Can the Acoustic Change Complex Be Recorded in an Individual with a Cochlear Implant? Separating Neural Responses from Cochlear Implant Artifact

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Abstract

The purpose of this case study was to determine whether the P1-N1-P2 acoustic change complex (ACC) could be recorded in an individual with a cochlear implant. In a cochlear implant recipient, stimulus-related artifact from the implant can overlap the evoked potential of interest, making it difficult to determine whether the recorded response is neural or a simple reflection of the artifact. This is an even greater technical challenge for the ACC because stimuli having relatively long durations are used. The subject was a 24-year-old with a diagnosis of auditory neuropathy/auditory dys-synchrony and used a MED-EL Tempo+ cochlear implant in her left ear. The ACC was recorded to synthetic vowels containing a change of F2 at midpoint ranging from 0 (no change) to 1200 Hz (perceived as /ui/). The stimuli were presented randomly at 75 dB SPL via a loudspeaker. In one condition the subject ignored the stimuli and watched a captioned video. In the other, the subject pressed one button on a response pad if she perceived an acoustic change at stimulus midpoint and another if she did not. Cortical auditory evoked potentials were recorded from 32 scalp electrodes. Results indicated that the ACC was present and could be teased apart from the cochlear implant stimulus artifact. ACC thresholds showed good agreement with behavioral discrimination performance, and therefore, results are positive for the potential clinical application of the ACC technique to individuals with cochlear implants.

Key Words: Acoustic change complex, cochlear implant, cortical auditory evoked potential, implant artifact, speech

Abbreviations: ACC = acoustic change complex; F2 = second formant frequency; ICA = independent components analysis; PCA = principal components analysis

Sumario

El propósito de este estudio de caso fue determinar si el complejo de cambio acústico (ACC) P1-N2-P2 podía ser registrado en un individuo con un implante coclear. En un receptor de un implante coclear, los artefactos del implante relacionados con el estímulo se traslapan el potencial evocado de interés, haciendo difícil la determinación de si la respuesta registrada es neural o un simple reflejo del artefacto. Esto es un reto técnico aún más grande para los ACC porque se usan estímulos de relativa larga duración. El sujeto tenía 24 años con un diagnóstico de neuropatía/dis-sincronía auditiva, y utilizaba un implante coclear MED-EL Tempo+ en el oído izquierdo. El ACC se registró ante

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vocales sintéticas que contenían un cambio en el F2 a la mitad del rango entre 0 (sin cambio) a 1200 Hz (percibido como /ui/). El estímulo fue presentado al azar a 75 dB SPL por medio de parlantes. En una condición, el sujeto ignoró el estímulo y miró un video subtitulado. En la otra, el sujeto presionó un botón de respuesta si percibía un cambio acústico en el punto medio del estímulo y otro si no lo percibía. Se registraron los potenciales evocados auditivos corticales con 32 electrodos craneanos. Los resultados indicaron que el ACC estaba presente y podía ser separado de los artefactos del estímulo en el implante coclear. Los umbrales del ACC coincidieron con el desempeño en la discriminación conductual, y por lo tanto, los resultados son positivos para la aplicación clínica potencial de la técnica de ACC a individuos con implante coclear.

Cortical auditory evoked potentials (CAEPs) such as the P1-N1-P2 complex, the mismatch negativity (MMN), and P3 have been used to study cortical detection and discrimination of sound in populations with normal hearing as well as hearing loss (Rapin and Graziani, 1967; Rapin et al, 1970; Polen, 1984; Wall et al, 1991; Kraus et al, 1995; Oates et al, 2002; Tremblay et al, 2003). This paper will focus on the P1-N1-P2 complex obtained in response to formant frequency change within a vowel in an individual using a cochlear implant.

The auditory P1-N1-P2 complex is typically obtained in response to the onset of brief stimuli such as clicks, tones, or speech. When evoked by these short-duration stimuli, the CAEP is comprised of a positive-negative-positive complex (P1-N1-P2). In individuals with normal hearing, P1 occurs approximately 50 msec after stimulus onset; N1 occurs with a latency of approximately 100 msec; and then P2 occurs with a latency of approximately 180–200 msec. This P1-N1-P2 complex indexes sound encoding at the level of the auditory cortex (Hillyard and Kutas, 1983). The complex is sensitive to the physical parameters of sound stimuli, such as intensity, frequency, duration, and timing (for review, see Picton, 1990; Hyde, 1997).

The P1-N1-P2 complex is not solely an onset response. It can also be elicited in response to stimulus offset (Hillyard and Picton, 1978). More importantly, it can be elicited by changes within a sound stimulus, such as intensity or frequency modulations of a sustained tone (Clynes, 1969; Spoor et al, 1969; Jerger and Jerger, 1970; Yingling and Nethercut, 1983; Näätänen and Picton, 1987), or in response to acoustic changes within more complex sounds such as speech (Kaukoranta et al, 1987; Ostroff et al, 1998; Martin and Boothroyd, 1999, 2000; Tremblay et al, 2003). The P1-N1-P2 complex has been obtained to acoustic changes of spectrum, amplitude, and periodicity in consonant-vowel stimuli (Kaukoranta et al, 1987; Ostroff et al, 1998), and amplitude and formant frequency changes in an ongoing vowel (Martin and Boothroyd, 2000). When obtained in response to acoustic change within a sound, the evoked P1-N1-P2 response is called the "acoustic change complex" (ACC) (Martin and Boothroyd, 1999). There is growing interest in the potential clinical utility of the ACC for assessing the neural detection and discrimination of speech in individuals with impaired speech perception, because the ACC shows reasonable agreement with behavioral psychophysical discrimination performance (Ostroff, 1999; Martin and Boothroyd, 2000) and can be reliably recorded in individuals (Tremblay et al, 2003; Martin and Boothroyd, 1999). The ACC does not index behavioral discrimination per se; rather, it provides an

index that the auditory cortex has encoded an acoustic change within a sound (for review, see Hillyard and Picton, 1978; Näätänen and Picton, 1987; Hyde, 1997; Picton, Alain, et al, 2000). The ACC therefore provides an index of discrimination capacity (Martin and Boothroyd, 1999, 2000), because detection of an acoustic change is a prerequisite for the potential behavioral discrimination of the change.

