Psychophysiology, 45 (2008), 20–24. Blackwell Publishing Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2007.00610.x

BRIEF REPORT

Source localization of auditory evoked potentials after cochlear implantation

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Abstract

Little is known about how the auditory cortex adapts to artificial input as provided by a cochlear implant (CI). We report the case of a 71-year-old profoundly deaf man, who has successfully used a unilateral CI for 4 years. Independent component analysis (ICA) of 61-channel EEG recordings could separate CI-related artifacts from auditory-evoked potentials (AEPs), even though it was the perfectly time-locked CI stimulation that caused the AEPs. AEP dipole source localization revealed contralaterally larger amplitudes in the P1–N1 range, similar to normal hearing individuals. In contrast to normal hearing individuals, the man with the CI showed a 20-ms shorter N1 latency ipsilaterally. We conclude that ICA allows the detailed study of AEPs in CI users.

Descriptors: Auditory evoked potential, Cochlear implant, Independent component analysis, Dipole source analysis, N1

Cochlear implants (CI) are bionic devices that enable people suffering from a profound cochlear hearing loss to hear. CIs transform the acoustic signal into electric pulses that directly stimulate residual fibers of the auditory nerve. As a result, cortical auditory evoked potentials (AEP), which indicate the detection of any discrete change in the auditory environment (Hyde, 1997), may be generated. It has been suggested that AEPs provide valuable information about the adaptation and cortical reorganization of the auditory system in response to CI stimulation (Pantev, Dinnesen, Ross, Wollbrink, & Knief, 2006). Moreover, deafness may be characterized by a recruitment of auditory cortex areas by the visual modality (Finney, Fine, & Dobkins, 2001) and the success of the CI treatment may be related to the degree of cortical adaptation in response to deafness-induced plasticity (Doucet, Bergeron, Lassonde, Ferron, & Lepore, 2006). Therefore, AEPs may help to monitor the adaptation of the auditory system to restored auditory input as provided by CIs, and event-related potentials (ERPs) may be of predictive value with regard to the outcome of the CI treatment. However, the analysis of AEPs in CI users is hampered by the fact that CI devices create artifacts that corrupt the EEG signal.

Positron emission tomography (PET) studies have shown that cortical reorganization can be observed in postlingually deafened adults after CI implantation (Giraud, Truy, & Frackowiak, 2001). However, PET is not well suited for longitudinal research, and because of the static magnetic field, functional magnetic resonance imaging (fMRI) may not be feasible. In a seminal magnetoencephalogram (MEG) study, Pantev et al. (2006) recently reported the magnetic counterpart of the AEP N1 (N1m) in two CI users who were monitored for 2 years following implantation. This analysis was possible due to sophisticated RF shielding and usage of a specifically designed stimulus, and it revealed auditory responses contralateral to the CI device. MEG recordings from CI users are technically challenging and may be difficult to achieve in modern whole-head MEG systems. Therefore, it seems that EEG recordings are best suited for the routine study of auditory cortex function in CI users. However, few studies have reported AEPs from CI users (Kelly, Purdy, & Thorne, 2005), and none has reported success in providing the spatial information provided by high-density EEG recordings.

The onset of any CI stimulation evokes an electrical artifact and therefore inevitably corrupts the EEG signal. The CI artifact may largely be due to the radio frequency transmission of the signal to the receiver (Martin, 2007). The strength, morphology, and spatial distribution of the CI artifact may be different across CI users, because different CI devices may be placed at different locations and can be used with different stimulation modes. Probably even more problematic is the fact that this artifact is perfectly time-locked to the acoustic stimulus and can be orders of magnitude larger than the signal of interest (Gilley et al., 2006; Martin, 2007). Accordingly, averaging over trials—the usual approach of improving the signal-to-noise ratio (SNR) of

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ERPs—does not solve the problem. In a recent study, the CI artifact could be reduced and the AEP P1 could be recovered using independent component analysis (ICA; Gilley et al., 2006), although others were less successful (Martin, 2007). Here we demonstrate that ICA-based reduction of CI artifacts enables the detailed investigation of the spatial and temporal properties of cortical AEPs in CI users.

