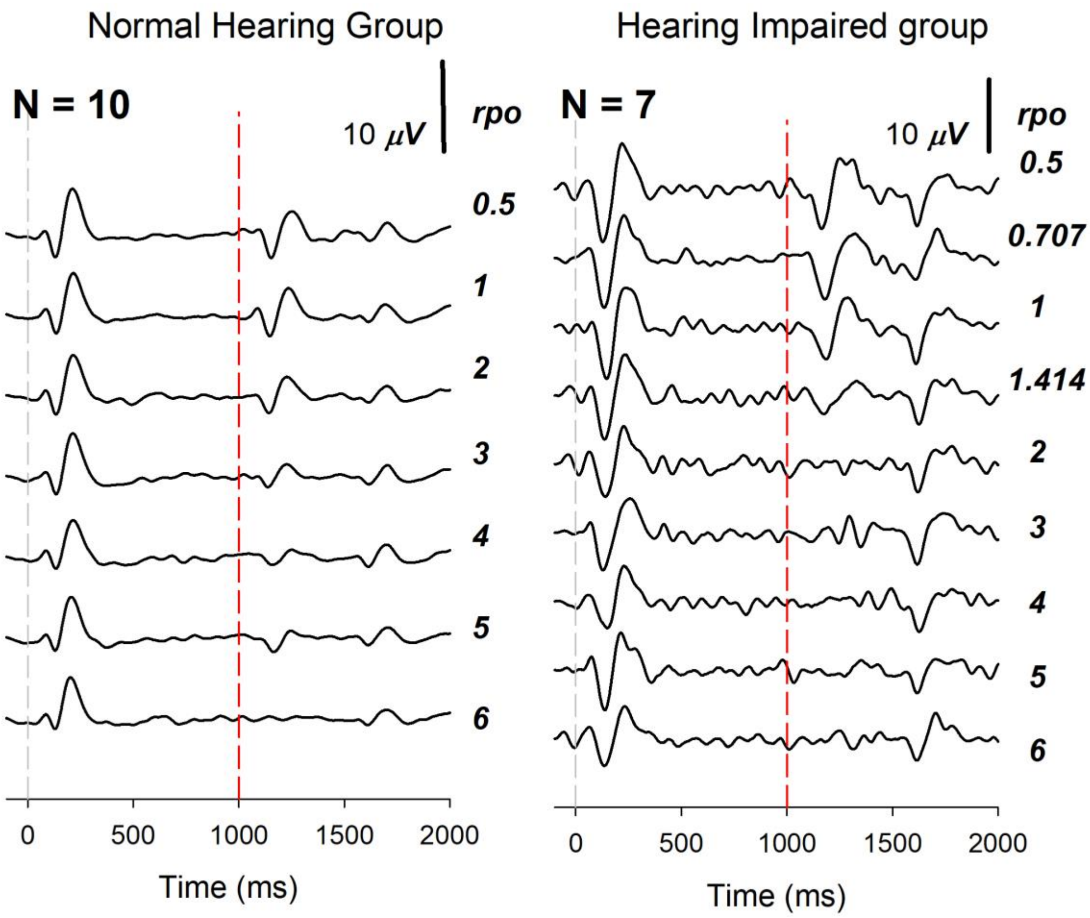

Figure 20. Grand average waveform of NH and HI groups

Threshold (rpo)	SRD test	SR-ACC test
NH group	6.48	4.60
HI group	1.33	1.26

Table VI. The thresholds of behavioral SRD test and electrophysiological SR-ACC test for NH and HI groups

Figure 21 shows the relationship between the SRD test and the SR-ACC test for data obtained from whole participants. Each symbol represents the results of each group. The linear regression was applied to analysis to examine the correlation between the behavioral SRD test and electrophysiological SR-ACC test. The correlation between the two tests was found to be statistically significant (DF=16, r=0.764, p<0.001).