There are important technical considerations when recording CAEPs such as P1-N1-P2 from listeners with cochlear implants. The cochlear implant itself produces a stimulus-related artifact that occurs at sound onset and continues until sound offset (Shallop, 1993). The stimulus-related artifact is caused, to a large extent, by radio frequency transmission of the signal from the implant transmitter to the receiver, although other parts of the implant also contribute to the artifact. This artifact is picked up by the scalp electrodes used to record the CAEPs. When the artifact overlaps the neural response of interest, waveform interpretation becomes more difficult. The artifact is particularly problematic when recording the P1-N1-P2 complex compared to some of the other CAEPs because this response complex is relatively short in latency. Some researchers have opted to use stimuli having very short durations, such as clicks or tone pips, so that stimulus offset occurs prior to the neural response of interest (e.g., Ponton et al, 1996). When longer duration stimuli are used, the implant artifact can potentially overlap the neural response of interest.

As a result of this overlap, it is not clear whether the ACC can be obtained from listeners using cochlear implants. In order to separate the neural response to stimulus onset from stimulus change, most ACC studies have used relatively long-duration stimuli containing an acoustic change at midpoint. In a cochlear-implanted listener, the resulting artifact in response to such a long-duration sound will overlap with the resulting neural response. It has yet to be determined whether the artifact and neural responses can be successfully teased apart. Several studies have examined the P1 and/or the P1-N1-P2 complex in individuals with cochlear implants (e.g., Ponton et al, 1996; Eggermont et al, 1997; Firszt, Chambers, Kraus, et al, 2002; Maurer et al, 2002). These studies all used short-duration stimuli and direct stimulation of the implant processor. Further, these studies examined onset responses, not the response to acoustic change within a stimulus, which potentially represents a more difficult technical problem. Whether or not implant artifact is reported, it can potentially contaminate all CAEP recordings, not just the ACC. However, because of the long-duration stimuli used for the ACC, these recordings are more challenging.

Several approaches have been used over the years to remove artifact from auditory evoked potential recordings, and these are relevant to the current study. One technique that has been used for auditory brainstem response recordings in order to reduce the stimulus-related artifact is to alternate the polarity of the stimulus. The stimulus-related electromagnetic artifact from the earphone associated with each polarity is effectively canceled out during averaging of the rarefaction and condensation stimuli (Hall, 1992). Another approach has been to move the reference electrode away from the cochlear implant, often to the contralateral mastoid. Similarly, the reference electrode can be placed on the zero isopotential field of the artifact, so that the contribution of the artifact to the recording is minimized. These approaches can also be accomplished post hoc by re-referencing the waveforms. This approach has been used previously for recording CAEPs in implant recipients (e.g., Kelly et al, 2005; Sharma et al, 2002, 2005). Filtering is often used to remove, or filter out, unwanted signals from EEG recordings. For CAEPs, commonly used band-pass filter settings are approximately 1 to 30 Hz because the spectrum of the response of interest is low frequency (<30 Hz) (Hall, 1992; Hyde, 1997).

Another type of approach to the removal of eyeblink artifact is principal components analysis (PCA), which is a way of linearly separating the averaged waveform data into a small number of independent components (waveforms) that are orthongonal. Principal components are weighted in terms of their contribution to data. This procedure, however, can result in a lack of agreement between possible physiologic components and the resultant PCA components, because of the requirement for orthongonicity. Noise in the data also contributes to this problem (Wood and McCarthy, 1984; Achim and Marcantoni, 1997; Picton, Bentin, et al, 2000).

Independent components analysis (ICA) generates these components using stricter criteria for independence. As a result, different physiologic processes are more likely to result in independent components (Makeig et al, 1997; Neuroscan 4.3 manual). Further, spatially overlapping sources affect PCA more than ICA (Richards, 2004).

Several different spatial cancellation techniques have been used to remove artifact from EEG recordings, such as eyeblink artifact (Semlitsch et al, 1986; Berg and Scherg, 1991; Picton, van Roon, et al, 2000). These techniques share the principles that the artifact is largest near the source and that the contribution of the artifact to the recorded response lessens as the recording electrode is placed farther from the source. Mathematical techniques, such as regression, are used to model the artifact and its contribution at each electrode site. Then the artifact is mathematically eliminated from the data. The mathematical technique of singular value decomposition (SVD) has been added to this approach more recently. SVD divides an EEG epoch into linearly independent components, which are expressed as waveforms, along with factors that indicate the contribution of each component to the original EEG epoch. Using SVD, a new EEG sweep can be reconstructed that eliminates (in theory) the contribution of the artifact (Harner, 1990; Lagerlund et al, 1997).

The purpose of the present study was to determine whether the ACC could be recorded in an individual with a cochlear implant, and whether the cochlear implant artifact could be removed from the data using the techniques described above. This study was designed to examine the potential feasibility of the ACC technique for application to individuals with cochlear implants.

METHOD

Subject

The subject was a 24-year-old female with a diagnosis of auditory neuropathy/auditory dys-synchrony. This diagnosis was supported by a clinical history of inconsistent pure-tone thresholds that gradually worsened over the years, very poor speech recognition even in quiet listening situations, present transient-evoked otoacoustic emissions for several frequency bands, and a present cochlear microphonic but absent auditory nerve and brainstem components upon auditory brainstem response testing. She has used a MED-EL Tempo+ cochlear implant in her left ear since the age of 22 years. She was tested using her preferred map, which utilizes the CIS strategy set at program 2, volume "X."

Stimuli

The stimuli for the study were created using DaDisp software. The basic stimulus was the sound /u/, which was 400 msec long. The amplitude of F1 was set to 10 and 20 dB above the amplitudes of F2 and F3, respectively. This decrease in amplitude with increasing frequency was intended to simulate the natural amplitude relationship between the formants that occurs in natural speech.