Methods

Participant

We report data from a 71-year-old male CI user, who had suffered from gradually deteriorating deafness since the age of 4. He had used a hearing aid in his left ear since the age of 35. A profound bilateral sensorineural hearing loss was diagnosed in 2001, with speech scores on standard clinical tests providing only 4% or less correct performance (IHR, UCL, CUNY sentences tests, with hearing aid on and lip reading). In December 2002, a Nucleus CI24R(CS) device was implanted in his left ear and an ESPrit 3G speech processor was fitted 6 weeks later. Speech scores then quickly improved and since then have remained at a constantly high level (e.g., CUNY scores: after 2 weeks 69%, 3 months 90%; 9 months 96%; 1 year 92%; 4 years 91%). By the time of the EEG recording, the subject could communicate well, even without lip reading, and reported being able to use the telephone. The study was approved by the local ethics committee.

Stimuli and Task

Free field stimuli were presented using two speakers (Quad L12) positioned at an azimuth of 45° in front of the subject. Otherwise, recording procedures were the same as described by Hine and Debener (2007). Stimuli were 1-kHz tones and white noise, 220 ms long with 10 ms rise and fall time, sampled at 44.1 kHz and presented at 70 dB SPL. We presented 399 repetitions of the four different conditions (tone left/right, noise left/right) in randomized order with an interstimulus interval between 1000 and 1400 ms, while the subject watched a silent movie.

EEG Recording

EEG data were recorded using a high-input impedance 68-channel amplifier system (Neuroscan, Compumedics, El Paso, TX) and a customized electrode cap that spans a substantially larger part of the head sphere than usual 10–20 montages (Easycap, Herrsching, Germany). The cap was fitted with 66 Ag/AgCl electrodes in an equidistant layout. Signals from 7 electrodes, located over the left hemisphere, could not be recorded due to the location of the CI device. Two electrodes were placed below the left and right eyes to monitor electrooculagraphic activity. Data were analog filtered (0.1–200 Hz) and recorded with a sampling rate of 1000 Hz using the nose tip as reference. Impedances were maintained below 20 kΩ prior to data acquisition.

Data Processing

EEG data were processed using EEGLAB (Delorme & Makeig, 2004) running under MATLAB (Mathworks, Natick, MA). Data were bandpass filtered (1–80 Hz) and down-sampled (250 Hz) to reduce computation time and epoched from 200 to 600 ms relative to stimulus onset. Epochs were automatically screened for unique, nonstereotyped artifacts using a probability function built into EEGLAB (Delorme, Sejnowski, & Makeig, 2007). Extended infomax ICA, as implemented in EEGLAB, was applied to the remaining concatenated single trials. Independent components representing common EEG artifacts such as eyeblinks or electrical heartbeat artifacts were visually identified as done previously (e.g., Debener, Makeig, Delorme, & Engel, 2005) and removed along with those components representing CI artifacts. The latter could be identified by screening the respective independent component ERPs, which were characterized by the CI pedestal and slopes 8 ms after the onset and offset of the acoustic stimulation. Back-projected single trials were again screened for residual artifacts and 1201 trials used for averaging.

Source Modeling

AEP source modeling was used to obtain information about the spatial quality of the artifact-corrected AEPs and to investigate auditory cortex asymmetries (Hine & Debener, 2007). AEPs were very similar across conditions and were therefore averaged and submitted to BESA, version 5.1.8 (Megis, Graefelfing, Germany). A standard four-shell head model with default parameters was used. Two symmetric equivalent regional current dipoles were seeded into superior temporal lobes (Talairach coordinates $[x, y, z] = \pm 49.5, -17, 9$) and used to model the AEP source waveforms (cf. Debener et al., 2007; Hine, Davis, & Debener, 2007; Hine & Debener, 2007). The adequacy of this location was evaluated by determining the Euclidean distance to a free, symmetric bilateral source model and comparing the results with normal hearing and unilateral hearing loss individuals that underwent an almost identical protocol (Hine & Debener, 2007; Hine et al., 2007).