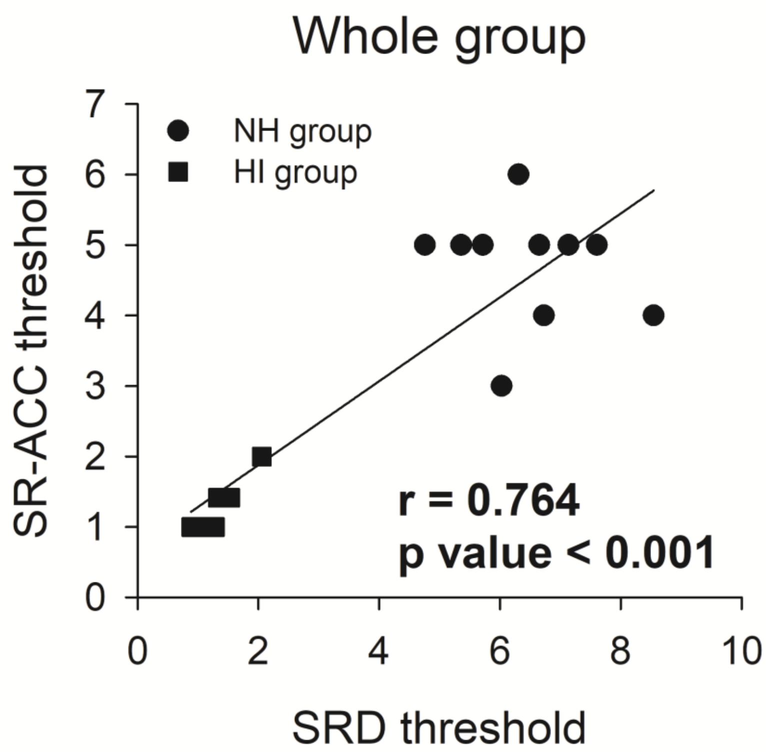

Figure 21. Correlation between behavioral SRD threshold and electrophysiological SR-ACC threshold for the whole data

Figure 22 displays the separated results to for the two groups. The left column (figure 22A) shows the scatterplot of the thresholds resulted in two measures for the NH group, and the right column (figure 22B) shows the scatterplot for the HI group. The two graphs at the bottom are drawn by expanding the scale of the two graphs above to show more detailed results clearly. As different from data of the whole group, there was no significant relationship between SRD test and SR-ACC test for the NH group (r=-0.191, p>0.597). However, for the HI group, the correlation between two tests was statistically significant (r=0.938, p=0.00177) and has the stronger relationship than that of result from the whole group.