Small shifts in the second formant frequency were created in order to produce nine stimuli having a different F2 center frequency. The standard stimulus /u/ was then concatenated with two cycles of overlap (approximately 14 msec) with each of the stimuli containing higher F2 values to create eight stimuli that contain a spectral change at the temporal midpoint. The overlap was intended to produce a smooth transition and avoid spectral splatter at the point of concatenation. The two concatenated portions of the stimulus were equalized for root mean squared intensity. The standard stimulus was also concatenated with itself to produce a ninth control stimulus with no spectral change. Total duration of each stimulus was 786 msec. The frequencies of the formants for each stimulus are shown in Table 1. It should be noted that the frequency of F2 changes at stimulus midpoint for all but the first stimulus (the control).

The synthetic vowel stimuli were 16-bit, binary, signed integer files with a sampling rate of 22,050 Hz. The control stimulus was perceived by naïve listeners as /u/, and the stimulus containing the largest F2 change was perceived by naïve listeners as /ui/. These stimuli differ in F2 transition at stimulus midpoint and therefore contain a contrast in vowel place of articulation.

Table 1. Formant Frequencies (Hz) for Each of the Nine Stimuli

					STIMULUS				
FORMANT	1	2	3	4	5	6	7	8	9
F3	3000	3000	3000	3000	3000	3000	3000	3000	3000
F2	1050;1050	1050;1059	1050;1069	1050;1088	1050;1125	1050;1200	1050;1350	1050;1650	1050;2250
F1	300	300	300	300	300	300	300	300	300
F0	150	150	150	150	150	150	150	150	150

Note: For F2, the first number shows the value for the first half of the stimulus, and the second value indicates the frequency in the second half of the stimulus.

Electrophysiologic Testing

The subject was seated in a shielded, sound-attenuated booth. A Neuroscan system was used to present the stimuli and to collect behavioral and electrophysiologic responses. Stimuli were presented at 75 dB SPL via a loudspeaker set at 0 degrees azimuth. The onset-to-onset interstimulus interval was two seconds. Stimuli were presented in two conditions. In the ignore condition, the listener was instructed to ignore the stimuli and to watch a captioned video of her choice (sound turned off). In the attend condition, the subject was instructed to attend to the stimuli and to press one button on a response pad if no acoustic change at stimulus midpoint was perceived and to press another button if an acoustic change was perceived. All nine stimuli were presented randomly. There were five runs of 540 stimuli for each listening condition (attend and ignore) so that each stimulus was presented in each condition a total of 300 times. The conditions were counterbalanced. Breaks were provided between each run.

The continuous EEG was recorded from 32 channels. The reference electrode was placed on the tip of the nose, while the ground electrode was located between electrodes Fz and FCz. Eye blink activity was monitored using electrodes above and below the right eye. The continuous EEG was amplified (1000x), digitized (1000 Hz), and filtered (.15 to 100 Hz). Post hoc analyses included application of an eyeblink reduction algorithm, epoching (-100 to 1600 msec), baseline correction on the entire sweep, filtering (1 to 30 Hz, 12 dB/octave), and averaging by stimulus and condition.

The ACC was measured at electrode site Cz, which was the electrode site where largest amplitude responses were obtained. Measures included the amplitude of the N1-P2 portion of the ACC as well as peak latencies of N1 and P2 ACC components. P1 was not measured because it is typically small in adults, and therefore, ACC thresholds are determined by N1-P2. In addition to the electrophysiologic measures, behavioral percent correct discrimination performance was computed.

RESULTS

Basic Results

The averaged waveforms obtained from this subject in response to each stimulus and each listening condition are displayed in Figure 1. Data are shown from electrode site Cz (the vertex). The ACC is highlighted by the inset boxes. When the listener ignored the stimuli, the ACC was obtained in response to F2 changes of 1200 Hz through 300 Hz; response presence was questionable in response to the 150 Hz F2 change and was absent in responses to smaller increments in F2. When the listener attended to the stimuli, however, the ACC was obtained in response to F2 changes of 1200 through 150 Hz. Latencies are longer in the attend condition, and amplitudes are quite a bit larger compared to the ignore condition (see Table 2). This increase in amplitude with attention suggests that the ACC obtained in this study is largely neural in origin, and not simply a manifestation of the stimulus artifact.

Behavioral change detection data are shown in Table 3. As can be seen, behavioral performance clearly exceeds the noise floor in the 300 through 1200 Hz F2 change conditions, which was in good agreement with the ACC results from the ignore condition. Further, behavioral results begins to exceed the noise floor in the 150 Hz F2 change condition, and this condition matches the ACC threshold from the attend condition.

Evoked potentials to second formant frequency change in a speech sound recorded from an adult with auditory neuropathy using a cochlear implant (Cz)
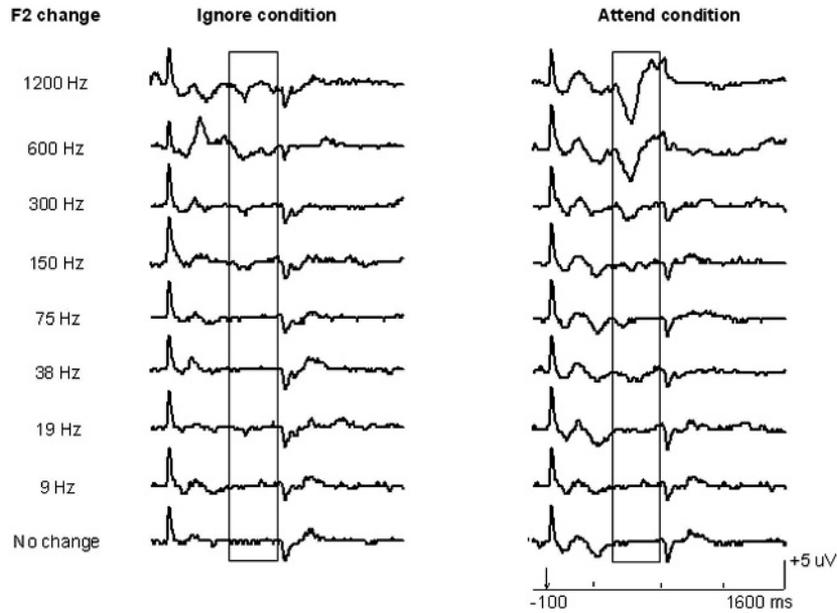
Figure 1. Averaged waveforms in the ignore and attend conditions are displayed as a function of F2 change at stimulus midpoint. The ACC is shown in the inset boxes.