Results

Inspection of the data revealed that acoustic stimulation produced an artifact that was evident in every single trial and visible in several EEG channels. The artifact morphology resembled a pedestal, with the onset and offset ramp starting approximately 8 ms after stimulus onset and offset, respectively. Figure 1 shows a butterfly plot of the AEPs before (a) and after (c) ICA artifact reduction, illustrating that the topographies of the uncorrected AEPs were dominated by the CI artifact. All independent components (ICs) identified as representing artifact are show in Figure 1b. Whereas some ICs reflected common artifacts such as eyeblinks (IC 1, 5) and electrical heartbeats (IC 9), ERPs of the other nine ICs were dominated by the CI artifact pedestal; that is, they showed their largest amplitude changes in the onset and/or offset ramp intervals. Back-projection of all but those 12 ICs revealed AEPs with small residual artifact activity (Figure 1c) and AEP components P1 (peak latency 60 ms) and N1 (112 ms) that were clearly distinguishable from residual noise. Note the topography of the P1 and N1 at peak latencies, both suggesting contralaterally larger amplitudes. The N1 peak topography is further illustrated in Figure 1d, suggesting a tangential dipolar map for the right side of the head, contralateral to the CI device. For ipsilateral stimulation, a negative potential was also evident at lateral temporal sites, which was not an interpolation artifact caused by the missing channels over the left hemisphere.[1] Figure 1e,f illustrates the improvement of data quality by ICA artifact reduction for electrode Cz. Here, ERP images represent

[1]This was tested by removing the homologous electrodes over the left hemisphere, which did not substantially change the N1 topography (not shown).

