A PHYSIOLOGICAL CORRELATE OF ELECTROACOUSTIC PITCH MATCHING IN COCHLEAR IMPLANT USERS WITH RESIDUAL HEARING

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ABSTRACT

One challenge facing postlingually deafened cochlear implant (CI) users is the frequency mismatch between the incoming acoustic signal and the characteristic frequency of the electrically stimulated neurons. Current CI will require extensive effort in fine tuning to help users to adapt to this mismatch. A recent work [1] attempts to address this issue using a closed-loop CI system with evoked potentials as feedback. However, the stimulus artifact produced by CI and the limitation of subcortical responses in assessing speech perception are yet to resolve. In this paper we present our proposed cortical auditory evoked potential (AEP) evolved from a study [2] that addresses this mismatch. We describe the background then the experiments involved in the development of the AEP with recordings from 3 normal hearing (NH) listeners and 2 CI users. We also discuss how the AEP could be used in a closed-loop CI system.

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Index Terms— Auditory evoked potentials, electro-acoustic pitch matching, cochlear implant, closed-loop system

1. INTRODUCTION

Most current CIs attempt to restore hearing by electrically stimulating the neurons via an electrode array implanted in the cochlea. The electrical stimulation is controlled by an externally worn speech processor and communicated to the implanted receiver via a radio-frequency (RF) link. One challenge facing these CI users, particularly postlingually deafened, is the frequency mismatch between the incoming acoustic input signal to the speech processor and the characteristic frequency of the neurons electrically stimulated by CI. For a CI user to successfully understand speech, it is most critical for the speech processor to deliver effective speech information which can be best interpreted by the brain when it is presented in the form of electrical stimulation. Individualized "fitting" or "mapping" the CI with appropriate speech processing and electrical stimulation parameters to meet each individual CI user's need is necessary. However, this fitting process is based on the verbal responses from each individual CI user on speech perception elicited by the audiologist, which is time and effort consuming, and might not be feasible with very young CI users. Furthermore, postlingually deafened CI user needs time for the brain to adjust and interpret the spectrally impoverished electrical stimulation as meaningful auditory input.

McLaughlin and colleagues [1] attempted to resolve these issues by designing a closed-loop CI system which monitors neural activity at various stages along the auditory pathway and dynamically adjust the electrical stimulation. However, one problem in obtaining evoked potentials with CI users is that stimulus artifact occurs around first few milliseconds when turning on and off the electrical stimulation. The artifact may totally obscure the evoked potentials from being observed.

Moving from peripheral (auditory nerve) to central (cortex) along the auditory pathway, the physiological latency of the major components of the evoked responses can range in an order of one ms to hundreds ms. Clearly it is technically more difficult to separate auditory nerve response from the artifact as they overlapped each other. Furthermore, auditory nerve response may not provide a good assessment of more complex outcomes like speech perception [3]. Relatively, it is much easier to separate auditory brainstem response and cortical response from the artifact as their major components, i.e. Wave V and N1, occur around 4ms and 100ms from the onset of the stimulus.

Neural activity in response to the frequency mismatch as described in the earlier paragraph will certainly provide useful information for CI user to re-learn to 'hear' via electrical stimulation. It would also naturally be an appropriate candidate to monitor in a closed-loop CI system. In our laboratory, we have been examining how unilateral CI user with residual hearing in the un-implanted ear adapts to this frequency mismatch behaviorally and physiologically. We compare the pitch percepts elicited by electrical stimulation with those elicited acoustically in the contralateral ear, and observe whether those percepts change over time. In this paper, we present our proposed cortical AEP in response to electro-acoustic pitch mismatch [2] that evolved from this study, and demonstrate how it correlates

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to the behavioral data. In Section 2, we describe the background of this study. We then describe the pitch matching experiment and physiological experiment in Section 3 and show AEP recorded from 3NH subjects and 2CI users. Finally, we discuss how the AEP could be used in a closed-loop CI system in last section.

2. EXPERIMENTS

2.1 Pitch-matching experiment

In this experiment, we asked postlingually deafened adult CI users who have sufficient residual hearing in the contralateral ear to match the pitch elicited by stimulation of a given electrode to the pitch elicited by a tone presented to the acoustic-hearing ear.