Stimulus Artifact

Figure 2 shows an example of the stimulus artifact at electrode site T7 (a left temporal electrode site adjacent to the implant) where it is highest in amplitude. As can be seen in this figure, the artifact is large (321 µV) and greatly exceeds the amplitude of the ACC. The artifact presents in the averaged waveforms as essentially a square wave that lasts for the duration of the stimulus. There are peaks in the wave that

Table 2. ACC N1-P2 Amplitudes and N1 and P2 Peak Latencies for Each Condition

Ignore Condition			
Frequency Change (Hz)	ACC Amplitude (µV)	N1 Latency (ms)	P2 Latency (ms)
0	NR	NR	NR
9	NR	NR	NR
18	NR	NR	NR
37	NR	NR	NR
75	NR	NR	NR
150	NR?	NR?	NR?
300	2.46	542	655
600	2.27	525	642
1200	3.97	535	628
Attend Condition			
Frequency Change (Hz)	ACC Amplitude (µV)	N1 Latency (ms)	P2 Latency (ms)
0	NR	NR	NR
9	NR	NR	NR
18	NR	NR	NR
37	NR	NR	NR
75	NR	NR	NR
150	1.7	559	727
300	10	554	655
600	8.6	564	655
1200	12	564	654

Table 3. Behavioral Discrimination Performance as a Function of F2 Change

Frequency Change (Hz)	Percent Correct	Standard Deviation
0	13	23.9
9	12	10.2
18	13	12.2
37	16	13.1
75	13	16.8
150	27	19.0
300	44	8.4
600	90	7.8
1200	92	6.9

occur at stimulus onset, stimulus offset, and more importantly also at the onset of the acoustic change at stimulus midpoint. This is a potentially problematic finding for recording the ACC in listeners with cochlear implants, because of the difficulty determining whether the response obtained is neural or whether it is an artifact.

Approaches to Separating Stimulus Artifact from the ACC

Attention

As described above and shown in Figure 1, the amplitude of the ACC increases when the subject attended to the stimuli presented to her. This indicates that the ACC obtained in this study was largely neural in origin and not simply a manifestation of the stimulus artifact.

Polarity

Figure 3 shows the averaged responses obtained to the 1200 Hz F2 change at stimulus midpoint in the attend condition at electrode sites Cz, C3, C4, T8, and T7 (the vertex, left and right lateral central, and right and left temporal electrode sites, respectively). The stimulus artifact is extensive in this subject and is present at all electrode sites. The scalp distribution shown in this figure provides evidence that a neural component is present. At electrode site C3 (for example), the *stimulus artifact inverts* in polarity relative to the other electrode sites shown. *The ACC, in contrast, does not show this inversion at C3* (as would be expected based on the known topography of these components), and therefore the generators of the ACC are neural in origin.

Re-referencing

The response to the 1200 Hz F2 change in the attend condition was re-referenced to M2, the mastoid electrode site contralateral to the implant in order to determine whether this approach might minimize the
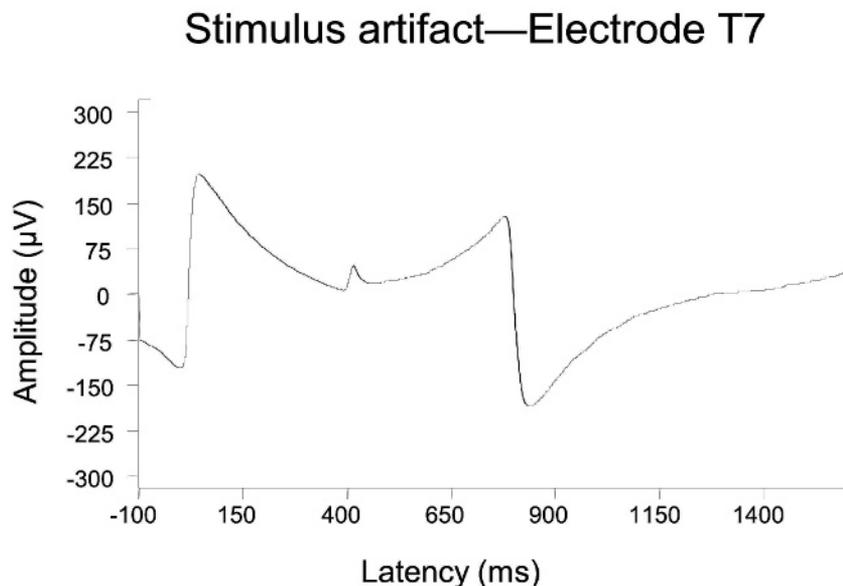