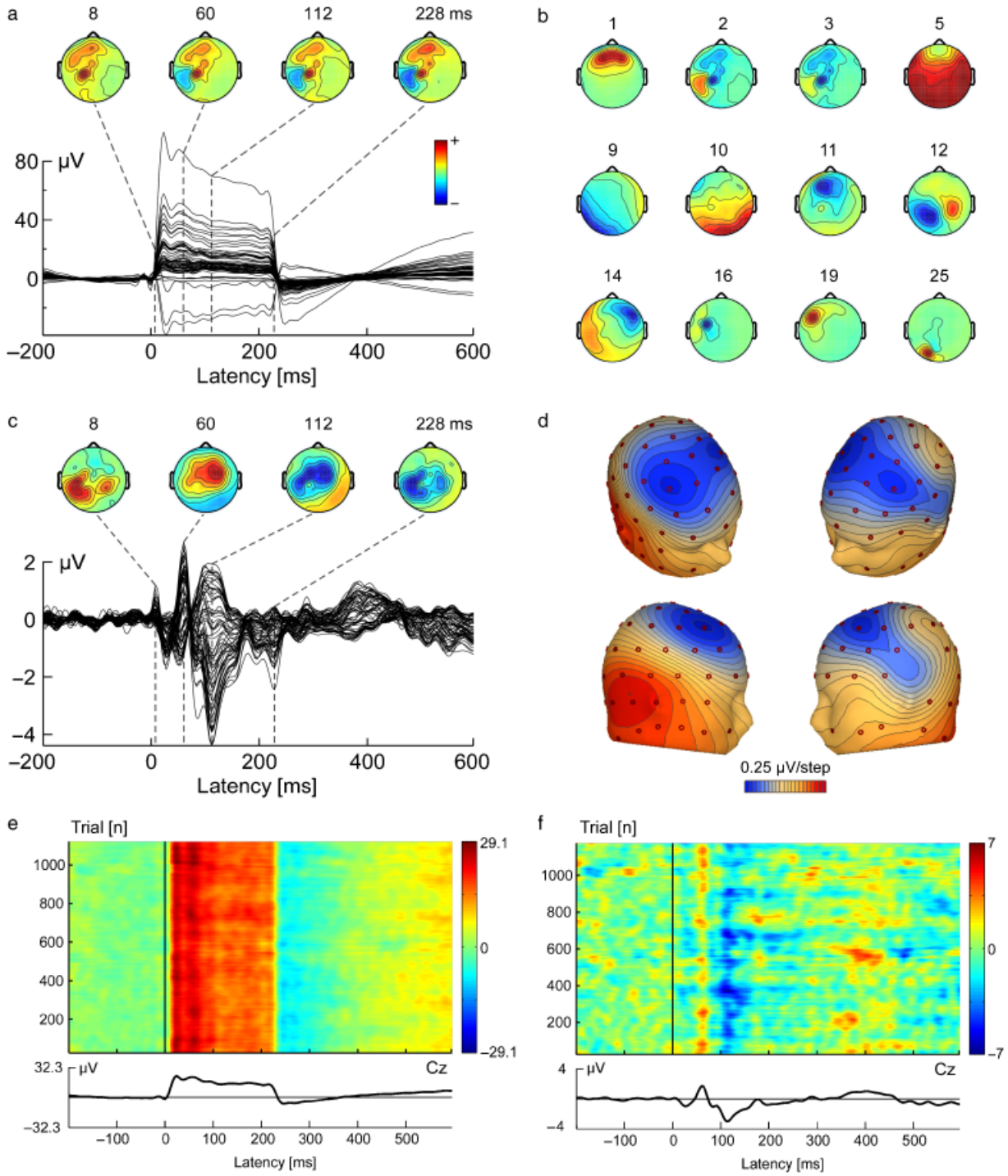

Figure 1. AEPs before (a) and after (c) ICA-based artifact reduction, together with voltage maps at selected artifact latencies and P1 and N1 peaks latencies, scaled to the absolute maximum. b: Independent component maps (inverse unmixing weights) identified as artifacts and removed by back-projection of all other components (arbitrary units). d: Three-dimensional voltage maps for the artifact-corrected AEPs at the N1 peak latency (112 ms). Note the location of missing channels at left temporal sites. e,f: ERP images illustrating single-trial EEG amplitudes color codes at electrode Cz, before (e) and after (f) ICA-based artifact reduction. Corresponding ERPs are plotted below the ERP images.

color-coded single-trial amplitudes. After artifact reduction, the P1–N1 AEP complex at 60 and 112 ms could be identified and was consistent across the single trials. Residual CI artifact activity at latencies 8 and 228 ms was not visible for this channel. At electrode Cz, the AEP N1 signal-to-noise ratio (SNR), determined by dividing the N1 peak amplitude by the standard deviation of the prestimulus interval, was 21.17. Compared to our previous study (Hine & Debener, 2007), this value was above the group average (13.1) and within the SNR range of normal hearing individuals (3.71–44.23).

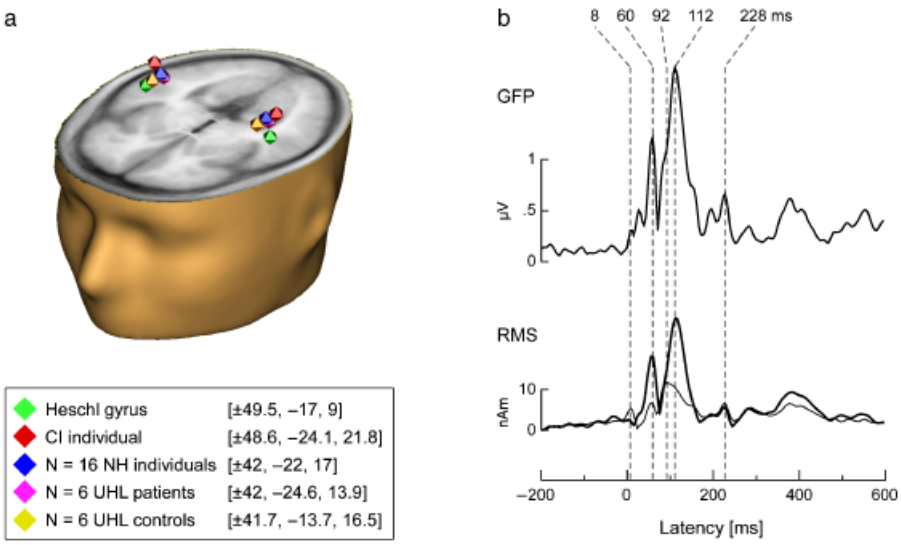

Figure 2. a: AEP source localization results in three-dimensional view, plotted on a standardized brain, as provided by BESA software. Talairach coordinates are given for the reference location in Heschl Gyrus, the CI user, and, for comparison, the grand average AEP of normal hearing controls (Hine & Debener, 2007), unilateral hearing loss (UHL) subjects, and their matched controls (Hine et al., 2007). See figure legend for color codes and sample sizes. b: Global field power, given as spatial standard deviation across all 61 channels, and root mean square regional source waveform activity for the reference region in Heschl Gyrus contralateral (bold line) and ipsilateral (thin line) to the CI prosthesis in the left ear.