2.1.1 Subjects

The two postlingually deafened adult subjects participated in this study were unilaterally implanted with Cochlear devices. All electrodes in their devices were active. They were implanted at the Cochlear Implant Center, New York University Department of Otolaryngology. Both of them have near-normal hearing in their non-implanted ears (at least up to 2000Hz), and had 10 and 16 months of experience with their devices at the point of testing. They all had some good degree of residual acoustic hearing in the vicinity of 500Hz. 3 NH subjects with hearing thresholds equal or better than 20 dB HL also participated in the study. They all had otologically normal ears and none had history of ear surgery.

2.1.2 Setup

We developed a real-time pitch matching platform that stimulates the electrode of interest directly at the user's most-comfortable level (MCL) via the NIC research interface provided by Cochlear Corporation. The acoustic tone is amplified by gains prescribed by the NAL-RP formula, based on the user's pure tone audiogram in the un-implanted ear. The acoustic signal is further amplified by a Graham Slee Solo SRGII Amplifier and presented via an ER-2 insert earphone or a Sennheisser HD580 headphone. The choice of earphone or headphone is to ensure the acoustic tone is delivered at the desired MCL without much distortion.

2.1.3 Stimuli

All acoustic and electric signals are presented in an alternating sequence, in which electrical pulses are presented via stimulation of a single channel in the implanted ear for 500 ms, followed by 500 ms of electrical inactivity. During this period of electrical inactivity, the acoustic tone is presented to the contralateral ear for 500 ms; the acoustic tone is shaped by a trapezoidal window with a rising/falling time of 10 ms to prevent spectral splatter.

2.1.4 Procedure

All CI users are instructed to adjust the frequency of the acoustic tone until the pitch percept elicited by the acoustic tone matches the percept elicited by electrical stimulation. Before the experiment, they were first asked to adjust loudness of the acoustic tones to be as close to that of the electrical stimulation. Then, they were asked to ignore loudness difference (if any) in both ears, and focus only to match them in pitch percept. This procedure is repeated six times for each active electrode in the array. The pitch-matched frequency for each electrode is the average of the six frequencies selected. Prior to each selection, the starting frequency of the acoustic tone is randomized to avoid any range bias effects.

2.2 Physiological Experiment

In this experiment, we examine the electric-acoustic evoked interactions in the P1-N1-P2 complex to obtain an objective measure of adaptation to frequency mismatch.

2.2.1 Test conditions

The same platform used for pitch matching is used to generate electric and acoustic stimulation in the same manner as in the pitch matching experiment. The intent is to evoke electric-acoustic interactions in the AEP's. In each recording session, the CI user listens passively to different testing conditions. In these conditions, a single electrode in the implanted array (electrode 20, which is commonly assigned to a frequency channel centered at 500 Hz), is stimulated, followed by a pure tone presented to the contralateral ear. The frequency of this tone is varied for each of 6 testing conditions, listed below:

1. **250 Hz – one octave below the target 500 Hz frequency,**
2. **375 Hz – center frequency of the adjacent apical electrode,**
3. **500 Hz – center frequency of the frequency channel allocated to electrode 20,**
4. **625 Hz – center frequency of adjacent basal electrode,**
5. **1000 Hz – one octave higher than the target 500 Hz signal,**
6. **frequency value of the pitch match obtained in the first experiment.**

2.2.2 Setup

All AEP's are recorded using the Neuroscan system with interleaved presentations of single-electrode electrical stimulation for 1000 ms and a contralateral acoustic tone during the 1000ms of electrical inactivity. Stimuli were lengthened for longer inter-stimulus interval to elicit greater response and minimize unnecessary artifact in recording when switching from electrical stimulus to acoustic stimulus. In all conditions, the electrode of interest is stimulated for 1000 ms, followed by 1000 ms of electrical inactivity. During this period of electric inactivity, the acoustic tone is presented to the contralateral ear for 1000 ms; the acoustic tone is shaped by a trapezoidal window with a rising/falling time of 10 ms. Each pair of electric and acoustic stimuli is repeated 500 times. The AEP response

recording is initiated by a trigger inserted at the end of each electrical stimulus. For NH subjects, the electrical stimulation is replaced with an acoustic tone at 500 Hz. Since all NH subjects obtained pitch-matched frequencies within 5 Hz of 500 Hz, condition 6 was not included in their AEP recording. Acoustic signals are presented to the subject via ER-2 insert earphones, and the levels of all acoustic signals are adjusted by the user to MCL.