Figure 2. The stimulus artifact at electrode site T7 is displayed in the attend condition in response to the 1200 Hz acoustic change.
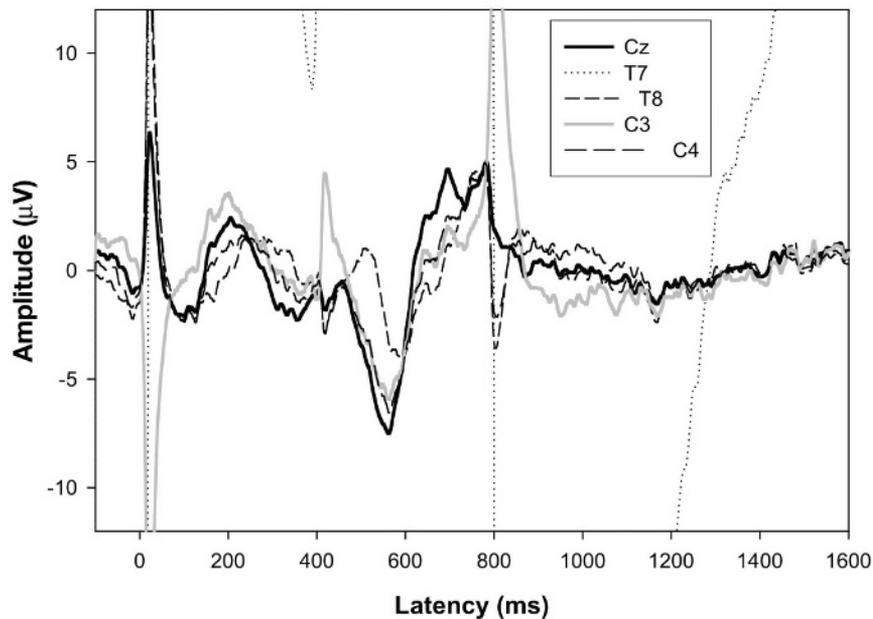
Figure 3. The ACC is shown in the attend condition in response to the 1200 Hz acoustic change at electrode sites Cz, T7, T8, C3, and C4. Note that the polarity of the implant artifact is reversed prior to the ACC at electrode site C3 relative to the other electrode sites, yet the polarity of the N1-P2 component of the ACC is not.

contribution of stimulus artifact to the evoked potentials. Figure 4 (top) shows the results. As can be seen, the artifact is reduced in amplitude at electrode sites on the right side of the head, is *increased* at electrode site C3, and is not substantially reduced in amplitude at Cz. The artifact is inverted in polarity at electrode site Cz, relative to the nose reference condition, and the stimulus offset artifact is increased. It has been suggested in the literature that referencing responses to a frontal electrode might reduce the implant artifact because a frontal electrode is likely to be on the zero isopotential line for the artifact itself (Sharma et al, 2005). Figure 4 (bottom) demonstrates that the artifact is not eliminated when the response is re-referenced to a frontal site (data were re-referenced to electrode site F3 in this example). The amplitude of the artifact preceding the ACC is reduced at electrode site C3 but is increased at Cz, C4, and T8. Moreover, the amplitude of the ACC is substantially reduced relative to the other referencing conditions.

In addition to re-referencing of the data, attempts to cancel the implant artifact by alternating the polarity of the stimulus were unsuccessful (data not shown).

Filtering

Three different filter settings were compared in order to determine whether the stimulus artifact could be reduced. The bandpass settings were 1–50 Hz, 1–30 Hz, and 10–100 Hz. As can be seen in Figure 5, the filter settings contribute somewhat to the amplitude and morphology of the artifact. Shown are averaged waveforms from electrode site Cz in the 1200 Hz F2 change attend condition. The amplitude of the artifact is largest when data were filtered from 1–30 Hz. Setting the low-pass filter setting to 50 Hz reduces the amplitude of the artifact, but does not eliminate it (setting it to 100 Hz did not further reduce the artifact). Raising the high-pass filter to 10 Hz similarly reduces the amplitude of the artifact but has the drawback of nearly eliminating the ACC. It may be that ringing of the low-pass filter contributes somewhat to the peaks riding on the square wave portion of the artifact.[1] The ACC is largest in amplitude when bandpass filtered from 1–50 (and also 1–100 Hz) and smallest when filtered from 10–100 Hz as might be expected (Hyde, 1997).
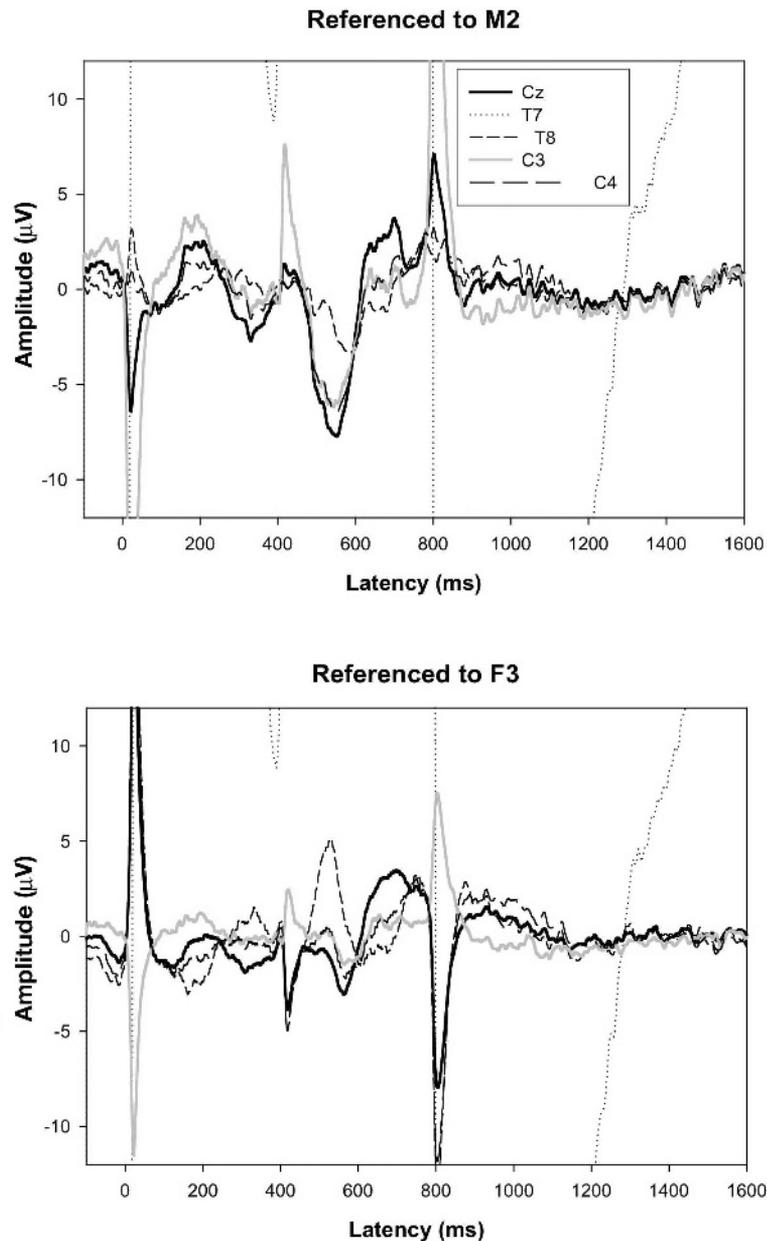
Figure 4. The data from Figure 3 are shown after being re-referenced to electrode site M2 (top) and F3 (bottom).