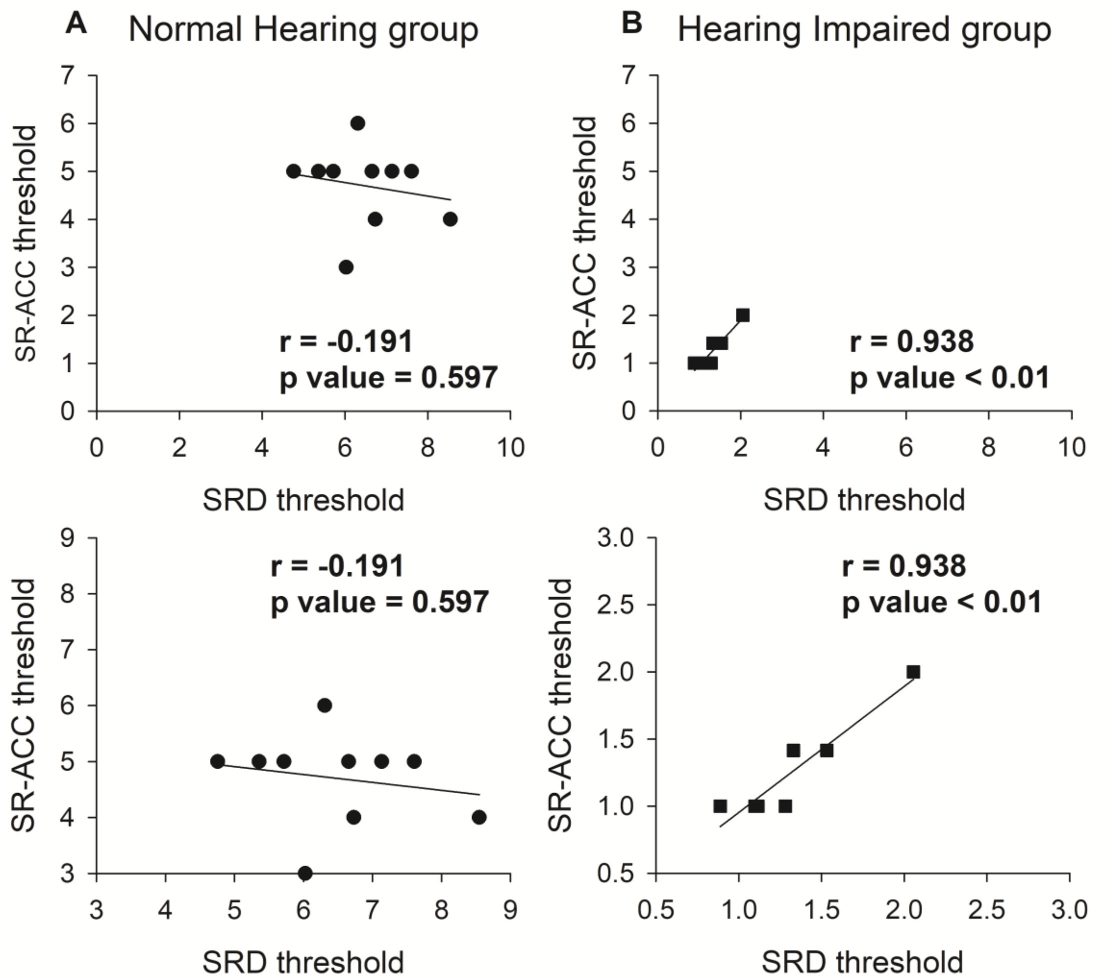

Figure 22. Correlation results between behavioral SRD threshold and electrophysiological SR-ACC threshold of NH and HI groups

3.3. Discussion

The aim of this study is to examine the effectiveness of electrophysiological approach to assess spectral resolution. The threshold of the spectral resolution resulted in the electrophysiological SR-ACC test for the NH group was statistically significantly higher than that of HI group. There was also statistically significant correlation between behavioral SRD test and electrophysiological SR-ACC test for the whole group. Though there was no significant relationship for the results of NH group, the results from the HI group had a statistically significant positive correlation. Furthermore, the correlation coefficient of results for the HI group was higher than that of the whole group. The normal hearing group seemed to have difficulty in discriminating by the SR-ACC test method because the frequency processing ability was superior. We expect to be able to observe differences in the SR-ACC threshold in the NH group through further studies with the finer step size of spectral density level. These results of the study suggest that electrophysiological approach using ACC response has potential to assess spectral resolution objectively in particular hearing impaired listeners.

Figure 23 displays correlation between the pure tone average of the better ear (calculated with four division method using the thresholds at 500, 1000, and 2000 Hz) and the both behavioral and electrophysiological spectral resolution threshold. The upper panel is the results to normal hearing group and the lower panel is the results to hearing-impaired group. The black circle and red rectangle indicates SRD and SR-ACC thresholds, respectively. There was no significant correlation in both groups for results between pure tone average and behavioral spectral resolution and electrophysiological spectral resolution. There was no difference of spectral resolution threshold according to the audiometric threshold within group though it is known that if the hearing deteriorates, the frequency processing ability decreases. It is similar to the results of the study of Henry et al. (2005) [15]. There was a significant correlation between absolute threshold and speech recognition (vowel, consonant recognition) in the HI group, but the relationship between absolute threshold and spectral resolution threshold was not significant correlation. The study had also suggested that spectral resolution threshold is associated with accurate speech recognition. Both absolute threshold and spectral resolution are correlated with speech recognition, but there was no significant correlation between absolute threshold and spectral resolution. It could be interpreted that two aspects affect speech performance differently. Therefore, spectral resolution information that affects speech performance could be the important factor in order to improve the speech performance to hearing-impaired listeners. In this study, it was meaningful to extend the test in an objective method for individuals who are unsuitable to behavioral test and to examine the feasibility of SR-ACC test. The relationship between the SR-ACC test and the speech performance also needs to be examined to confirm the relationship between objective resolution threshold and speech performance. Since SRD test and the SR-ACC test showed a strong correlation as mentioned above, the result is expected that has good correlation. We would expect that the SR-ACC test has the feasibility to assess spectral resolution for the population like the infant, young children, individuals who are not inclined to cooperate objectively.