2.2.3 Processing

AEPs are recorded from 64 channels referenced to an electrode near Cz, including vertical and horizontal EOG channels to monitor eye movements and eliminate myogenic activity resulting from eye blinks. The ongoing EEG is digitized at 1000Hz, amplified 1000 times, and filtered between 0.15 and 200 Hz. AEP analysis is conducted offline using the Neuroscan Edit software. AEP responses are broken into 991ms epochs after ocular artifact reduction. The responses in each epoch are baseline corrected and filtered using an IIR bandpass filter between 1 and 30 Hz at 12dB/Oct. After artifact rejection (+/- 100 microvolts) and averaging and re-referencing, the grand mean waveform in each condition is obtained for each subject. N1 and P2 peak amplitudes and latencies are determined automatically in each condition.

3. RESULTS

In this paper, we present the results obtained with 2 CI subjects and 3 NH subjects.

In pitch matching experiment, CI subjects observe a trend toward increasing pitch percepts being elicited by progressively more basal electrodes and reported pitch percepts that closely matched the center frequency of the range that is indicated by their frequency map at the most apical electrodes. We performed reliability checks on the pitch matching data for non-sensory biases as suggested by Carlyon et al [4] and found that they were able to produce consistent and reliable pitch matches and passed the checks. Highly reliable pitch matching data freed from non-sensory biases is necessary when interpreting studies that require subjects to judge the pitches of stimuli that are likely to differ on other perceptual dimensions.

In physiological experiment, we recorded the P1-N1-P2 complex with 2 CI subjects under the experimental setup described in Section 3.2.2., with 500 repetitions of sequentially interleaving short intervals of electrical stimulation and acoustic tone stimulation were presented across two ears. The testing paradigm is similar to the Experiment IIB in Butler (1972) [5]. Figure 1 shows a typical P1-N1-P2 complex recorded at FCz with CI subject 1 with electrode 20 stimulated in the left ear and acoustics tones to the right ear in 6 conditions as describe in Section 3.2.1. Latency of N1 is measured from the beginning of the P1-N1-P2 complex to the center of the first negative peak N1. Table 1 shows the latencies of N1 for each individual CI subject estimated from the P1-N1-P2 complexes recorded at locations FCz and Cz. Observe with the 2 CI subjects, N1 latency decreases when the frequency of the acoustic tone becomes larger. The shortest N1 latency occurs at the subject's pitch-matched frequency obtained for electrode 20 in the psychoacoustic experiment described in Section 3.1.

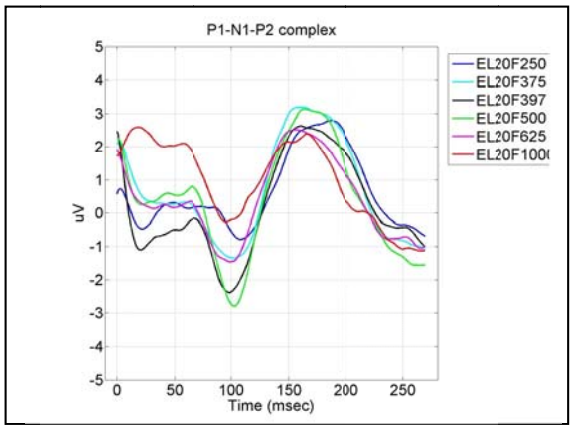

Figure 1: P1-N1-P2 complexes recorded at FCz with CI subject 1 electrode 20 stimulated in the left ear and tones of 250, 375, 397, 500, 625, and 1k Hz to the right ear. All tones are of 1 second interval adjusted by subject to obtain equal loudness with reference to electrical stimulation.

CI Subject 1						
Freq(Hz)	250	375	500	625	809	1000
FCz	140	126	124	125	118	121
Cz	140	127	124	125	110	113
CI Subject 2						
Freq(Hz)	250	375	397	500	625	1000
FCz	108	102	98	103	99	95
Cz	110	105	99	103	101	104

Table 1: Latencies of N1 (ms) for 2 CI subjects estimated from the P1-N1-P2 complexes recorded at locations FCz and Cz. Their average pitch-matched frequencies for electrode 20 were 809 Hz and 397 Hz. (shaded in yellow).