Principal Components and Independent Components Analyses

Principal components and independent components analyses (PCA and ICA, respectively), as implemented by Neuroscan Scan 4.3, were conducted on the averaged waveform data from the 1200 Hz F2 change in the attend condition.

The results of PCA are shown in Figure 6. The implant artifact can be clearly identified in the first and second loadings (top two tracings) and is the dominant response as reflected by the mean global field power (bottom tracing). Unfortunately, even though neural components of the ACC appear to be present in the third, fourth, fifth, sixth, perhaps in the seventh, ninth, and tenth loadings as well, the signal-to-noise ratio of these responses is small (≤ 1), and there is no factor that does not reflect contributions from the stimulus artifact.

The results of ICA analysis are shown in Figure 7. Once again, the large-amplitude implant artifact dominates the responses and could not completely be factored out.[2]
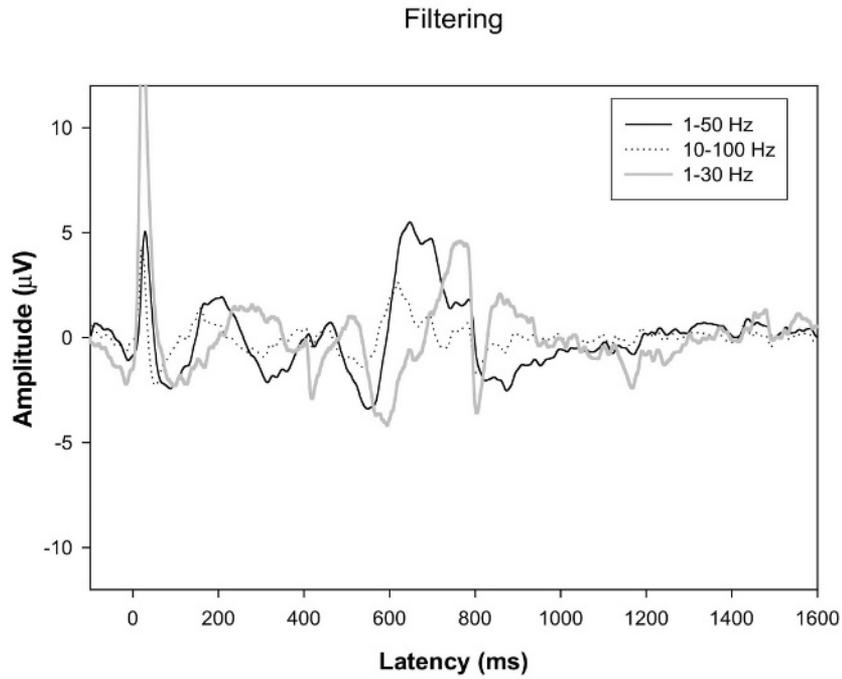
Filtering

Figure 5. The effects of post hoc filtering of the EEG from 1–50, 1–30, and 10–100 Hz on the ACC and implant artifact are shown at electrode site Cz.
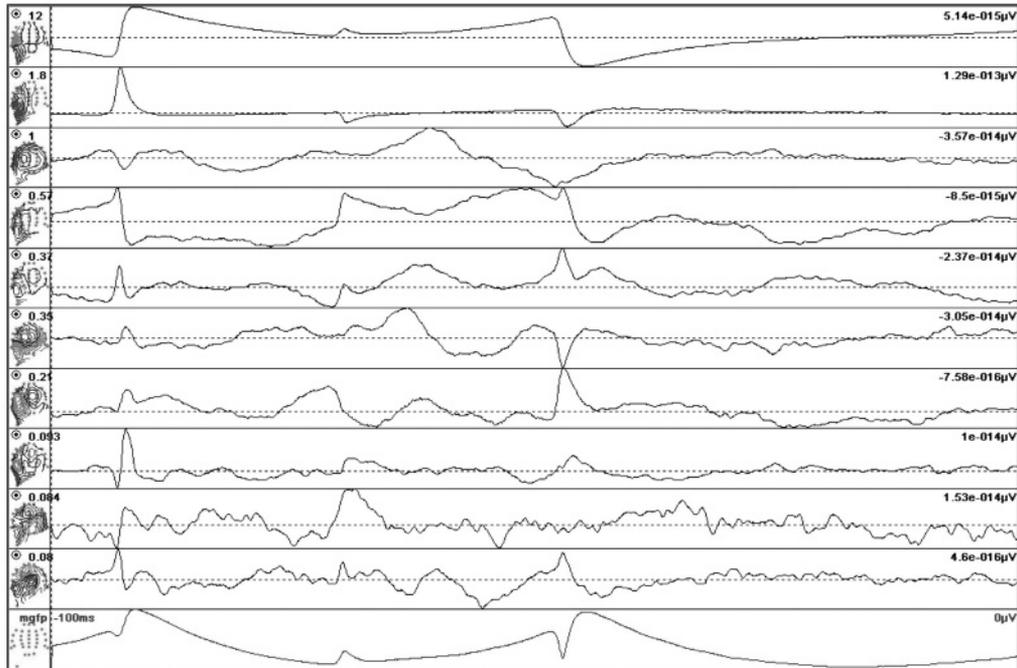
PCA

Figure 6. The results of principal components analysis are shown along with the mean global field power (bottom). The principal components are displayed in each row as a function of factor loading.