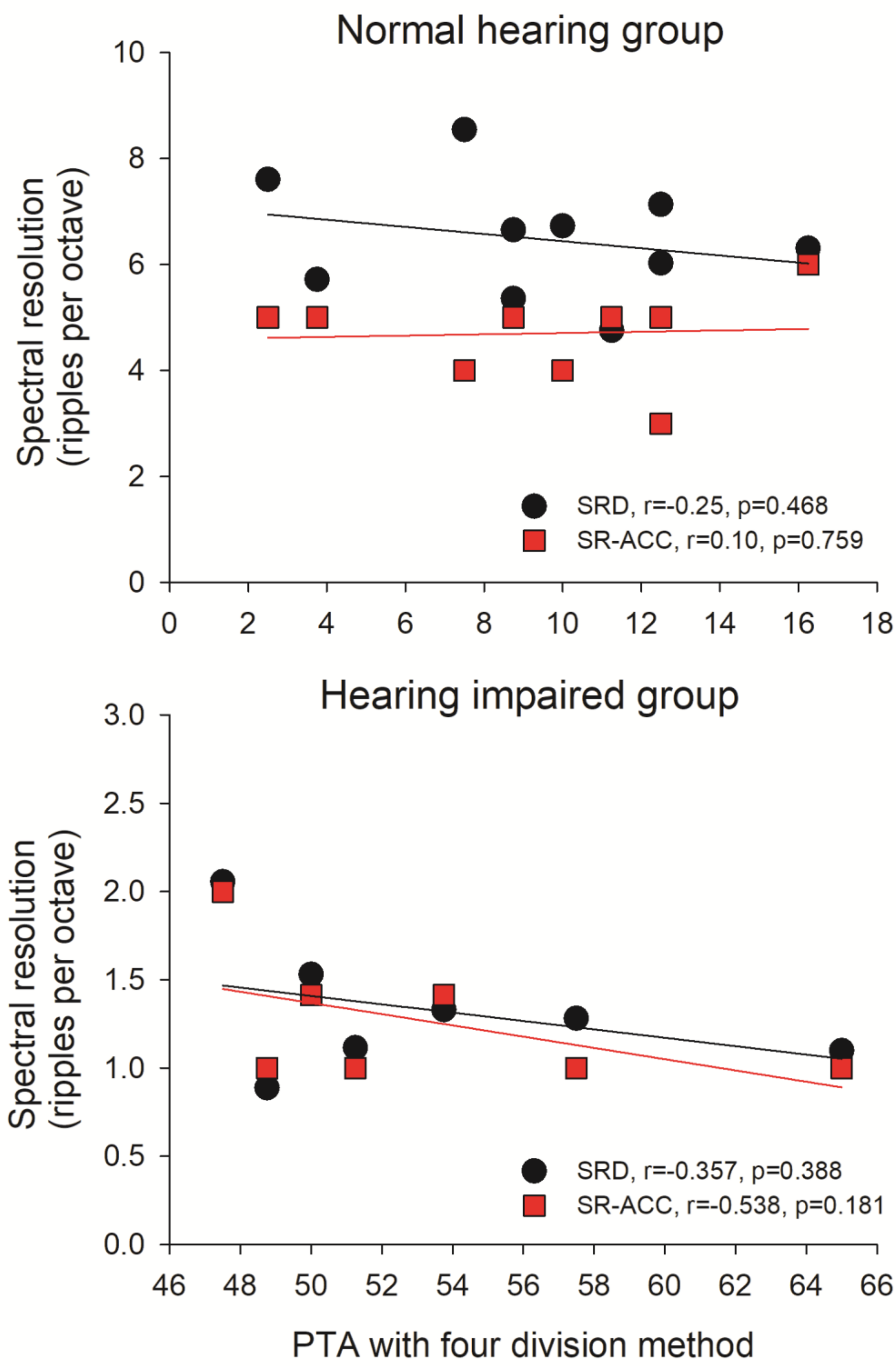

Figure 23. Relationship between pure tone average and behavioral/electrophysiological spectral resolution

Won et al. (2011) demonstrated that the ACC could be provoked using vocoded spectral ripple stimuli in three NH listeners [54]. They showed that the physiological threshold improved as a function of number of channels. The results also showed a similar growth tendency of threshold as a function of the number of channels in both physiological and behavioral data. The correlation between the electrophysiological and behavioral thresholds are also described in this SR-ACC study. Further, the SR-ACC study examined the results obtained from normal hearing and hearing-impaired listeners.

Scheperle and Abbas (2015) also described that electrophysiological measures of spectral selectivity provides valuable information for speech perception in CI users [55]. While they explored using the ACC amplitude evoked at a single condition, the SR-ACC test was conducted at multiple rpo levels as like behavioral SRD test. It allows a more intuitive comparison of behavioral and electrophysiological measures for spectral resolution, and also could show other aspects of how the ability to spectral ripple discrimination is reflected in cortex level.