We also cross-examined with this phenomenon with NH subjects. In total, we recorded the P1-N1-P2 complex with 3 NH subjects under the same experimental setup used by the CI subjects. In place of electrical stimulation, we presented a fixed 500Hz to one ear. In the contralateral ear, the acoustic tone frequency was either 250 Hz, 375 Hz, 500 Hz, 625 Hz or 1000 Hz. Table 2 shows the latencies of N1 estimated the P1-N1-P2 complex waveforms recorded at locations FCz and Cz. Similar to the outcome with CI subject, N1 latency increases when the difference between left and right ear frequencies becomes larger.

To summarize, our current findings with our proposed AEP suggest that all subjects seemed to show that N1 latency was minimized when both ears were stimulated with the tones of same frequency (for NH subjects) or when pitch-matched electrical and acoustic stimulation were provided to the implanted and the un-implanted ear respectively (for CI users). Currently, we are collecting more recordings with CI and NH subjects to further substantiate this phenomenon and examine the possibility of

using N1 latency as a physiological indicator of electric-acoustic pitch matching across the two ears.

Freq(Hz)	250	375	500	625	1000
NH Subject 1					
FCz	114	104	101	105	103
Cz	126	100	101	105	101
NH Subject 2					
FCz	110	109	100	107	128
Cz	118	143	102	158	128
NH Subject 3					
FCz	105	119	118	125	123
Cz	105	117	104	127	123

Table 2: Latencies of N1 (ms) for three NH subjects estimated from their corresponding P1-N1-P2 complexes recorded at various locations. NH subjects were presented with 500 Hz tone in the left ear and tones of 250, 375, 500, 625, and 1k Hz to the right ear. All tones are of 1 second interval presented at 70 dBSPL with reference to 2cc coupler.

4. DISCUSSION

We have demonstrated that it is possible to record our proposed AEP with CI user in presence of stimulus artifact at the onset and offset of electrical stimulation. With the similar recordings obtained with NH subject, we also demonstrate that the AEP is responding to the difference in pitch percepts across two ears and independent of the mode of stimulation (acoustic vs. electric). To date, our current finding with a small set of data seems to suggest latency of N1 response correlates to electric-acoustic pitch matching across the two ears.

To illustrate one possible way of using our proposed AEP, we will use our previously developed a software tool [6] that enables CI users to self-select a "most intelligible" frequency table as a starting example. Inclusion of N1 latency as a feedback indicator into the software tool with a fixed tone to both ears will enable unilateral CI users to self-select and brain-select "pitch-matched" frequency table for bimodal hearing. Based on our findings so far, the brain-selected frequency table should indicate itself with a minimum N1 latency showing at the electrode position Cz or FCz. Similarly, the AEP could be used in the same way in a closed-loop CI system. We envisage that the close-loop CI system will be able to dynamically move the frequency table according to N1 latency indicator to adjust the processing of incoming speech for bimodal hearing by unilateral CI users in real-time. This is most useful for the long language learning process with prelingually deafened CI users as well as the long re-learning process with postlingually deafened CI users. Another possible application of such system is to provide real time feedback to guide intracochlear electrode insertion [7] during unilateral CI implantation. However, further understanding of the AEP recorded with CI users sedated or asleep is necessary. Cortical responses can certainly be used to assess more complex tasks other than pitch perception, like suprathreshold discrimination and recognition. We would expect responses obtained from different tasks may have to be used with a close-loop system differently in its own unique way.

In our paradigm, we are making our assessment based on one P1-N1-P2 complex at one scalp electrode at vertex. This implies that the AEP can be easily accessible with a simple hardware implementation with less interference from the RF link used in the present CI. This will essentially prevent any unnecessary distortion on the major vertical and radial dipoles for generating N1 response. To fully integrate into a closed-loop CI system, it would also be necessary to record and analyze the AEP automatically and in real-time. At present, the AEP obtained is an average outcome of many trials. Single trial technique may have to be explored in obtaining the response.

One limitation of using the AEP is that different subject populations can have markedly different morphologies and latencies. N1 is not fully developed until around age 13 in NH children. A full understanding on the effects of age and developmental state on the AEP is necessary. In addition, we have shown the AEP is responding to the difference in pitch percepts across two ears and independent of the mode of stimulation (acoustic vs. electric). Theoretically, the AEP should be responding in the same manner with bilateral CI users. Currently, we are working towards verification.

5. ACKNOWLEDGEMENT

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