Spatial Cancellation Techniques

Two spatial cancellation techniques were used in an attempt to correct the EEG for the implant artifact. In the first, the implant artifact was treated in the same manner as an eyeblink artifact (Neuroscan Edit 4.3 Manual, pp. 216–217; Semlitsch et al, 1986). The EEG data was scanned to identify the maximum amplitude voltage of the implant artifact. An average of the artifact response was constructed using electrode site T7, when the maximum potential in this channel exceeded 10% of this value. From this average, transmission coefficients were computed by estimating the covariance of the averaged potentials at T7 with the EEG channels according to the following equation, in which "b" is the transmission coefficient, and "cov" and "var" the covariance and variance, respectively:

$$b = cov(T7,EEG)/var(T7) \qquad (1)$$

The transmission coefficients were computed separately for all EEG channels. Finally, the artifact is subtracted from the EEG channels on a sweep-by-sweep and point-by-point basis:

$$\text{Corrected EEG} = \text{original EEG} - b*T7 \qquad (2)$$

Results are shown in Figure 8. As can be seen, the implant artifact has not been completely eliminated by this procedure. It is larger compared to the original data (see Figure 2). Further, the polarity of the peak occurring at stimulus offset is inverted.

The second method used spatial filtering combined with spatial singular value decomposition to remove the volume-conducted implant artifact (for details, see Neuroscan Edit 4.3 manual, pp. 255–258), again using the recording at electrode site T7 to model the artifact. Results are shown in Figure 9 at electrode site Cz (dark line). Results are overlaid with the results of the first technique also taken from electrode site
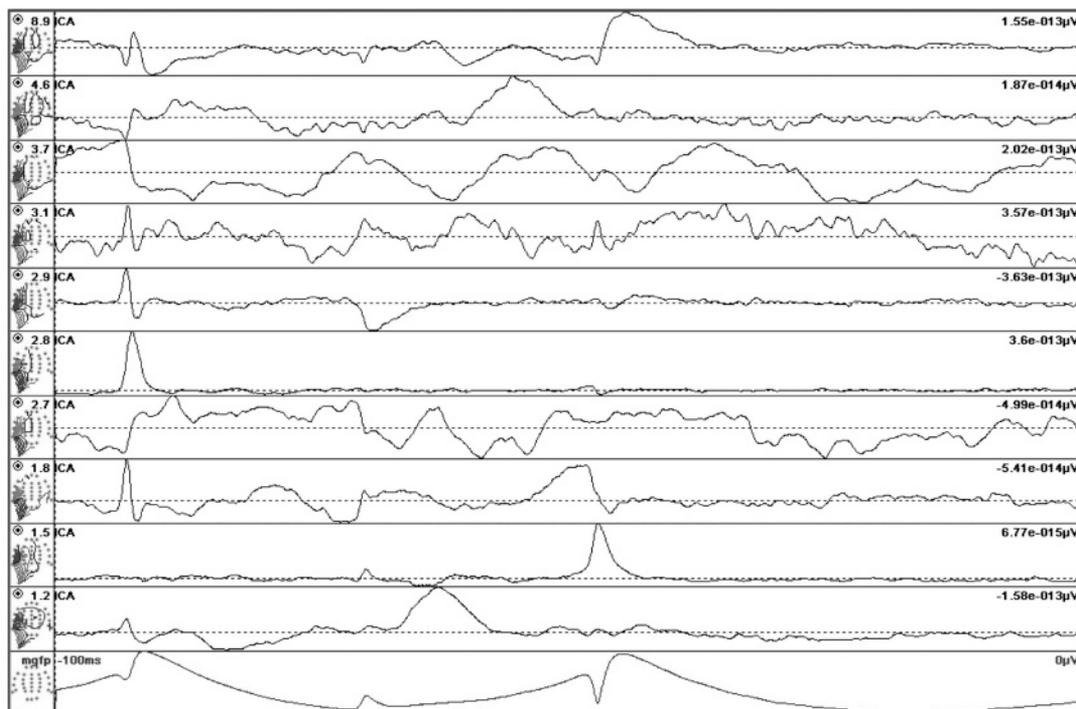
ICA

Figure 7. The results of independent components analysis are displayed.
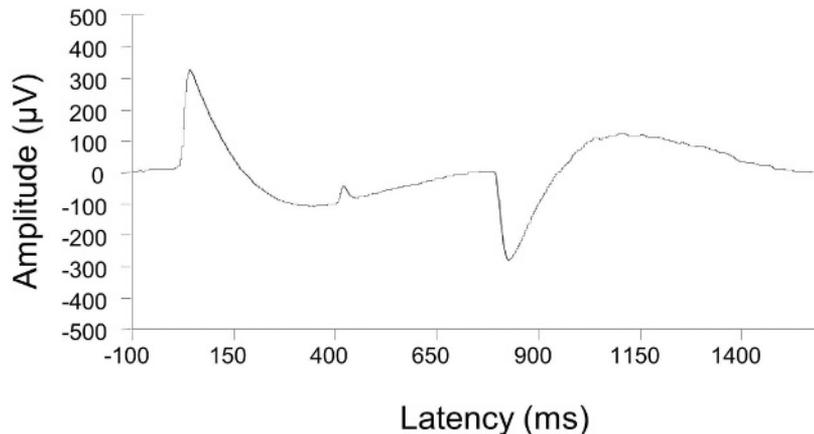
Artifact reduction algorithm-T7

Figure 8. This figure shows the implant artifact at electrode site T7 after application of an artifact reduction algorithm.

Cz (gray line). The implant artifact has not been completely eliminated by these procedures.

DISCUSSION

This paper shows that the ACC can be recorded in an individual using a MED-EL cochlear implant. The ACC was robust in response to large changes of second formant frequency within a synthetic vowel, and was small or absent in response to smaller changes of second formant frequency. Electrophysiologic ACC change detection threshold showed reasonable agreement with behavioral change detection threshold when the listener ignored the stimuli presented, and the relationship between ACC and behavioral thresholds was even better when the subject attended to the stimuli. These findings are positive for the potential clinical application of the ACC to individuals with cochlear implants.