Source localization of the ICA-corrected AEPs focused on the N1 onset-to-peak interval and is summarized in Figure 2. A residual variance of 7.77% confirmed a reasonable fit and a localization similar to normal hearing individuals (Hine & Debener, 2007) and unilaterally deaf subjects (Hine et al., 2007). The distance between the fitted location (Talairach coordinates $\pm$ 48.6, – 24.1, 21.8 mm) and the reference location in Heschl Gyrus was 14.7 mm for the AEPs of the CI individual, which is similar to the mean single subject localization distance to Heschl Gyrus for normal hearing subjects (mean: 15.1 mm, range 10.2–24.2 mm; Hine & Debener, 2007). The orientations of the left and right regional sources substantially differed, probably reflecting the altered N1 topography between left and right hemispheres. Therefore, the root mean square (RMS) of the regional source waveforms was considered further. A comparison of the RMS between ipsi- and contralateral sources revealed larger residual artifact activity at latencies 8 ms and 228 ms for the ipsilateral source. Activity in the P1–N1 latency range, however, was larger in the contralateral hemisphere, as could be expected based on the principle of contralateral dominance (Hine & Debener, 2007). Interestingly, the latency for the P1 peak was 60 ms and identical between ipsi- and contralateral hemispheres, whereas for the second peak corresponding to the N1, a 20-ms shorter latency was observed for the ipsi- compared to the contralateral hemisphere (92 and 112 ms). This is in sharp contrast to findings for normal hearing listeners (Hine & Debener, 2007).

Discussion

The present report demonstrates that ICA, when applied correctly, can reduce CI artifacts such that the study of cortical AEPs, including AEP source localization, becomes possible. In contrast to previous speculations, this was possible even though brain signal and artifact activity here are perfectly time-locked and spatially and temporally overlapping (cf. Luck, 2005, p. 172). A direct comparison of the resulting AEP SNR and the source localization results revealed an accuracy that was well within the range of what can be obtained in normal hearing (Hine & Debener, 2007) and unilaterally deaf individuals (Hine et al., 2007). The data quality was also beyond what seems currently possible for AEPs recorded inside the MRI scanner (Debener et al., 2007).

Regarding the CI-artifact reduction, our findings replicate and extend those reported by Gilley et al. (2006), who found that ICA minimized the CI artifact in a sample of five subjects. Our source localization findings are unique so far and demonstrate that, in addition to the AEP morphology, a detailed spatial analysis of AEPs is possible. This is important given that the degree of contralateral dominance might be a measure of cortical reorganization in response to unilateral hearing loss, and thus may directly inform about the plastic changes of the auditory system in response to CI stimulation. A recent failure in reducing the CI artifact with ICA (Martin, 2007) might be related to the used method. ICA should be applied to concatenated single trials or to continuous data, but not to averages (e.g., Makeig, Debener, Onton, & Delorme, 2004). In our experience, the success of ICA also depends on the preprocessing of the data, which should be guided by the assumptions underlying ICA.

Our findings agree with the MEG study of Pantev et al. (2006), who found that the magnetic counterpart of the N1 reflects adaptation of the auditory cortex in response to restored auditory input. Unlike MEG and other AEP studies (Kelly et al., 2005), in our study it was also possible to recover information from the auditory cortex ipsilateral to the CI device. The comparison between ipsi- and contralateral AEP activity revealed larger amplitudes contralateral to the stimulated ear and, specifically for the N1, a substantially faster response ipsilateral.

Whereas the former aspect was to be expected, the latter finding is surprising and in contrast to AEP peak latency asymmetries in normal (Hine & Debener, 2007) and unilateral deaf subjects (Hine et al., 2007). We speculate that this latency shift, if it can be replicated in larger CI populations, may relate to the adaptation of the auditory cortex to artificial monaural stimulation as provided by a CI device.

In the future, a better understanding of the central physiology of CI stimulation will help to enhance the restoration of hearing in humans (Middlebrooks, Bierer, & Snyder, 2005). We speculate that AEPs can help to improve the design and fitting of CIs, because they provide an objective means of evaluating the device and thus give information complementary to subject reports (Middlebrooks et al., 2005). On the other hand, CI users have been shown to provide important insights into the plastic changes of the human brain (Giraud et al., 2001), and noninvasive procedures offering a good temporal and reasonable spatial resolution, such as high-density AEPs, should help to further our knowledge in this matter.

The presented findings are promising and demonstrate that ICA can recover AEPs even in such adverse conditions as CI stimulation. Given that we only investigated one subject, our results are necessarily preliminary and descriptive at the time being. We are nevertheless confident that it is possible to routinely and noninvasively determine the degree of auditory cortex responses and adaptation to restored auditory input as provided by CIs.

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(Received July 20, 2007; Accepted July 27, 2007)