These two previous works of literature have examined CI performance as a function of the mapping strategies (number of channels, choice of the activated electrode) using electrophysiological measures with ACC response. The CI performance could predictable using the electrophysiological method. Thus, it is expected that further research with CI users may be showed that the SR-ACC test could evaluate the spectral resolution of CI users but also predict CI performance.

The sample size required for inter-group mean comparison could be obtained by the following formula:

$$\mathbf{N} = \frac{\mathbf{2} \cdot \left(\boldsymbol{Z_{\alpha/2}} + \boldsymbol{Z_{\beta}}\right)^{\mathbf{2}} \cdot \boldsymbol{\sigma}^{\mathbf{2}}}{\boldsymbol{\delta}^{\mathbf{2}}}$$

When the significance level alpha (α) is 0.05, the rate of the type 2 error beta (β) is 0.05, that is the power (1-β) is 0.95, the variance (σ2) is 7, and the average difference delta (δ) is 5, the required sample size of each group is 7. The values of variance and delta were referenced from the results of SRD test. The subjects in participated in this study were 10 NH listeners and 7 HI listeners. This number of subjects satisfied the required sample size for mean comparison analysis.

The sample size required for the correlation analysis could be obtained by the following formula:

$$\mathbf{N} = \left(\frac{Z_{\beta} + Z_{\frac{\alpha}{2}}}{W_{ES}}\right)^{2} + 3, \quad W_{ES} = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$

The required sample size for correlation analysis is 13 when the significance level alpha is 0.05, the beta is 0.2 (that is the power is 0.8), and the correlation coefficient r is 0.7. The correlation coefficient was referenced from coefficient for the behavioral and electrophysiological results for frequency discrimination in the prior study [39]. In this study, the sample size of 17 for whole data was satisfied required sample size for correlation analysis. However, the sample size for analysis within the group was insufficient. Thus, more subject recruitment is necessary to derive significant statistical power.

To confirm the feasibility of the SR-ACC test, further studies with more data of larger subject number and CI subject are necessary. Also, the comparative research of results between SR-ACC test and speech performance is needed.

4. General conclusion

The main purpose of the thesis is to investigate an objective method using the electrophysiological approach with ACC response to examine if it is possible to assess specific auditory property like CDR and spectral resolution.

In section 1, as an electrophysiological approach referred as TEN-ACC test, the ACC response evoked using TEN combined with a pure tone stimulus was used to assess the presence of CDR. The results of this section suggest that the TEN-ACC test has a potential to determine the presence of CDR.

In section 2, spectral ripple stimulus was used in an electrophysiological approach mentioned as the SR-ACC test to assess spectral resolution. The results of this section suggest that the SR-ACC test shows the possibility to assess spectral resolution objectively.

These results indicate that the ACC response is useful to assess specific auditory property objectively. The objective electrophysiological measures of specific auditory property would be a valuable additional tool in the decision of hearing aid fitting and cochlear implant mapping formula and for assessment of rehabilitation outcomes. Further studies with higher sample size, specific parameter adjustments, and various clinical populations are needed to confirm the feasibility of this approach.

Because the stimulus used in the behavioral test was utilized in suggested TEN-ACC test and SR-ACC test in this study to evaluate the specific auditory property, the results of the behavioral and electrophysiological tests could be compared and interpreted more intuitively. Also, it showed how the stimuli of the behavioral test were reflected in the cortex level with regard to stimulus conditions or subject groups. In this study, only the threshold value was analyzed. In the previous literature, ACC amplitude was analyzed as an objective index to predict speech performance. Therefore, it is also necessary to investigate more proper factors that could reproduce speech performance by analyzing factors of various ACC responses such as amplitude and latency besides threshold.

The objective approach is needed more for young children or infants than adults for assessing the specific auditory property. The auditory evoked potentials have maturation as reflected age-related changes hence, the morphology of the AEP changes as over the age [56, 57]. Therefore, further clinical studies in young children are certainly necessary to obtain underlying data to apply the objective approach to young children and infants.

There is still a time-consuming issue to implement the electrophysiological tests of this study in clinical settings. Efforts are needed to derive optimal settings in order to reduce test time. More clinical studies with a larger number of subjects and various clinical populations are also essential to establish normative data for accurate interpretation of test results.

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