While the ACC response was overlapped by stimulus-related cochlear implant artifact, it was possible to tease apart the neural response from the implant artifact. Two procedures that were shown to be useful for the identification of the neural response were these: (1) the neural response increases in amplitude with attention whereas the implant artifact does not; and (2) there are electrode sites where the implant artifact inverts in polarity but the neural response does not.

Unfortunately, no technique assessed in this paper successfully eliminated or cancelled the artifact. Alternating the polarity of the stimulus did not cancel the artifact, suggesting that the artifact may not be constant. Re-referencing of the data neither cancelled nor substantially reduced the artifact at all electrode sites. Furthermore, re-referencing to a frontal electrode site, as has been suggested previously by Sharma and colleagues (2005), actually diminished rather than enhanced the ability to measure the ACC response. It was not entirely clear from the scalp distribution of the ACC in this study precisely where the zero isopotential point for the implant artifact was located, because the scalp distribution for the artifact was so extensive in this subject. This finding suggests that implant artifact may be problematic in some subjects for the measurement of nearly all auditory evoked potentials, and not just the ACC. Not all cochlear implant recipients, however, show such a widespread scalp distribution of the artifact (Friesen and Tremblay, 2006).

As would be expected, filtering did not eliminate the artifact, and setting the low-pass filter to 30 Hz increased the artifact. The cochlear implant artifact is largely an effect of the radio-frequency transmission of the
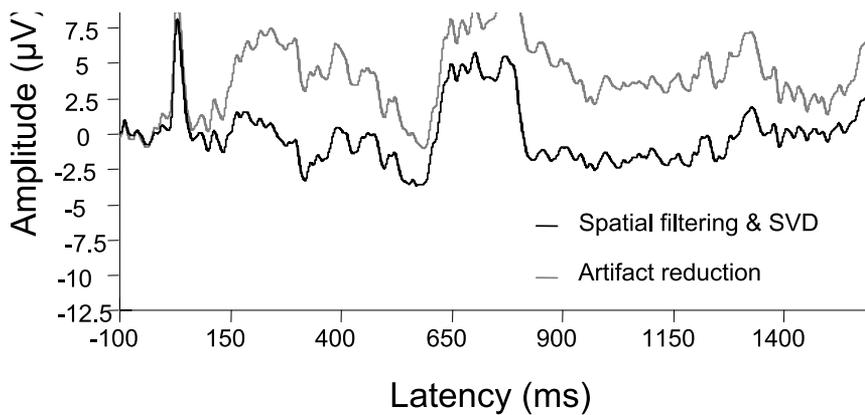
Figure 9. The results of two different implant artifact reduction algorithms are displayed at electrode site Cz.

signal from the implant transmitter to the receiver, and this signal is high in frequency. Some researchers have used a radio-frequency filter prior to the EEG amplifier (Kelly et al, 2005) for recording evoked potentials in implanted patients. While this approach has been successful, it is not without limitations. These filters typically have a steep slope, and even though the spectrum of the cortical potentials has a much lower frequency composition, abrupt filtering can alter response morphology. Further, when commercially available, these filters often cannot handle 32 or more channels of data, and the settings required may differ across implant manufacturers. These data suggest that, in order to reduce the implant artifact, the low-pass filter setting should be set to at least 30 Hz and preferably higher. To reduce possible ringing, the use of a gentle filter slope (6 dB/octave) might be helpful.

Another approach has been to send the sound stimulus directly to the implant processor, bypassing the microphone (e.g., Firszt, Chambers, Kraus, 2002; Firszt, Chambers, Kraus, et al, 2002). The disadvantage of this approach is that in the real world, sound enters the cochlear implant system through the microphone, and therefore, studies presenting sound via loudspeaker have greater ecological validity. For certain research studies, however, direct stimulation minimizes the number of

variables that speech introduces. Therefore, each approach has strengths and weaknesses.

Neither PCA nor ICA successfully eliminated the implant artifact, in part because the large amplitude of the implant artifact dominated the resulting factor loadings, particularly those with high signal-to-noise ratios. Finally, two attempts to reduce or cancel the artifact by handling it as one might handle eyeblink artifact were unsuccessful.

It is likely that a statistical algorithm can be developed to factor out the stimulus artifact from the neural response, and future research is needed to compute a successful algorithm. This algorithm may need to be modified as a function of implant manufacturer, speech processing strategy, and perhaps factors such as the number of channels, and the number and placement of the electrode (Loizou, 1998). An algorithm to cancel the contribution of the implant artifact at each electrode site would be clinically useful, and until such an algorithm is developed, widespread clinical application of cortical auditory evoked potentials such as the ACC should proceed cautiously. It will be important to record from a sufficient number of electrode sites so that any algorithm developed could later be used to spatially cancel the artifact. Further, the ACC should be recorded with relatively open filter settings so that most of the filtering occurs post hoc. In the mean time, auditory evoked potential studies in listeners with cochlear implants

should carefully document the type of device tested, how the neural response is identified, and any methods that are used to tease apart the artifact from the neural response.

In spite of the implant artifact, this case study clearly demonstrates that the ACC could be recorded and identified in this cochlear implant recipient. The ACC thresholds showed good agreement with behavioral discrimination performance, and therefore, results are positive for the potential application of the ACC technique for the evaluation of speech discrimination capacity in individuals with cochlear implants.

NOTES

1. It should be noted that a pilot study was conducted in which a silver-silver chloride electrode cap was used. This permitted the data to be recorded using a relatively open filter setting of DC to 200 Hz. This procedure neither eliminated the square wave portion of the implant artifact nor the peaks occurring at stimulus onset, stimulus change, and stimulus offset.
2. Following acceptance of this manuscript, success reducing CI artifact using ICA and re-referencing was reported (Gilley et al, 2006). As can be seen in the current study, however, these approaches are not always fully successful.

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